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A

Main Attributes of Nuclides Presented in this Book

The data given in Table A.1 can be used to determine the various decay energies for the specific radioactive decay examples as well as for the nuclear activation examples presented in this book. M stands for the nuclear rest mass; $\mathcal{M}$ stands for the atomic rest mass. The data were obtained as follows:

1. Data for atomic masses $\mathcal{M}$ were obtained from the NIST and are given in unified atomic mass units u (http://physics.nist.gov/PhysRefData/Compositions/index.html).
2. The rest mass of the proton m_{p}, neutron m_{n}, electron m_{e}, and of the unified atomic mass unit u is given by the NIST as follows:

$$m_{\mathrm{p}} = 1.672\ 621\ 637 \times 10^{-27}\ \mathrm{kg} = 1.007276\ 467\ \mathrm{u} = 938.272\ 013\ \mathrm{MeV}/c^2 \quad \text{(A.1)}$$

$$m_{\mathrm{n}} = 1.674\ 927\ 211 \times 10^{-27}\ \mathrm{kg} = 1.008664\ 916\ \mathrm{u} = 939.565\ 346\ \mathrm{MeV}/c^2 \quad \text{(A.2)}$$

$$m_{\mathrm{e}} = 9.109\ 382\ 215 \times 10^{-31}\ \mathrm{kg} = 5.485799\ 094 \times 10^{-4}\mathrm{u} = 0.510\ 998\ 910\ \mathrm{MeV}/c^2 \quad \text{(A.3)}$$

$$1\ \mathrm{u} = 1.660\ 538\ 782 \times 10^{-27}\ \mathrm{kg} = 931.494\ 028\ \mathrm{MeV}/c^2 \quad \text{(A.4)}$$

3. For a given nuclide, its nuclear rest energy Mc^2 was determined by subtracting the rest energy of all atomic orbital electrons $(Zm_{\mathrm{e}}c^2)$ from the atomic rest energy $\mathcal{M}(\mathrm{u})c^2$ as follows

$$Mc^2 = \mathcal{M}(\mathrm{u})c^2 - Zm_{\mathrm{e}}c^2 = \mathcal{M}(\mathrm{u}) \times 931.494\ 028\ \mathrm{MeV/u} - Z \times 0.510\ 999\ \mathrm{MeV}. \quad \text{(A.5)}$$

   The binding energy of orbital electrons to the nucleus is ignored in (A.5).
4. The nuclear binding energy E_{B} for a given nuclide was determined using the mass deficit equation given in (1.25) to get

$$E_{\mathrm{B}} = Zm_{\mathrm{p}}c^2 + (A-Z)m_{\mathrm{n}}c^2 - Mc^2, \quad \text{(A.6)}$$

   with Mc^2 given in (A.5) and the rest energy of the proton $m_{\mathrm{p}}c^2$, neutron $m_{\mathrm{n}}c^2$, and electron $m_{\mathrm{e}}c^2$ given in (A.1), (A.2), and (A.3), respectively.
5. For a given nuclide the binding energy per nucleon E_{B}/A is calculated by dividing the binding energy E_{B} of (A.6) with the number of nucleons equal to the atomic mass number A of a given nuclide.

Table A.1. Main attributes of nuclides presented in this book (a = year; d = day; h = hour)

Element and its nuclide	Symbol	Z	A	Atomic mass $\mathcal{M}$(u) NIST	Nuclear rest energy Mc^2(MeV) (A.5)	Binding energy E_B(MeV) (A.6)	E_B(MeV)/ nucleon E_B/A	Half-life $t_{1/2}$
Hydrogen	H	1	1	1.007825	938.2720	–	–	Stable
Deuterium	D	1	2	2.014102	1875.6128	2.22458	1.1123	Stable
Tritium	T	1	3	3.016049	2808.9209	8.48182	2.8273	12.3 a
Helium	He	2	3	3.016029	2808.3913	7.71808	2.5727	Stable
	He	2	4	4.002603	3727.3791	28.29569	7.0739	Stable
	He	2	5	5.012220	4667.8311	27.40906	5.4818	8×10^{-22} s
Lithium	Li	3	5	5.012540	4667.6182	26.32865	5.2657	10^{-21} s
	Li	3	7	7.016004	6533.8330	39.24459	5.6064	Stable
Beryllium	Be	4	7	7.016929	6534.1838	37.60044	5.3715	53 d
	Be	4	8	8.005305	7454.8500	56.49955	7.0624	Stable
	Be	4	9	9.012182	8392.7499	58.16497	6.4628	Stable
Boron	B	5	9	9.013329	8393.3071	56.31450	6.2572	8.5×10^{-19} s
	B	5	10	10.012937	9324.4362	64.75071	6.4751	Stable
Carbon	C	6	12	12.000000	11174.8625	92.16175	7.6801	Stable
	C	6	13	13.003355	12109.4816	97.10812	7.4699	Stable
	C	6	14	14.003242	13040.8703	105.28455	7.5203	5730 a
Nitrogen	N	7	13	13.005739	12111.1910	94.10534	7.2389	10 min
	N	7	14	14.003074	13040.2028	104.65871	7.4756	Stable
Oxygen	O	8	16	15.994915	14895.0796	127.61927	7.9762	Stable
	O	8	17	16.999132	15830.5019	131.76231	7.7507	Stable
	O	8	18	17.999160	16792.0227	139.88713	7.7671	Stable
Fluorine	F	9	18	18.000938	16763.1673	137.36925	7.6316	1.83 h
Neon	Ne	10	20	19.992440	18617.7287	160.64489	8.0323	Stable
Chromium	Cr	24	43	42.997710	40039.8468	330.42378	7.6843	21 ms
Manganese	Mn	25	44	44.006870	40979.3623	329.18028	7.4814	0.1 μs
Iron	Fe	26	45	45.014560	41917.5085	329.30608	7.3179	0.35 μs
Cobalt	Co	27	59	58.933200	54822.1279	517.30835	8.7679	Stable
	Co	27	60	59.933822	55814.2014	524.80028	8.7467	5.26 a
Nickel	Ni	28	60	59.930791	55810.8665	526.81866	8.7807	Stable

Table A.1. Main attributes of nuclides presented in this book (Continued)

Element and its nuclide	Symbol	Z	A	Atomic mass $\mathcal{M}$(u) NIST	Nuclear rest energy Mc^2(MeV) (A.5)	Binding energy E_B(MeV) (A.6)	E_B(MeV)/ nucleon E_B/A	Half-life $t_{1/2}$
Molybdenum	Mo	42	98	97.905408	91 176.8422	846.24319	8.6351	Stable
	Mo	42	99	98.907712	92 110.4811	852.16816	8.6077	65.94 h
Technetium 99(m)	Tc	43	99	98.906255	92 108.6140	852.74339	8.6136	6 h
Technetium	Tc	43	99	98.906255	92 108.6140	852.74339	8.6136	2.13×10^5 a
Ruthenium	Ru	44	99	98.905939	92 107.8075	852.25510	8.6086	Stable
Cesium	Cs	55	137	136.907084	127 500.0283	1149.29287	8.3890	30.2 a
Barium	Ba	56	137	136.905821	127 498.3408	1149.68701	8.3919	Stable
Osmium	Os	76	192	191.961479	178 772.1383	1526.11771	7.9485	Stable
Iridium	Ir	77	191	190.960591	177 839.3062	1518.09123	7.9481	Stable
	Ir	77	192	191.962602	178 772.6733	1524.28931	7.9390	74 d
	Ir	77	193	192.962924	179 704.4673	1532.06069	7.9381	Stable
Platinum	Pt	78	192	191.961035	178 770.7027	1524.96663	7.9425	Stable
Gold	Au	79	197	196.966552	183 432.8010	1559.40165	7.9158	Stable
Lead	Pb	82	206	205.974449	191 820.0106	1622.34012	7.8754	Stable
	Pb	82	207	206.975881	192 754.8983	1629.07791	7.8699	Stable
	Pb	82	208	207.976636	193 687.0956	1636.44573	7.8675	Stable
Bismuth	Bi	83	209	208.980383	194 621.5690	1640.24403	7.8481	Stable
Radon	Rn	86	222	222.017571	206 764.0985	1708.18500	7.6945	3.8 d
Radium	Ra	88	226	226.025403	210 496.3482	1731.61005	7.6620	1602 a
Thorium	Th	90	232	232.038050	216 096.0718	1766.69194	7.6151	1.4×10^{16} a
Uranium	U	92	233	233.039628	217 028.0134	1771.72828	7.6040	1.6×10^6 a
	U	92	235	235.043923	218 895.0023	1783.87084	7.5909	0.7×10^9 a
	U	92	238	238.050783	221 695.8740	1801.69521	7.5010	4.5×10^9 a
	U	92	239	239.054288	222 630.6331	1806.50145	7.5586	23.5 min
Neptunium	Np	93	239	239.052913	222 628.8587	1806.98260	7.5606	2.35 d
Plutonium	Pu	94	239	239.052157	222 627.6258	1806.92208	7.5603	24×10^3 a
Californium	Cf	98	252	252.081620	234 762.4495	1881.27476	7.4654	2.65 a
	Cf	98	256	256.093440	238 499.3459	1902.54981	7.4318	12.3 min
Fermium	Fm	100	256	256.091767	238 496.8555	1902.54353	7.4318	158 min

B

Basic Characteristics of the Main Radioactive Decay Modes

The following decay modes are presented: α decay, β^- decay, β^+ decay, electron capture, γ decay, internal conversion, proton emission decay, and neutron emission decay. For each decay mode the table gives the basic relationship, the decay energy Q, and the kinetic energy E_K of the decay products. P stands for the parent nucleus or atom; D for the daughter nucleus or atom. M represents the nuclear rest mass, $\mathcal{M}$ the atomic rest mass, m_e the electron rest mass, m_p the proton rest mass, and m_n the neutron rest mass

Table B.1. Alpha (α) Decay

Basic relationship: [see (11.2)]

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\mathrm{D} + \alpha + Q_\alpha \tag{B.1} $$

Decay energy: [see (11.3) and (11.4)]

$$ \begin{aligned} Q_\alpha &= \{M(\mathrm{P}) - [M(\mathrm{D}) + m_\alpha]\}\, c^2 = \left\{\mathcal{M}(\mathrm{P}) - [\mathcal{M}(\mathrm{D}) + \mathcal{M}({}^4_2\mathrm{He})]\right\} c^2 \\ &= E_\mathrm{B}(\mathrm{D}) + E_\mathrm{B}(\alpha) - E_\mathrm{B}(\mathrm{P}) = (E_\mathrm{K})_\alpha + (E_\mathrm{K})_\mathrm{D} \end{aligned} \tag{B.2} $$

Kinetic energy of α particle: [see (11.7)]

$$ (E_\mathrm{K})_\alpha = \frac{Q_\alpha}{1 + \dfrac{m_\alpha}{M(\mathrm{D})}} \approx \frac{A_\mathrm{P} - 4}{A_\mathrm{P}} Q_\alpha \tag{B.3} $$

Daughter recoil kinetic energy: [see (11.8)]

$$ (E_\mathrm{K})_\mathrm{D} = \frac{Q_\alpha}{1 + \dfrac{M(\mathrm{D})}{m_\alpha}} \approx \frac{4}{A_\mathrm{P}} Q_\alpha \tag{B.4} $$

Table B.2. Beta minus (β^-) Decay

Basic relationship: [see (11.15)]

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}_{\mathrm{Z}+1}^{\quad\mathrm{A}}\mathrm{D} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + Q_{\beta^-} \tag{B.5} $$

Decay energy: [see (11.19), (11.25), and (11.26)]

$$ \begin{aligned} Q_{\beta^-} &= \{M(\mathrm{P}) - [M(\mathrm{D}) + m_\mathrm{e}]\}\, c^2 = \{\mathcal{M}(\mathrm{P}) - \mathcal{M}(\mathrm{D})\}\, c^2 \\ &= (E_{\beta^-})_{\max} + (E_\mathrm{K})_{\mathrm{D}\max} = (E_\beta)_{\max} \left\{ 1 + \frac{m_\mathrm{e}c^2 + \frac{1}{2}(E_\beta)_{\max}}{M(\mathrm{D})c^2} \right\} \end{aligned} \tag{B.6} $$

Daughter maximum recoil kinetic energy: [see (11.23)]

$$ (E_\mathrm{K})_{\mathrm{D}\max} = \frac{m_\mathrm{e}}{M(\mathrm{D})} (E_{\beta^-})_{\max} \left\{ 1 + \frac{(E_{\beta^-})_{\max}}{2M(\mathrm{D})c^2} \right\} \tag{B.7} $$

Combined energy given to electron/antineutrino

$$ (E_{\beta^-})_{\max} = Q_{\beta^-} - (E_\mathrm{K})_{\mathrm{D}\max} \approx Q_{\beta^-} \tag{B.8} $$

Table B.3. Beta plus (β^+) Decay

Basic relationship: [see (11.16)]

$$ {}^{A}_{Z}P \rightarrow {}^{\ \ \ A}_{Z-1}D + e^{+} + \nu_{e} + Q_{\beta+} \tag{B.9} $$

Decay energy: [see (11.19), (11.33), and (11.34)]

$$ \begin{aligned} Q_{\beta+} &= \{M(P) - [M(D) + m_e]\}\, c^2 = \{\mathcal{M}(P) - \mathcal{M}(D) + 2m_e\}\, c^2 \\ &= (E_{\beta+})_{\max} + (E_K)_{D\max} = (E_\beta)_{\max} \left\{ 1 + \frac{m_e c^2 + \frac{1}{2}(E_\beta)_{\max}}{M(D)c^2} \right\} \end{aligned} \tag{B.10} $$

Daughter maximum recoil kinetic energy: [see (11.24)]

$$ (E_K)_{D\max} = \frac{m_e}{M(D)} (E_{\beta+})_{\max} \left\{ 1 + \frac{(E_{\beta+})_{\max}}{2mM(D)c^2} \right\} \tag{B.11} $$

Combined energy given to positron/neutrino

$$ (E_{\beta+})_{\max} = Q_{\beta+} - (E_K)_{D\max} \approx Q_{\beta+} \tag{B.12} $$

Table B.4. Electron Capture (EC)

Basic relationship: [see (11.17)]

$$ {}^{A}_{Z}P + e^{-} = {}^{\ \ \ A}_{Z-1}D + \nu_{e} + Q_{EC} \tag{B.13} $$

Decay energy: [see (11.42) and (11.43)]

$$ \begin{aligned} Q_{EC} &= \{[M(P) + m_e] - M(D)\}\, c^2 = \{M(P) - [M(D) - m_e]\}\, c^2 \\ &= \{\mathcal{M}(P) - \mathcal{M}(D)\}\, c^2 = (E_K)_D + E_{\nu_e} \end{aligned} \tag{B.14} $$

Daughter recoil kinetic energy: [see (11.45)]

$$ (E_K)_D = \frac{E_\nu^2}{2M(D)c^2} \approx \frac{Q_{EC}}{2M(D)c^2} \tag{B.15} $$

Energy given to neutrino: [see (11.48)]

$$ E_\nu = \left\{ -1 + \sqrt{1 + \frac{2(Q_{EC} - E_B)}{M(D)c^2}} \right\} M(D)c^2 \approx Q_{EC} - E_B \tag{B.16} $$

Table B.5. Gamma (γ) Decay

Basic relationship: [see (11.52)]

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P}^{*} \rightarrow {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} + \gamma + Q_{\gamma} \tag{B.17} $$

Decay energy: [see (11.53)]

$$ Q_{\gamma} = E^{*} - E = E_{\gamma} + (E_{\mathrm{K}})_{\mathrm{D}} = E_{\gamma}\left\{1 + \frac{E_{\gamma}}{2M(\mathrm{D})c^{2}}\right\} \tag{B.18} $$

Daughter recoil kinetic energy: [see (11.54)]

$$ (E_{\mathrm{K}})_{\mathrm{D}} = \frac{E_{\gamma}^{2}}{2M(\mathrm{D})c^{2}} \tag{B.19} $$

Energy of gamma photon: [see (11.55)]

$$ E_{\gamma} = Q_{\gamma} - (E_{\mathrm{K}})_{\mathrm{D}} = Q_{\gamma}\left\{1 - \frac{E_{\gamma}}{2M(\mathrm{D})c^{2}}\right\} \approx Q_{\gamma} \tag{B.20} $$

Table B.6. Internal Conversion (IC)

Basic relationship: [see (11.56)]

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P}^{*} \rightarrow {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P}^{+} + \mathrm{e}^{-} + Q_{\mathrm{IC}} \tag{B.21} $$

Decay energy: [see (11.57)]

$$ Q_{\mathrm{IC}} = (E^{*} - E) - E_{\mathrm{B}} = (E_{\mathrm{K}})_{\mathrm{IC}} + (E_{\mathrm{K}})_{\mathrm{D}} \tag{B.22} $$

Daughter recoil kinetic energy: [see (11.58)]

$$ (E_{\mathrm{K}})_{\mathrm{D}} = \frac{m_{\mathrm{e}}}{M(\mathrm{D})}(E_{\mathrm{K}})_{\mathrm{IC}} + \frac{(E_{\mathrm{K}})_{\mathrm{IC}}^{2}}{2M(\mathrm{D})c^{2}} = \frac{(E_{\mathrm{K}})_{\mathrm{IC}}}{M(\mathrm{D})c^{2}}\left\{m_{\mathrm{e}}c^{2} + \frac{1}{2}(E_{\mathrm{K}})_{\mathrm{IC}}\right\} \tag{B.23} $$

Kinetic energy of internal conversion electron

$$ (E_{\mathrm{K}})_{\mathrm{IC}} = Q_{\mathrm{IC}} - (E_{\mathrm{K}})_{\mathrm{D}} \approx Q_{\mathrm{IC}} \tag{B.24} $$

Table B.7. Proton Emission Decay

Basic relationship: [see (11.63)]

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}^{\mathrm{A-1}}_{\mathrm{Z-1}}\mathrm{D} + \mathrm{p} + Q_{\mathrm{p}} \tag{B.25} $$

Decay energy: [see (11.64) and (11.65)]

$$ \begin{aligned} Q_{\mathrm{P}} &= \{M(\mathrm{P}) - [M(\mathrm{D}) + m_{\mathrm{p}}]\} c^2 = \left\{\mathcal{M}(\mathrm{P}) - [\mathcal{M}(\mathrm{D}) + \mathcal{M}({}^{1}_{1}\mathrm{H})]\right\} c^2 \\ &= E_{\mathrm{B}}(D) - E_{\mathrm{B}}(P) = (E_{\mathrm{K}})_{\mathrm{p}} + (E_{\mathrm{K}})_{\mathrm{D}} \end{aligned} \tag{B.26} $$

Kinetic energy of the emitted proton: [see (11.67)]

$$ (E_{\mathrm{K}})_{\mathrm{p}} = \frac{Q_{\mathrm{p}}}{1 + \dfrac{m_{\mathrm{p}}}{M(\mathrm{D})}} \tag{B.27} $$

Daughter recoil kinetic energy: [see (11.68)]

$$ (E_{\mathrm{K}})_{\mathrm{D}} = \frac{Q_{\mathrm{p}}}{1 + \dfrac{M(\mathrm{D})}{m_{\mathrm{p}}}} \tag{B.28} $$

Table B.8. Neutron Emission Decay

Basic relationship: [see (11.85)]

$$ {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}^{\mathrm{A-1}}_{\mathrm{Z}}\mathrm{D} + \mathrm{n} + Q_{\mathrm{n}} \tag{B.29} $$

Decay energy: [see (11.86) and (11.87)]

$$ \begin{aligned} Q_{\mathrm{n}} &= \{M(\mathrm{P}) - [M(\mathrm{D}) + m_{\mathrm{n}}]\} c^2 = \{\mathcal{M}(\mathrm{P}) - [\mathcal{M}(\mathrm{D}) + m_{\mathrm{n}}]\} c^2 \\ &= E_{\mathrm{B}}(\mathrm{D}) - E_{\mathrm{B}}(\mathrm{P}) = (E_{\mathrm{K}})_{\mathrm{n}} + (E_{\mathrm{K}})_{\mathrm{D}} \end{aligned} \tag{B.30} $$

Kinetic energy of the emitted neutron: [see (11.89)]

$$ (E_{\mathrm{K}})_{\mathrm{n}} = \frac{Q_{\mathrm{n}}}{1 + \dfrac{m_{\mathrm{n}}}{M(\mathrm{D})}} \tag{B.31} $$

Daughter recoil kinetic energy: [see (11.90)]

$$ (E_{\mathrm{K}})_{\mathrm{D}} = \frac{Q_{\mathrm{n}}}{1 + \dfrac{M(\mathrm{D})}{m_{\mathrm{n}}}} \tag{B.32} $$

C

Short Biographies of Scientists Whose Work is Discussed in This Book

The biographical data were obtained mainly from two sources:

1. Book by William H. Cropper: "*Great Physicists: The Life and Times of Leading Physicists from Galileo to Hawking*"' published by Oxford University Press in 2001.
2. The website: www.Nobelprize.org that contains biographies and Nobel lectures of all Nobel Prize winners in Physics, Chemistry, Physiology or Medicine, Literature, Peace, and Economic Sciences from 1901 to date.

ANDERSON, Carl David (1905–1991)

American physicist, educated at the California Institute of Technology (Caltech) in Pasadena (B.Sc. in engineering physics in 1927; Ph.D. in engineering physics in 1930). He spent his entire professional career at Caltech, becoming Professor of Physics in 1939, Chairman of the Physics, Mathematics & Astronomy division (1962–1970), and Professor Emeritus in 1976.

Early in his career Anderson concentrated on studies of x rays, later on on studies of cosmic rays with cloud chambers that lead to the discovery of the positron in 1932. Positron was the first known particle in the category of antimatter. *Paul A.M. Dirac* enunciated its existence in 1928 with his relativistic quantum theory for the motion of electrons in electric and magnetic fields. Dirac's theory incorporated Albert Einstein's special theory of relativity and predicted the existence of an antiparticle to the electron (same mass, opposite charge). In 1933 Anderson succeeded in producing positrons by gamma radiation through the effect of pair production. In 1936 Anderson, in collaboration with his graduate student Seth Neddermeyer, discovered, again while studying cosmic radiation, the muon (μ meson), the first known elementary particle that is not a basic building block of matter.

In 1936 Anderson shared the Nobel Prize in Physics with Victor Franz Hess, an Austrian physicist. Anderson received the Prize *"for his discovery of the positron"* and Hess *"for his discovery of cosmic radiation."*

AUGER, Pierre Victor (1899–1993)

French physicist who was active as a basic scientist in atomic, nuclear and cosmic ray physics but also made important contributions to French and international scientific organizations. The world's largest cosmic ray detector, the Pierre Auger observatory, is named after him. Auger is also credited with the discovery in 1925 of radiation*less* electronic transitions in atoms that are followed by emission of orbital electrons. The process is named after him as the Auger effect and the emitted electrons are called Auger electrons. *Lise Meitner* actually discovered the radiation*less* atomic transition process in 1923, two years before Auger; nonetheless, the process is referred to as the Auger effect.

AVOGADRO, Amedeo (1776–1856)

Italian lawyer, chemist, physicist, best known for the "Avogadro principle" and "Avogadro number." The Avogadro's principle states that "equal volumes of all gases at the same temperature and pressure contain the same number of molecules." The concepts of gram–atom and gram-mole were introduced long after Avogadro's time; however, Avogadro is credited with introducing the distinction between the molecule and the atom. The number of atoms per gram-atom and number of molecules per gram-mole is constant for all atomic and molecular entities and referred to as Avogadro number $\left(N_{\mathrm{A}} = 6.022\times 10^{23}\ \text{atom/mol}\right)$ in honor of Avogadro's contributions to chemistry and physics.

BALMER, Johann Jakob (1825–1898)

Swiss mathematician who studied in Germany at the University of Karlsruhe and the University of Berlin before receiving a doctorate at the University of Basel. He then spent his professional life teaching mathematics at the University of Basel.

Balmer is best known for his work on spectral lines emitted by the hydrogen gas. In 1885 he published a formula that predicted the wavelengths of the lines in the visible part of the hydrogen spectrum. The formula predicted the lines very accurately but was empirical rather than based on any physical principles. Several other scientists subsequently proposed similar empirical formulas for hydrogen lines emitted in other portions of the photon spectrum (Lymann in the ultraviolet and Paschen, Brackett and Pfund in the infrared). In 1913 *Niels Bohr* derived from first principles the general relationship for spectral lines of hydrogen. The relationship is governed by n, the principal quantum number, and contains a constant that is now referred to as the Rydberg constant $\left(R_{\infty} = 109\,737\ \text{cm}^{-1}\right)$. The spectral line series for $n = 1$ is called the Lymann series; for $n = 2$ the Balmer series; for $n = 3$ the Paschen series; for $n = 4$ the Brackett series; for $n = 5$ the Pfund series, and for $n = 6$ the Humphreys series.

BARKLA, Charles Glover (1877–1944)

British physicist, educated in mathematics and physics at the University College in Liverpool from where he graduated in 1898. He worked as research assistant with *Joseph J. Thomson* in the Cavendish Laboratory in Cambridge and as academic physicist at the University of London. In 1913 he was appointed Chair of Natural Philosophy at the University of Edinburgh and held the position until his death in 1944.

Barklas's most important research involved studies of the production of x rays and of their interactions with matter. He is credited with the discovery of characteristic (fluorescent) radiation and the polarization of x rays between 1904 and 1907.

In 1917 Barkla was awarded the Nobel Prize in Physics *"for his discovery of the characteristic Röntgen radiation of the elements."*

BECQUEREL, Henri Antoine (1852–1908)

French physicist, educated at the École Polytechnique in basic science and at the École des Ponts et Chaussées becoming an *ingénieur* in 1877. In 1888 he acquired the degree of *docteur-ès-sciences*. In 1895 he became Professor of Physics at the École Polytechnique in Paris, the foremost French "grande école" of engineering, founded in 1794.

Becquerel was active in many areas of physics investigating polarization of visible light, naturally occurring phosphorescence in uranium salts, and terrestrial magnetism. In 1896, shortly after *Wilhelm Röntgen*'s discovery of x rays, Becquerel accidentally discovered natural radio-activity while investigating phosphorescence in uranium salts upon exposure to light. He observed that when the salts were placed near a photographic plate covered with opaque paper, the developed plate was nonetheless fogged. Becquerel concluded that the uranium salts were emitting penetrating rays that were emanating from uranium atoms. He subsequently showed that the rays were causing ionization of gases and that, in contrast to Röntgen's x rays, they were deflected by electric and magnetic fields.

In 1903 Becquerel shared the Nobel Prize in Physics with *Pierre* and *Marie Curie*. He was awarded the prize *"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"* and the Curies received their prize *"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel."*

Becquerel and his work are honored by the SI unit of radioactivity named Becquerel (Bq). In addition, there are Becquerel craters on the moon and Mars.

BERGER, Martin Jacob (1922–2004)

Austrian-born American physicist, educated at the University of Chicago where he received his degrees in Physics: B.Sc. in 1943, M.Sc. in 1948, and doctorate in 1951. In 1952 Berger joined the Radiation Theory Section at the National Bureau of Standards (NBS), now National Institute of Science and Technology (NIST) in Washington D.C. In 1964 he became the Section Chief and later, as well, Director of the Photon and Charged-Particle Data Center at the NBS/NIST, a position he held until his retirement in 1988.

Berger is best known for his early work on the transport of gamma rays and applications of Monte Carlo calculations in complex media involving boundaries and inhomogeneities. He also worked on charged-particle transport with emphasis on electrons and protons, and developed algorithms for use in charged particle Monte Carlo codes. His ETRAN code, first published in the 1960s, became the industry standard for coupled electron-photon transport. Berger, in collaboration with *Stephen Seltzer*, also developed cross-section data for electron and heavy charged particle interactions as well as for electron bremsstrahlung production. He was also involved in applications of Monte Carlo calculations to important problems in radiological physics and radiation dosimetry.

BETHE, Hans Albrecht (1906–2005)

German-born American physicist, educated at the Universities of Frankfurt and Munich. He received his doctorate in theoretical physics under Arnold Sommerfeld in 1928. For four years he worked as Assistant Professor at the University of Munich, then spent a year in Cambridge and a year in Rome with *Enrico Fermi*. He returned to Germany as Assistant Professor at the University of Tübingen but lost the position during the rise of Nazism. He first emigrated to England and then in 1935 moved to Cornell University in Ithaca, New York as Professor of Physics. He stayed at Cornell essentially all his professional life, but also served as Director of Theoretical Physics on the Manhattan project at Los Alamos (1943–1946).

Bethe made important theoretical contributions to radiation physics, nuclear physics, quantum mechanics, and quantum electrodynamics. He was also a strong advocate for peaceful use of atomic energy, despite having been involved with the Manhattan project as well as with the development of the hydrogen bomb. In collision theory Bethe derived the stopping power relationships that govern inelastic collisions of fast particles with atoms. With Heitler, he developed the collision theory for relativistic electrons interacting with atomic nuclei and producing bremsstrahlung radiation in the process. Bethe's work in nuclear physics lead to the discovery of the reactions that govern the energy production in stars.

In 1967 Bethe was awarded the Nobel Prize in Physics "*for his theory of nuclear reactions, especially his discoveries concerning the energy production in stars.*"

BHABHA, Homi Jehandir (1909–1966)

Indian nuclear physicist, educated in Mumbai (Bombay) and Cambridge (U.K.) where he first studied engineering and later-on physics and received his Ph.D. in physics in 1935 studying cosmic rays. He was already well respected in the international physics community when he returned to India in 1939. He took a post in theoretical physics at the Indian Institute of Science in Bangalore under C.V. Raman and carried out experimental work in cosmic radiation and theoretical work in mathematics. In 1945 he became director of the newly established Tata Institute of Fundamental Research (TIFR) in Mumbai and remained in the position until 1966 when he died in an airplane crash.

Under Bhabha's leadership TIFR became a leading nuclear science institute committed to peaceful use of nuclear energy. He was very influential in Indian nuclear policy and developed a close personal relationship with India's first Prime Minister Jawaharlal P. Nehru. He was instrumental in getting the Indian Constituent Assembly to pass the Indian Atomic Energy Act and creating the Indian Atomic Energy Commission.

Bhabha's important contributions to nuclear physics are recognized by the term Bhabha scattering which defines position scattering on electrons. He was also elected Fellow of the Royal Society and his contribution to Indian nuclear science was recognized in 1967 by renaming the TIFR into Bhabha Atomic Research Centre (BARC).

BLOCH, Felix (1905–1983)

Swiss-born American physicist, educated at the Eidgenössische Technische Hochschule in Zürich (ETHZ) and at the University of Leipzig where he received his doctorate in physics in 1928. During the next few years he held various assistantships and fellowships that gave him the opportunity to work with the giants of modern physics (Pauli, Heisenberg, Bohr, and Fermi) and to further his understanding of solid state physics in general and stopping powers of charged particles in particular. In 1933 Bloch left Germany and in 1934 accepted a position at Stanford University where he got involved with experimental physics of neutron momenta and polarized neutron beams. During the war years he worked on the Manhattan project at Los Alamos and on radar technology at Harvard where he became familiar with modern techniques of electronics. This helped him upon return to Stanford in 1945 with development of new techniques for measuring nuclear moments that culminated in 1946 with the invention of the nuclear magnetic resonance (NMR) technique, a purely electromagnetic procedure for the study of nuclear moments in solids, liquids, and gases. At Harvard *Edward M. Purcell* with students Robert Pound and Henry C. Torrey invented the NMR technique independently and at about the same time as Bloch.

In 1952 Bloch and Purcell received the Nobel Prize in Physics "*for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith.*" Since the late 1970s NMR provided the basis for magnetic resonance imaging (MRI), which is widely used as a non-invasive diagnostic imaging technique.

BOHR, Niels Henrik David (1885–1962)

Danish physicist, educated at the University of Copenhagen where he obtained his M.Sc. degree in physics in 1909 and doctorate in physics in 1911. Between 1911 and

1916 Bohr held various academic appointments in the U.K. and Copenhagen. In 1911 he worked in Cambridge with *Joseph J. Thomson* and in 1912 he worked in Manchester with *Ernest Rutherford*. He was a lecturer in physics at the University of Copenhagen in 1913 and at the University of Manchester between 1914 and 1916. In 1916 he was appointed Professor of Theoretical Physics and in 1920 he also became the first Director of the Institute of Theoretical Physics (now Niels Bohr Institute) at the University of Copenhagen. He remained in both positions until his death in 1962.

Bohr was an exceptionally gifted theoretical physicist who made important contributions to atomic, nuclear, and quantum physics. He is best known for his expansion in 1913 of the Rutherford's atomic model into the realm of Planck's quantum physics to arrive at a model that is now called the Rutherford-Bohr atomic model. With four postulates that merged simple classical physics concepts with the idea of quantization of angular momenta for electrons revolving in allowed orbits about the nucleus, he succeeded in explaining the dynamics of one-electron structures and in predicting the wavelengths of the emitted radiation.

Bohr is also known as the author of the principle of complementarity which states that a complete description of an atomic scale phenomenon requires an evaluation from both the wave and particle perspective. In 1938 he proposed the so-called liquid drop nuclear model and in 1939 he succeeded in explaining the neutron fission of natural uranium in terms of fissionable uranium-235 (an isotope with an abundance of only 0.7 % in natural uranium) and the much more abundant non-fissionable uranium-238.

During World War II Bohr worked on the Manhattan project in Los Alamos but his contribution to the development of atomic weapons was only minor. After the war he used his considerable credibility and influence to promote peaceful use of the atomic energy and in 1954 helped found the CERN (Centre Européen de Recherche Nucléaire) in Geneva, touted as the world's largest particle physics laboratory and the birthplace of the *worldwide web*. In addition to producing his theoretical masterworks, Bohr was also keenly interested in politics and advised Presidents Roosevelt and Truman as well as Prime Minister Churchill on nuclear matters. Only Albert Einstein and Marie Curie among scientists of the 20th century have attained such esteem from physics colleagues, world leaders, and the general public.

In tribute to Bohr's contributions to modern physics the element with atomic number 107 is named bohrium (Bh). Bohr received the 1922 Nobel Prize in Physics *"for his services in the investigation of the structure of atoms and of the radiation emanating from them."*

BORN Max (1882–1970)

German mathematician and physicist, educated at universities of Breslau (1901), Heidelberg (1902), Zürich (1903), and Göttingen where he received his doctorate in 1907. In 1909 he was appointed lecturer at the University of Göttingen and in 1912 he moved to the University of Chicago. In 1919 he became Professor of Physics at the University of Frankfurt and then in 1921 Professor of Physics at the University of Göttingen. From 1933 until 1936 he lectured at the University of Cambridge and from 1936 until 1953 at the University of Edinburgh.

Born is best known for his work on relativity in general and the relativistic electron in particular. He was also working on crystal lattices and on quantum theory, in particular on the statistical interpretation of quantum mechanics. He is best known for his formulation of the now-standard interpretation of the probability density for $\psi^*\psi$ in the Schrödinger equation of wave mechanics.

In 1954 Born shared the Nobel Prize in Physics with Walther Bothe. Born received his half of the prize "*for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction*" and Bothe "*for the coincidence method and his discoveries made herewith.*"

BRAGG, William Henry (1862–1942)

British physicist, educated at King William College on Isle of Man and at the Trinity College at Cambridge where he graduated in 1884. His first academic appointment was at the University of Adelaide in Australia from 1885 until 1909. In 1909 he returned to England and worked as Professor of Physics at the University of Leeds from 1909 until 1915 and at the University College in London from 1915 until 1923. From 1923 until 1942 he was Director of the Royal Institution in London.

Henry Bragg is best known for the work he carried out in collaboration with his son Lawrence on the diffraction of x rays on crystalline structures. *Von Laue* discovered the diffraction of x rays on crystals; however, it was the father-son Bragg team that developed the discipline of x-ray crystallography based on the Bragg crystal spectrometer, a very important practical tool in solid state physics and analytical chemistry.

The 1915 Nobel Prize in Physics was awarded to William Henry Bragg and his son *William Lawrence Bragg* "*for their services in the analysis of crystal structure by means of x rays.*"

BRAGG, William Lawrence (1890–1971)

Australian-born British physicist, educated at Adelaide University where he graduated at age 18 with an honors B.A. degree in mathematics. He then entered Trinity College in Cambridge, continued his studies in mathematics but switched to physics the second year and graduated in physics in 1912. He first worked as lecturer at the Cavendish Laboratory in Cambridge but from 1915 spent three years in the army. He became Langworthy Professor of Physics at the University of Manchester in 1919. During 1938 he was Director of National Physical Laboratory in Teddington and then worked in Cambridge as the Cavendish Professor of Experimental Physics from 1939 until 1954 and as Director of the Royal Institution from 1954 until 1966.

In 1912 William L. Bragg became interested in the great debate on the nature of x rays: were they waves or particles? Following the experiments of *von Laue* and colleagues he developed an ingenious way of treating the phenomenon of x-ray diffraction on crystalline structures. He pointed out that the regular arrangement of atoms in a crystal defines a large variety of planes on which the atoms effectively lie. This means that the atoms in a regular lattice simply behave as if they form reflecting planes. The well-known Bragg equation is then expressed as $2d \sin\phi = n\lambda$, with d the separation between two atomic planes, ϕ the angle of incidence of the x-ray beam, λ the x-ray wavelength, and n an integer. The basis of a Bragg spectrometer is then as follows. For a known d, an x-ray spectrum can be analyzed by varying ϕ and observing the intensity of the reflected x rays that are scattered through and angle $\theta = 2\phi$ from the direction of the incident collimated beam. On the other hand, if mono-energetic x rays with a known λ are used, it is possible to determine various effective values of d in a given crystal and hence the basic atomic spacing a. With the knowledge of a one may determine the *Avogadro*'s number N_A with great accuracy.

The 1915 Nobel Prize in Physics was awarded to William Lawrence Bragg and his father William Henry Bragg *"for their services in the analysis of crystal structure by means of x rays."*

CHADWICK, James (1891–1974)

British physicist, educated at Manchester University (B.Sc. in 1911 and M.Sc. in 1913) before continuing his studies in the Physikalisch Technische Reichanstalt at Charlottenburg. In 1919 he moved to Cambridge to work with *Ernest Rutherford* on nuclear physics research. He remained in Cambridge until 1935 when he became the Chairman of Physics at the University of Liverpool. From 1943 to 1946 he was the Head of the British Mission attached to the Manhattan project.

Chadwick is best known for his 1932 discovery of the neutron, a constituent of the atomic nucleus that in contrast to the proton is devoid of any electrical charge. In recognition of this fundamental discovery that paved the way toward the discovery of nuclear fission, Chadwick was awarded the 1935 Nobel Prize in Physics *"for the discovery of the neutron."*

COMPTON, Arthur Holly (1892–1962)

American physicist, educated at College of Wooster (B.Sc. in 1913) and Princeton University (M.A. in 1914 and Ph.D. in 1916). He worked as physics instructor at the University of Minnesota, research engineer at Westinghouse in Pittsburgh, and research fellow at Cambridge University. Upon return to the U.S. in 1920 he worked as Chairman of the Physics department at the Washington University in St. Louis and in 1923 he moved to the University of Chicago as Professor of Physics.

Compton is best known for his experimental and theoretical studies of x-ray scattering on atoms that lead to his discovery, in 1922, of the increase in wavelength of x rays scattered on essentially free atomic electrons. This effect illustrates the corpuscular nature of photons and is now known as the Compton effect. As Chairman of the National Academy of Sciences Committee to Evaluate Use of Atomic Energy in War, Compton was instrumental in developing the first controlled uranium fission reactors and plutonium-producing reactors.

In 1927 Compton was awarded the Nobel Prize in Physics *"for the discovery of the effect that bears his name."* The co-recipient of the 1927 Nobel Prize was C.T.R. Wilson for his discovery of the cloud chamber.

COOLIDGE, William David (1873–1975)

American physicist and inventor, educated at the Massachusetts Institute of Technology (MIT) in Boston (B.Sc. in electrical engineering in 1896) and the University of Leipzig (doctorate in physics in 1899). In 1899 he returned for five years to Boston as a research assistant in the Chemistry department of the MIT. In 1905 Coolidge joined the General Electric (GE) Company in Schenectady, and remained with the company until his retirement in 1945. He served as director of the GE Research Laboratory (1932–1940) and as vice president and director of research (1940–1944).

During his 40-year career at General Electric, Coolidge became known as a prolific inventor and was awarded 83 patents. He is best known for his invention of ductile tungsten in the early years of his career. He introduced ductile tungsten for use as filament in incadescent lamps in 1911 producing a significant improvement over Edison's design for incadescent lamps. In 1913 he introduced ductile tungsten into x-ray tubes and revolutionized x-ray tube design that at the time was based on three major components: cold cathode, low pressure gas, and anode (target). The role of the low pressure gas was to produce ions which produced electrons upon bombardment of the cold aluminum cathode. This x-ray tube design was based on the Crookes device for studying cathode rays, and is now referred to as the Crookes tube. The performance of the Crookes x-ray tube was quite erratic and Coolidge introduced a significant improvement when he replaced the cold aluminum cathode with a hot tungsten filament and replaced the low pressure gas with high vacuum. Coolidge's x-ray tube design is now referred to as the Coolidge tube and is still used today for production of superficial and orthovoltage x rays. In the Coolidge x-ray tube the electrons are produced by thermionic emission from the heated filament cathode and accelerated in the applied electric field toward the anode (target).

In honor of Coolidge's contribution to radiology and medical physics through his hot filament innovation, the highest award bestowed annually by the American Association of Physicists in Medicine is named the William D. Coolidge Award.

CORMACK, Allen MacLeod (1924–1990)

South African-born American physicist, educated in x-ray crystallography at the University of Cape Town where he obtained his B.Sc. in 1944 and M.Sc. in 1945. For a year he continued his studies in nuclear physics at the Cavendish Laboratory in Cambridge, and then returned to a lectureship in the Physics department at the University of Cape Town. On a part time basis he assumed responsibilities for supervising the use of radioactive nuclides in the Groote Shuur hospital, thus learning about medical physics in a radiotherapy department. In 1956 Cormack took a sabbatical at Harvard and developed there a crude theory for the x-ray absorption problem to be used in future CT algorithms. From Harvard he returned to Cape

Town for a few months and carried out actual experiments on a crude cylindrical CT phantom. In 1957 Cormack moved to Tufts University in Boston and continued intermittent work on his tomography idea.

During 1963 and 1964 Cormack published two seminal CT papers in the "Journal of Applied Physics." The two papers were largely ignored, but earned him the 1979 Nobel Prize in Medicine and Physiology which he shared with *Godfrey N. Hounsfiled* "*for the development of computer assisted tomography.*"

COULOMB, Charles–Augustin (1736–1806)

French physicist, educated at the Collège des Quatre–Nations in Paris and in Ecole du Génie at Mézières from where he graduated in 1761 as military engineer. For 20 years after graduation he held various military posts in France and Martinique related to engineering and structural design. During 1770s he wrote several theoretical works in mathematics and produced prize-winning work in applied physics, most notably on torsion balance for measuring very small forces and on friction. In the early 1780s he became recognized as eminent scientist, was elected to the Académie des Sciences, and produced seminal work on electricity and magnetism. After the French Revolution in 1789 the Académie des Sciences was abolished and replaced by the "Institut de France" to which Coulomb was elected in 1795. During the last years of his life he was involved with education as inspector general of public education and as such was responsible for setting up the system of lycées across France. The system is still in use today with the lycée representing the second and last stage of secondary education and completed with the exit exam referred to as the "baccalauréat."

Coulomb is considered the father of the renaissance in French physics and is best known for the Coulomb law of electrostatics which states that the force between two electrical charges is proportional to the product of the charges and inversely proportional to the square of the distance between them. He is also honored by the SI unit of charge called the coulomb C.

CROOKES, William (1832–1919)

British chemist and physicist, educated in the Royal College of Chemistry in London where he also served as assistant from 1850–1854. Upon leaving the Royal College, he first worked as a superintendent at the Radcliffe Observatory in Oxford and then became a lecturer in chemistry at the Chester College in Chester. In 1880 he moved to London where he built and equipped his own laboratory and from then on devoted his life to his versatile research interests carrying out his research projects in his own private laboratory.

During his professional career Crookes was active as researcher in many areas of chemistry and physics, as member and officer of various scientific organizations, and as founder and long-time editor of the Chemical News. He discovered the rare earth element thallium; carried out pioneering work in the field of radioactivity, especially on radium; and invented the radiometer for measurement of radiant energy and the spinthariscope for counting single alpha particles. He is best known for his most important invention, the Crookes tube which he invented in the 1870s and which toward the end of 19^{th} century became a very important device in physics laboratories around the world for studies of "cathode rays" in particular and atomic physics in general. Most notable experiments based on the Crookes tube research are: Röntgen's serendipitous discovery of x rays in 1895; Thomson's discovery of the electron in 1897; and Millikan's determination of the charge of the electron in 1913.

The Crookes tube not only resulted in one of most important discoveries of all times, namely the discovery of x rays, it also served as a precursor to modern cathode ray TV tubes. To recognize the importance of Crookes's experimental work the European Physical Society (EPS) established the William Crookes Prize in plasma physics which is awarded to a mid-career (10 to 20 years post Ph.D.) researcher judged to have made a major contribution to plasma physics.

CURIE, Pierre (1859–1906)

French physicist and chemist, educated in Paris where, after obtaining his "licence ès sciences" (equivalent to M.Sc.) at the age of 18, he was appointed a laboratory assistant at the Sorbonne. In 1882 he was appointed supervisor at the École de Physique et Chimie Industrielle in Paris and in 1895 obtained his doctorate. In 1900 he was appointed lecturer and in 1904 Professor of Physics at the Sorbonne.

Pierre Curie's contributions to physics have two distinct components clearly separated by the date of his wedding to *Maria Sklodowska–Curie* in 1895. Before that date, he was involved in crystallography and magnetism discovering the piezoelectric effect as well as showing that magnetic properties of a given substance change at a certain temperature that is now referred to as the Curie point. To carry out his experiments he constructed delicate devices that proved very useful in his collaborative studies of radioactivity with his wife Marie Curie. After their discovery of polonium and radium, Pierre Curie concentrated on investigating the physical properties of radium while Marie concentrated on preparing pure compounds.

Pierre Curie and one of his students are credited with making the first observation of nuclear power through measuring the continuous production of heat in a sample of radium. He was also the first to report the decay of radioactive materials and the deleterious biological effects of radium after producing a radium burn and wound on his own skin.

In his honor the 1910 Radiology Congress accepted the definition of the curie (Ci), a unit of activity, as the activity of 1 g of radium–226 or $3.7\times10^{10}\ \text{s}^{-1}$. The curie is still defined as $3.7\times10^{10}\ \text{s}^{-1}$, however, subsequent measurements have shown that the specific activity of radium–226 is 0.988 Ci/g. In tribute to the work of Pierre and Marie Curie the element with atomic number 96 was given the name curium (Cm).

Pierre and Marie Curie shared the 1903 Nobel Prize in Physics with *Henri Becquerel* "*in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel.*" Becquerel was awarded his share of the Nobel Prize "*in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity.*"

CURIE–SKŁODOWSKA, Marie (1867–1934)

Polish-born French physicist and chemist, educated at the Sorbonne in Paris where she obtained a "licence ès sciences" (equivalent to M.Sc.) in physical sciences (1893) and mathematics (1894) and her doctorate in physics in 1903. Curie spent her professional life at various institutions in Paris. In 1906 she was appointed lecturer in physics at the Sorbonne and was promoted to Professor of Physics in 1908.

In 1914 Marie Curie helped found the "Radium Institute" in Paris dedicated to scientific disciplines of physics, chemistry and biology applied to prevention, diagnosis and treatment of cancer. The institute had two divisions: the Curie Laboratory dedicated to research in physics and chemistry of radioactivity and the Pasteur Laboratory devoted to studies of biological and medical effects of radioactivity. The Curie Laboratory was headed by Marie Curie; the Pasteur Laboratory by Claudius Regaud who is regarded as the founding father of both radiotherapy and radiobiology. In 1920, the Curie Foundation was inaugurated to raise funds to support the activities of the Radium Institute. In 1970 the Radium Institute and the Curie Foundation were merged into the Curie Institute mandated to carry out cancer research, teaching and treatment.

After obtaining her "licence" at the Sorbonne, Curie, looking for a doctoral degree subject, decided to investigate the phenomenon of radiation emission from uranium discovered by *Henri Becquerel* in 1896. She coined the name "radioactivity" for the spontaneous emission of radiation by uranium and established that radioactivity was an atomic rather than chemical phenomenon process. She then investigated if the peculiar property of uranium could be found in any other then-known element and discovered that thorium is also an element which exhibits radioactivity. Noticing that some minerals (for example, pitchblende uranium ore) exhibited a much larger rate of radioactivity than warranted by their uranium or thorium content, she surmised that the minerals must contain other highly radioactive unknown elements. In collaboration with her husband *Pierre Curie*, Marie Curie discovered miniscule amounts of new elements radium and polonium after sifting through several tons of pitchblende uranium ore. In tribute to the work of Pierre and Marie Curie the element with atomic number 96 was given the name curium (Cm).

The discovery of the new radioactive elements in 1898 earned Marie Curie a doctorate in physics and, in addition, both Marie and Pierre Curie shared, with *Henry Becquerel*, the 1903 Nobel Prize in Physics "*in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel.*"

In 1911 Marie Curie was awarded another Nobel Prize, this time in Chemistry, "*in recognition of her services to the advancement of chemistry by the discovery of the elements of radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element.*"

Marie Curie's contribution to science has been enormous not only in her own work but also in the work of subsequent generations of physicists whose lives she touched and influenced. She was the first woman to teach at the Sorbonne, the first woman to receive a Nobel Prize, and the first scientist to have received two Nobel Prizes.

ČERENKOV, Pavel Alekseevič (1904–1990)

Russian physicist, educated at the Voronež State University in Voronež in Central Russia, where he graduated with a degree in mathematics and physics in 1928. In 1930 he accepted a post as senior scientific officer in the Peter N. Lebedev Institute of Physics in the Soviet Academy of Sciences (now the Russian Academy of Sciences in Moscow) under the directorship of Sergei I. Vavilov. In 1940 Čerenkov was awarded a doctorate in physics and in 1953 he became Professor of Experimental Physics. In 1970 he became an Academician of the USSR Academy of Sciences.

Čerenkov is best known for his studies of the visible light emitted by energetic charged particles which move through a transparent medium with a velocity that exceeds c/n, the speed of light in the medium, where c is the speed of light in vacuum and n is the index of refraction. In 1934 Čerenkov and Sergei I. Vavilov observed that gamma rays from a radium source, besides causing luminescence in solutions, also produce a faint light from solvents. Their subsequent research lead to two important conclusions: firstly, the emitted light was not a luminescence phenomenon and secondly, the light they observed was not emitted by photons, rather, it was emitted by high energy electrons released in the medium by photon interactions with orbital electrons of the medium. The effect is now referred to as the Čerenkov effect (or sometimes as the Čerenkov-Vavilov effect) and the blue light emitted by energetic charged particles is called Čerenkov radiation. Ilja Frank and Igor Tamm, also from the Lebedov Institute, explained the Čerenkov effect theoretically in 1937 showing that Čerenkov radiation originates from charged particles that move through the medium faster then the speed of light in the medium. The Čerenkov effect is used in Čerenkov counters in nuclear and particle physics for determination of particle energy and velocity.

The 1958 Nobel Prize in Physics was awarded to Čerenkov, Frank, and Tamm "*for the discovery and the interpretation of the Čerenkov effect.*"

DAVISSON, Clinton Joseph (1881–1958)

American physicist, educated at the University of Chicago (B.Sc. in 1908) and Princeton University where he received his doctorate in physics in 1911. He spent most of his professional career at the Bell Telephone Laboratories. Upon retirement from Bell Labs he became Visiting Professor of Physics at the University of Virginia in Charlottesville.

Davisson is best known for his work on electron diffraction from metallic crystals. In 1927 he was studying elastic electron scattering on a nickel single crystal in collaboration with *Lester H. Germer*. When they analyzed the angular distribution of scattered electrons they discovered that electrons produced diffraction patterns similar to those produced by x rays. The diffraction patterns were governed by the Bragg formula with a wavelength λ given by the de Broglie equation: $\lambda = h/p$ with h the Planck's constant and p the momentum of the electron. The experiment, now known as the Davisson-Germer experiment, confirmed the hypothesis formulated in 1924 by *Louis de Broglie* that electrons exhibit dual nature, behaving both as waves and as particles. *George P. Thomson*, a physicist at the University of Aberdeen in Scotland, confirmed the de Broglie's hypothesis with a different experiment. He studied the behavior of electrons as they traversed very thin films of metals and also observed that electrons under certain conditions behave as waves despite being particles. Thomson's apparatus is referred to as an electron diffraction camera and produces a series of rings when a narrow electron beam is made to traverse a thin metallic foil.

In 1937 Davisson and Thomson shared the Nobel Prize in Physics "*for their experimental discovery of the diffraction of electrons by crystals.*"

DE BROGLIE, Louis (1892–1987)

French theoretical physicist, educated at the Sorbonne in Paris, first graduating with an arts degree in 1909 and then with Licence ès Sciences (equivalent to M.Sc.) in 1913. De Broglie spent the war years 1914–1918 in the army and in 1920 resumed his studies in theoretical physics at the Sorbonne. He obtained his doctorate in theoretical physics in 1924, taught physics at the Sorbonne for two years and became Professor of Theoretical Physics at the Henri Poincaré Institute. From 1932 to his retirement in 1962 he was Professor of Theoretical Physics at the Sorbonne.

De Broglie is best known for his theory of electron waves based on the work of *Max Planck* and *Albert Einstein*. The theory, presented in his doctorate work, proposed the wave-particle duality of matter. De Broglie reasoned that if x rays behave as both waves and particles, then particles in general and electrons in particular should also exhibit this duality. De Broglie's theory was confirmed experimentally by *Clinton J. Davisson* and *Lester H. Germer* in the United States and by *George P. Thomson* in the U.K. The theory was subsequently used by *Ervin Schrödinger* to develop wave mechanics.

The 1929 Nobel Prize in Physics was awarded to de Broglie "*for his discovery of the wave nature of electrons.*"

DIRAC, Paul Adrien Maurice (1902–1984)

British physicist, educated at the University of Bristol where he obtained his Bachelor's degree in electrical engineering in 1921 and at the St. John's College in Cambridge where he received his doctorate in mathematics in 1926. In 1927 he became a Fellow of the St. John's College and from 1932 until 1969 he was Lucasian Professor of Mathematics in Cambridge. In 1969 Dirac moved to Florida to become Professor of Physics at the Florida State University.

Dirac was an extremely productive and intelligent theoretical physicist, mainly involved with mathematical and theoretical aspects of quantum mechanics. Quantum mechanics, dealing with dimensions of the order of the atomic size, introduced the second revolution in physics, the first one being *Albert Einstein*'s special theory of relativity that deals with velocities of the order of the speed of light in vacuum.

In 1926 Dirac developed his version of quantum mechanics that merged the "matrix mechanics" of *Werner Heisenberg* with the "wave mechanics" of *Erwin*

Schrödinger into a single mathematical formalism. In 1928 he derived a relativistic equation for the electron that merged quantum mechanics with relativity and is now referred to as the Dirac equation. The equation predicts the existence of an anti-particle (same mass, opposite charge) to the electron and infers the electron quantum spin. Dirac also predicted that in an electron/anti-electron encounter the charges cancel, and the two particles annihilate with the combined mass transforming into radiation according to Albert Einstein's celebrated equation $E = mc^2$. Four year later, in 1932 Carl D. Anderson discovered the anti-electron, a new particle which is now called the positron. In 1931 Dirac showed theoretically that the existence of a magnetic monopole would explain the observed quantization of the electrical charge (all charges found in nature are multiples of the electron charge). No monopoles have been found in nature so far.

The 1933 Nobel Prize in Physics was awarded to Paul M. Dirac and *Erwin Schrödinger* "*for their discovery of new productive forms of atomic theory.*"

DUANE, William (1872–1935)

American physicist, educated at the University of Pennsylvania and Harvard, where he received a B.A. degree in 1893 and a M.A. degree in 1895. From 1895 to 1897 he held the Tyndall Fellowship of Harvard University and studied physics in Göttingen and Berlin receiving the Ph.D. degree from Berlin in 1897. From 1898 to 1907 he held a position of Professor of Physics at the University of Colorado. He then moved to Paris and worked for 6 years with Marie Curie at the Sorbonne on various projects involving radioactivity.

During his Paris period Duane also got interested in the application of radium and x rays in medicine and in 1913, when the newly formed Harvard Cancer Commission was formed, he accepted a job offer of Assistant Professor of Physics at Harvard and Research Fellow in Physics at the Harvard Cancer Commission. By 1917 he was promoted to Professor of Biophysics, probably filling the first such position in North America, and remained with Harvard and the Cancer Commission till his retirement in 1934. In view of his hospital appointment and significant contributions to imaging and cancer therapy one can conclude that Duane was among the first medical physicists in North America.

Duane is best known for the Duane-Hunt law that he discovered with his Ph.D. student Franklin Hunt in 1915. This law states that there is a sharp upper limit to the x-ray frequencies emitted from a target stimulated by the impact of energetic electrons. He also established that the Duane-Hunt law could be used as a very accurate method of determining Planck's constant h and the ratio h/e, where e is the charge of the electron. He was also the first to discover that the total intensity produced by and x-ray target depends linearly on the atomic number of the target.

Duane is one of the most important early contributors to radiation dosimetry of gamma rays and x rays used in treatment of cancer. He developed the technical details for measurement of radiation dose with ionization chambers and was instrumental in gaining national and international acceptance of 1 unit of x-ray intensity as "that intensity of radiation which produces under saturation conditions one electrostatic unit of charge per cm^3 of air under standard temperature and pressure." Duane's unit of x-ray intensity was subsequently named roentgen. During his professional career, Duane received numerous awards for his scientific work and was awarded honorary Sc.D. degrees by the University of Pennsylvania in 1922 and University of Colorado in 1923.

EINSTEIN, Albert (1879–1955)

German-born theoretical physicist, educated at the Eidgenössische Technische Hochschule in Zürich (ETHZ) from which he graduated in 1900 as a teacher of mathematics and physics. He did not succeed in obtaining an academic post after graduating and spend two years teaching mathematics and physics in secondary schools. From 1902 until 1909 he worked as a technical expert in the Swiss Patent Office in Bern. In 1905 he earned a doctorate in physics from the University of Zürich.

Following publication of three seminal theoretical papers in 1905 and submission of his "Habilitation" thesis in 1908, Einstein's credibility in physics circles rose dramatically; he started to receive academic job offers and entered a period of frequent moves and changes in academic positions. In 1908 he became lecturer at the University of Bern and in 1909 Professor of Physics at the University of Zürich. During 1911 he was Professor of Physics at the Karl-Ferdinand University in Prague and in 1912 he moved back to Zürich to take a chair in theoretical physics at the ETHZ. Finally, in 1914 he moved to Berlin to a research position without teaching responsibilities at the then world-class center of physics at the University of Berlin.

During the Berlin period (1914–1933) Einstein produced some of his most important work, became an international "star" physicist and scientist, got involved in political issues, and traveled a great deal to visit physics colleagues and present invited lectures on his work. In 1932 he moved to the United States to become Professor of Theoretical Physics at the Institute for Advanced Study in Princeton, one of the world's leading centers for theoretical research and intellectual inquiry.

Einstein was an extremely gifted physicist and his contribution to modern physics is truly remarkable. His three papers published in Volume 17 of the "Annalen der Physik" each dealt with a different subject and each is now considered a masterpiece. The first of the three papers dealt with the photoelectric effect and contributed to quantum theory by assuming that light under certain conditions behaves like a stream of particles (quanta) with discrete energies. The second paper dealt with statistical mechanics and lead to an explanation of Brownian motion of molecules. The third paper addressed the connection between the electromagnetic theory and ordinary motion and presented Einstein's solution as the "special theory of relativity." In 1916, after a decade of futile attempts, Einstein completed his "general theory of relativity" based on the "equivalence principle" stating that uniform acceleration of an object is equivalent to a gravitational field. The gravitational field causes curvature of space-time as observed experimentally by measuring the precession of the mercury perihelion and the bending by the sun of light from the stars.

At the end of the Berlin period and during his American period from 1933 until his death in 1955 Einstein concentrated on developing a unified field theory, unsuccessfully attempting to unify gravitation, electromagnetism and quantum physics. Throughout his life Einstein was a pacifist detesting both militarism as well as nationalism. In tribute to Einstein's contributions to modern physics the element with atomic number 109 is named einsteinium (Es).

In 1921 the Nobel Prize in Physics was awarded to Einstein "*for his services to Theoretical Physics and especially for his discovery of the law of the photoelectric effect.*"

In recognition of Einstein‘s tremendous contribution to modern physics the year 2005, the centenary of Einstein's "annus mirabilis," was proclaimed the world year of physics, a worldwide celebration of physics and its impact on humanity.

EVANS, Robley (1907–1995)

American nuclear and medical physicist, educated at the California Institute of Technology (Caltech) where he studied physics and received his B.Sc. in 1928, M.Sc. in 1929, and Ph.D. under Robert A. Millikan in 1932. After receiving his doctorate he studied biological effects of radiation as post-doctoral fellow at the University of California at Berkeley before accepting a faculty position at the Massachusetts Institute of Technology (MIT) in Boston. He remained an active member of the MIT faculty for 38 years and retired in 1972 to become a special project associate at the Mayo Clinic in Rochester, Minnesota.

At the MIT Evans was instrumental in building the first cyclotron in the world for biological and medical use. He established the Radioactivity Center in the Physics department at the MIT for research in nuclear physics related to biology, introduced the first iodine radionuclide for diagnosis and treatment of thyroid disease, and built the first total body counter to measure the uptake and body burden of radium in the human body. In 1941 he established one ten-millionth of a gram of radium ($0.1\,\mu$Ci) as the maximum permissible body burden. The standard is still internationally used and has been adapted for other radioactive substances including plutonium-239 and strontium–90. Evans's book "The Atomic Nucleus" was first published in 1955 and remained the definitive nuclear physics textbook for several decades and is still considered an important nuclear physics book.

In 1985 Evans received the William D. Coolidge Award from the American Association of Physicists in Medicine in recognition to his contribution to medical physics and in 1990 he received the Enrico Fermi Award in recognition of his contributions to nuclear and medical physics.

FANO, Ugo (1912–2001)

American physicist of Italian descent, educated in mathematics and physics at the University of Torino. He received postdoctoral training from Enrico Fermi at the University of Rome (1934–1936) and from Werner Heisenberg at the University of Leipzig (1936–1937). In 1940 Fano started his American career in radiation biology and physics at the Carnegie Institution at Cold Spring Harbor. In 1946 he joined the staff of the National Bureau of Standards (the predecessor of the National Institute of Standards and Technology) and during his two decades there made outstanding contributions to radiation physics and basic solid state physics.

From 1966 to 1982 Fano was on staff at the University of Chicago where he worked in atomic and molecular physics and continued his lifetime interest in radiation physics. He published over 250 scientific papers and made major contributions in radiation physics and radiation dosimetry. He developed the first general theory of the ionization yield in a gas; characterized statistical fluctuations of ionization by the now known Fano factor; developed methods for dealing with the transport of photons and charged particles in matter; and demonstrated the cavity principle of radiation equilibrium under general conditions. He was also a big proponent of the use of synchrotron radiation for spectroscopic studies.

Fano was recognized with many honors, most notably with the Enrico Fermi Award by the U.S. government; membership in the National Academy of Sciences of the United States; and several honorary doctorates.

FERMI, Enrico (1901–1954)

Italian-born physicist who graduated from the University of Pisa in 1921. He was a lecturer at the University of Florence for two years and then Professor of Theoretical Physics at the University of Rome from 1923 to 1938. In 1938 he moved to the United States and worked first for four years at Columbia University in New York and from 1942 till his death in 1954 at the University of Chicago.

Fermi is recognized as one of the great scientists of the 20-th Century. He is best known for his contributions to nuclear physics and quantum theory. In 1934 he developed the theory of the beta nuclear decay that introduced the neutrino and the weak force as one of the basic force in nature. The existence of the neutrino was actually enunciated by *Wolfgang Pauli* in 1930 and experimentally confirmed only in 1956.

In 1934, while at the University of Rome, Fermi began experiments bombarding various heavy elements with thermal neutrons. He discovered that the thermal neutrons bombarding uranium were very effective in producing radioactive atoms, but did not realize at the time that he succeeded in splitting the uranium atom. *Otto Hahn* and *Fritz Strassmann* in 1938 repeated Fermi's experiments and discovered that uranium bombarded with thermal neutrons splits into two lighter atoms. *Lise Meitner* and *Otto Frisch* explained the process theoretically and named it nuclear fission.

Upon his move to the United States Fermi continued his fission experiments at Columbia University and showed experimentally that uranium fission results in two lighter by-products, releasing several neutrons and large amounts of energy. In 1942 he was appointed Director of the Manhattan project at the University of Chicago with a mandate to develop an "atomic bomb." With his team of scientists Fermi produced the first nuclear chain reaction and developed the atomic bombs that were dropped on Hiroshima and Nagasaki by the United States at the end of the World War II.

In 1938 Fermi was awarded the Nobel Prize in Physics *"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons."*

Fermi's name is honored by the unit of length that is of the order of the size of the atomic nucleus (1 fermi = 1 femtometer = 1 fm = 10^{-15} m). One of the American national laboratories is named Fermi National Laboratory (Fermilab), and the oldest and most prestigious science and technology prize awarded in the United States is the Enrico Fermi Award. A common name for particles with half-integer spin, such as electron, neutron, proton and quark, is fermion; the artificially produced element with atomic number Z of 100 is fermium (Fm); and the quantum statistics followed by fermions is known as the Fermi-Dirac statistics, after its inventors.

FLEROV, Georgij Nikolaevič (1913–1990)

Russian nuclear physicist, educated in physics at the Polytechnical Institute of Leningrad (now Sankt Petersburg) from where he graduated in 1938. He started his scientific career at the Leningrad Institute of Physics and Technology and was involved in basic research in a number of fundamental and applied areas of nuclear physics. From 1941 to 1952 Flerov, together with Igor V. Kurčatov, participated in investigations linked with the use of atomic energy for military purposes and nuclear power industry. From 1960 to 1988 he was the director of the Nuclear Reactions Laboratory of the Joint Institute for Nuclear Research in Dubna.

Flerov is best known for his discovery in 1940 (in collaboration with Konstantin A. Petrzak) of the spontaneous fission of uranium–238. With colleagues in Dubna Flerov carried out research that resulted in the synthesis of new heavy elements (nobelium No–102, rutherfordium Rf–104, dubnium Db–105), the production of a large number of new nuclei on the border of stability, and the discovery of new types of radioactivity (proton radioactivity) and new mechanisms of nuclear interactions.

FRANCK, James (1882–1964)

German-born American physicist, educated at the Univeristy of Heidelberg and the University of Berlin where he received his doctorate in physics in 1906. He worked at the University of Berlin from 1911 to 1918 and at the University of Göttingen until 1933 when he moved to the United States to become Professor at Johns Hopkins University in Baltimore. From 1938 to 1947 he was Professor of Physical Chemistry at the University of Chicago.

Franck is best known for the experiment he carried out in 1914 at the University of Berlin in collaboration with *Gustav Hertz*. The experiment is now known as the Franck-Hertz experiment and it demonstrated the existence of quantized excited states in mercury atoms. This provided the first experimental substantiation of the Bohr atomic theory which predicted that atomic electrons occupied discrete and quantized energy states.

In 1925 James Franck and Gustav Hertz were awarded the Nobel Prize in Physics *"for their discovery of the laws governing the impact of electron upon an atom"*. In addition to the Nobel Prize, Franck was also honored by the 1951 Max Planck medal of the German Physical Society and was named honorary citizen of the university town of Göttingen.

GAMOW, George (1904–1968)

Ukranian-born American physicist and cosmologist, educated at the Novorossia University in Odessa (1922–1923) and at the Leningrad University (1923–1928) where he received his doctorate in physics in 1928. After a fellowship with Niels Bohr at the Institute for Theoretical Physics in Copenhagen and a short visit to Ernest Rutherford at the Cavendish Laboratory in Cambridge, he returned to SSSR in 1931 to become a Professor of Physics at the University of Leningrad. From 1934 until 1956 he was Chair of Physics at the George Washington University in Washington D.C. and from 1956 until his death in 1968 he was a Professor of Physics at the University of Colorado in Boulder. During World War II he was involved with the Manhattan nuclear weapon project in Los Alamos.

Gamow is best known for his (1928) theory of the alpha decay based on tunneling of the alpha particle through the nuclear potential barrier. He was also a proponent of the Big-Bang theory of the Universe and worked on the theory of thermonuclear reactions inside the stars that is still today relevant to research in controlled nuclear fusion. His name is also associated with the beta decay in the so-called Gamow-Teller selection rule for beta emission. Gamow was also well known as an author of popular science books and received the UNESCO Kalinga Prize for popularization of science.

GEIGER, Hans (1882–1945)

German physicist, educated in physics and mathematics at the university of Erlangen where he obtained his doctorate in 1906. From 1907 to 1912 he worked with *Ernest Rutherford* at the University of Manchester where, with *Ernest Marsden*, he carried out the α-particle scattering experiments that lead to the Rutherford–Bohr atomic model. He also discovered, in collaboration with John M. Nuttall, an empirical linear relationship between log λ and log R_α for naturally occurring α emitters with the decay constant λ and range in air R_α (Geiger–Nuttall law). In collaboration with Walther Müller he developed a radiation detector now referred to as the Geiger-Müller counter.

GERLACH, Walther (1889–1979)

German physicist, educated at the University of Tübingen where he received his doctorate in physics in 1912 for a study of blackbody radiation and the photoelectric effect. He worked at the Universities of Göttingen and University of Frankfurt before returning in 1925 to Tübingen as Professor of Physics. From 1929 to 1952 he was Professor of Physics at the University of Munich.

Gerlach made contributions to radiation physics, spectroscopy and quantum physics. He is best known for his collaboration with *Otto Stern* in 1922 at the University of Frankfurt on an experiment that demonstrated space quantization using a beam of neutral silver atoms that, as a result of passage through an inhomogeneous magnetic field, split into two district components, each component characterized by a specific spin (angular momentum) of the silver atoms.

GERMER, Lester H (1896–1971)

American physicist, educated at Columbia University in New York. In 1927 he worked as graduate student at Bell Laboratories under the supervision of *Clinton T. Davisson* on experiments that demonstrated the wave properties of electrons and substantiated the Louis de Broglie's hypothesis that moving particles exhibit particle-wave duality. The electron diffraction experiments on metallic crystals are now referred to as the Davisson-Germer experiment.

HAHN, Otto (1879–1968)

German chemist, educated at University of Munich and Universiy of Marburg. In 1901 he obtained his doctorate in organic chemistry at the University of Marburg. He spent two years as chemistry assistant at the University of Marburg, and then studied radioactivity for one year under William Ramsay at the University College in London and for one year under *Ernest Rutherford* at McGill University in Montreal. In 1905 he moved to the Kaiser Wilhelm Institute (now Max Planck Institute) for chemistry in Berlin and remained there for most of his professional life. From 1928–1944 he served as the Director of the Institute.

Early in his career in Berlin he started a life-long professional association with Austrian-born physicist *Lise Meitner*; a collaboration that produced many important discoveries in radiochemistry and nuclear physics. Hahn's most important contribution to science is his involvement with the discovery of nuclear fission. In 1934 the Italian physicist *Enrico Fermi* discovered that uranium bombarded with neutrons yields several radioactive products. Hahn and Meitner, in collaboration with *Friedrich Strassmann*, repeated Fermi's experiments and found inconclusive results. In 1938, being Jewish, Meitner left Germany for Stockholm to escape persecution by the Nazis; Hahn and Strassmann continued with the neutron experiments and eventually concluded that several products resulting from the uranium bombardment with neutrons were much lighter than uranium suggesting that the neutron bombardment caused uranium to split into two lighter components of more or less equal size. Hahn communicated the findings to Meitner in Stockholm, who, in cooperation with Otto Frisch, explained the theoretical aspects of the uranium splitting process and called it nuclear fission. The discovery of nuclear fission led to the atomic bomb and to modern nuclear power industry.

In 1944 Hahn alone was awarded the Nobel Prize in Chemistry *"for his discovery of the fission of heavy nuclei."* In 1966 Hahn, Strassmann and Meitner shared the Enrico Fermi Prize for their work in nuclear fission. It is now universally accepted that four scientists are to be credited with the discovery of the nuclear fission process: Hahn, Strassmann, Meitner and Frisch.

HARTREE, Douglas (1897–1958)

British mathematician and physicist, educated in Cambridge where he obtained a degree in Natural Sciences in 1921 and a doctorate in 1926. In 1929 he was appointed Professor of Applied Mathematics at the University of Manchester and in 1937 he moved to a Chair of Theoretical Physics. In 1946 he was appointed Professor of Mathematical Physics at Cambridge University and held the post until his death in 1958.

Hartree was both a mathematician and physicist and he is best known for applying numerical analysis to complex physics problems such as calculations of wave functions for multi-electron atoms. Hartree approached the problem by using the method of successive approximations, treating the most important interactions in the first approximation and then improving the result with each succeeding approximation. Hartree's work extended the concepts of the Bohr theory for one-electron atoms or ions to multi-electron atoms providing reasonable, albeit not perfect, approximations to inter-electronic interactions in multi-electron atoms.

HEISENBERG, Werner (1901–1976)

German theoretical physicist, educated in physics at the University of Munich and the University of Göttingen. He received his doctorate in physics at the University of Munich in 1923 and successfully presented his habilitation lecture in 1924. During 1924–1926 he worked with *Niels Bohr* at the University of Copenhagen. From 1927 until 1941 Heisenberg held an appointment as Professor of Theoretical Physics at the University of Leipzig and in 1941 he was appointed Professor of Physics at the University of Berlin and Director of the Kaiser Wilhelm Institute for Physics in Berlin. From 1946 until his retirement in 1970 he was Director of the Max Planck Institute for Physics and Astrophysics in Göttingen. The institute moved from Göttingen to Munich in 1958.

In 1925 Heisenberg invented matrix mechanics which is considered the first version of quantum mechanics. The theory is based on radiation emitted by the atom and mechanical quantities, such as position and velocity of electrons, are represented by matrices. Heisenberg is best known for his Uncertainty Principle stating that a determination of particle position and momentum necessarily contains errors the product of which is of the order of the Planck's quantum constant h. The principle is of no consequence in the macroscopic world, however, it is critical for studies on the atomic scale.

In 1932 Heisenberg was awarded the Nobel Prize in Physics "*for creation of quantum mechanics, the application of which has, inter alia, led to the discovery of allotropic forms of hydrogen.*"

HERTZ, Gustav (1887–1975)

German physicist, educated at universities of Göttingen, Munich and Berlin, and graduating with a doctorate in physics in 1911. During 1913–1914 he worked as research assistant at the University of Berlin. Hertz alternated work in industry (Philips in Eindhoven; Siemens in Erlangen) with academic positions at universities of Berlin, Halle and Leipzig.

Hertz made many contributions to atomic physics but is best known for the experiment in which he studied, in collaboration with *James Franck*, the impact of electrons on mercury vapor atoms. The experiment is now referred to as the Franck-Hertz experiment and demonstrated the existence of quantized excited states in mercury atoms, thereby substantiating the basic tenets of the Bohr atomic theory.

In 1925 James Franck and Gustav Hertz were awarded the Nobel Prize in Physics *"for their discovery of the laws governing the impact of an electron upon an atom."* Hertz was also the recipient of the Max Planck Medal of the German Physical Society.

HOFSTADTER, Robert (1915–1990)

American physicist, educated at the College of the City of New York (B.Sc., 1935) and Princeton University in Princeton, New Jersey (M.A. and Ph.D. in physics, 1938). During 1938 he was postdoctoral fellow at Princeton working on photoconductivity of willemite crystals and then a year at the University of Pennsylvania where he helped to construct a large Van de Graaff accelerator for nuclear research.

During the war years Hofstadter first worked at the National Bureau of Standards and later at Norden Laboratory. In 1945 he returned to Princeton as Assistant Professor of Physics and got involved in radiation detection instrumentation, discovering in 1948 that sodium iodide activated with thallium made an excellent scintillation counter that could also be used as spectrometer for measurement of energy of gamma rays and energetic charged particles. In 1950 he moved to Stanford University in Stanford, California to become Associate Professor and later on Professor of Physics carrying out important research work on development of radiation detectors and electron scattering by nuclei using W.W. Hansen's invention of electron linear accelerator. Hofstadter's work on using high-energy electrons to probe the nucleus resulted in much of the current knowledge on scattering form factors, nuclear charge distribution and size as well as charge and magnetic moment distributions of the proton and neutron.

Hofstadter was elected to the National Academies (USA) and was named California Scientist of the Year in 1959. In 1961 he shared the Nobel Prize in Physics with Rudolf L. Mössbauer. Hofstadter received the prize "*for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons*", Mössbauer for the discovery of gamma ray resonance in connection with the effect which bears his name.

HOUNSFIELD, Godfrey Neubold (1919–2004)

British electrical engineer and scientist, educated at the Electrical Engineering College in London from which he graduated in 1951. The same year he joined the research staff of the EMI in Middlesex. He remained associated with the EMI throughout his professional career.

Hounsfield made a significant contribution to early developments in the computer field and was responsible for the development of the first transistor-based solid-state computer in the U.K. He is best known, however, for the invention of computed tomography (CT), an x-ray-based diagnostic technique that non-invasively forms two-dimensional cross sections through the human body. Originally, the technique was referred to as computer assisted tomography (CAT), now the term computed tomography (CT) is more commonly used.

Following his original theoretical calculations, he first built a laboratory CT model to establish the feasibility of the approach, and then in 1972 built a clinical prototype CT-scanner for brain imaging. From the original single slice brain CT-scanner the technology evolved through four generations to the current 64 slice body and brain CT-scanners. Roentgen's discovery of x rays in 1895 triggered the birth of diagnostic radiology as an important medical specialty; Hounsfield's invention of the CT-scanner placed diagnostic radiology onto a much higher level and transformed it into an invaluable tool in diagnosis of brain disease in particular and human malignant disease in general. In 1979 Hounsfield shared the Nobel Prize in Medicine and Physiology with *Allan M. Cormack* "*for the development of computer assisted tomography.*" Cormack derived and published the mathematical basis of the CT scanning method in 1964.

Hounsfield's name is honored with the Hounsfield scale which provides a quantitative measure of x-ray attenuation of various tissues relative to that of water. The scale is defined in hounsfield units (HF) running from air at –1000 HF, fat at –100 HF, through water at 0 HF, white matter at $\sim$25 HF, grey matter at $\sim$40 HF, to bone at +400 HF or larger, and metallic implants at +1000 HF.

HUBBELL, John Howard (1925–2007)

American radiation physicist, educated at the University of Michigan in Ann Arbor in engineering physics (B.Sc. in 1949, MSc. in 1950). In 1950 he joined the staff of the National Bureau of Standards (NBS) now known as the National Institute of Science and Technology (NIST) in Washington D.C. and spent his professional career there, directing the NBS/NIST X-Ray and Ionizing Radiation Data Center from 1963 to 1981. He retired in 1988.

Hubbell's collection and critical evaluation of experimental and theoretical photon cross section data resulted in the development of tables of attenuation coefficients and energy absorption coefficients, as well as related quantities such as atomic form factors, incoherent scattering functions, and atomic cross sections for photoelectric effect, pair production and triplet production. Hubbell's most widely known and important work is the "National Standard Reference Data Series Report 29: Photon

Cross Sections, Attenuation Coefficients and Energy Absorption Coefficients from 10 keV to 100 GeV."

JOHNS, Harold Elford (1915–1998)

Born in Chengtu, China to Canadian parents who were doing missionary work in China, Johns obtained his Ph.D. in Physics from the University of Toronto and then worked as physicist in Edmonton, Saskatoon, and Toronto. His main interest was diagnosis and therapy of cancer with radiation and his contributions to the field of medical physics are truly remarkable. While working at the University of Saskatchewan in Saskatoon in the early 1950s, he invented and developed the cobalt-60 machine which revolutionized cancer radiation therapy and had an immediate impact on the survival rate of cancer patients undergoing radiotherapy.

In 1956 Johns became the first director of the Department of Medical Biophysics at the University of Toronto and Head of the Physics division of the Ontario Cancer Institute in Toronto. He remained in these positions until his retirement in 1980 and built the academic and clinical departments into world-renowned centers for medical physics. With his former student John R. Cunningham, Johns wrote the classic book "The Physics of Radiology" that has undergone several re-printings and is still considered the most important textbook on medical physics.

In 1976 Johns received the William D. Coolidge Award from the American Association of Physicists in Medicine.

JOLIOT-CURIE, Irène (1897–1956)

French physicist, educated at the Sorbonne in Paris where she received her doctorate on the alpha rays of polonium in 1925 while already working as her mother's (Marie Curie) assistant at the Radium Institute. In 1927 Irène Curie married Frédéric Joliot who was her laboratory partner and Marie Curie's assistant since 1924. In 1932 Joliot-Curie was appointed lecturer and in 1937 Professor at the Sorbonne. In 1946 she became the Director of the Radium Institute.

Joliot-Curie is best known for her work at the "Institut du Radium" in Paris, in collaboration with her husband Frédéric Joliot, on the production of artificial radioactivity through nuclear reactions in 1934. They bombarded stable nuclides such as boron-10, aluminum-27, and magnesium-24 with naturally occurring α particles and obtained radionuclides nitrogen-13, phosphorus-30, and silicon-27, respectively, accompanied by release of a neutron. The discovery of artificially produced radionuclides completely changed the periodic table of elements and added several hundred artificial radionuclides to the list. In 1938 Joliot-Curie's research of neutron bombardment of uranium represented an important step in eventual discovery of uranium fission by *Otto Hahn*, *Friedrich Strassmann*, *Lise Meitner*, and *Otto Frisch*.

The 1935 Nobel Prize in Chemistry was awarded to Frédéric Joliot and Irène Joliot-Curie "*in recognition of their synthesis of new radioactive elements.*"

JOLIOT, Jean Frédéric (1900–1958)

French physicist, educated at the École de Physique et Chimie Industriele in Paris where he received an engineering physics degree in 1924. Upon graduation he became Marie Curie's assistant at the "Institut du Radium" in Paris. He married Irène Curie, Marie Curie's daughter, in 1927 and worked on many nuclear physics projects in collaboration with his wife. In 1930 he obtained his doctorate in physics and in 1937 he became Professor of Physics at the Collège de France in Paris.

In 1934 Joliot discovered artificial radioactivity with Irène Curiie and in 1939 he confirmed the fission experiment announced by *Otto Hahn* and *Friedrich Strassmann*. He recognized the importance of the experiment in view of a possible chain reaction and its use for the development of nuclear weapons. In 1935 Joliot and *Irène Joliot-Curie* shared the Nobel Prize in Chemistry "*in recognition of their synthesis of new radioactive elements.*"

KERST, Donald William (1911–1993)

American physicist, educated at the University of Wisconsin in Madison where he received his doctorate in physics in 1937. From 1938 to 1957 he worked through academic ranks to become Professor of Physics at the University of Illinois. He then worked in industry from 1957 to 1962 and from 1962 to 1980 he was Professor of Physics at the University of Wisconsin. Kerst made important contributions to the general design of particle accelerators, nuclear physics, medical physics, and plasma physics. He will be remembered best for this development of the betatron in 1940, a cyclic electron accelerator that accelerates electrons by magnetic induction. The machine found important use in industry, nuclear physics and medicine during the 1950s and 1960s before it was eclipsed by more practical linear accelerators.

KLEIN, Oskar (1894–1977)

Swedish-born theoretical physicist. Klein completed his doctoral dissertation at the University of Stockholm (Högskola) in 1921 and worked as physicist in Stockholm, Copenhagen, Lund and Ann Arbor. He is best known for introducing the relativistic wave equation (Klein-Gordon equation); for his collaboration with *Niels Bohr* on the principles of correspondence and complementarity; and for his derivation, with *Yoshio Nishina*, in 1929 of the equation for Compton scattering (Klein-Nishina equation). Klein's attempts to unify general relativity and electromagnetism by introducing a five-dimensional space-time resulted in a theory now known as the Kaluza-Klein theory.

LARMOR, Joseph (1857–1942)

Irish physicist, educated at Queen's University in Belfast where he received his B.A. and M.A. In 1877 he continued his studies in mathematics at the St. Johns College in Cambridge. In 1880 he returned to Ireland as Professor of Natural Philosophy at Queens College Galway. In 1885 he moved back to Cambridge as lecturer and in 1903 he became the Lucasian Chair of Mathematics succeeding George Stokes. He remained in Cambridge until retirement in 1932 upon which he returned to Ireland.

Larmor worked in several areas of physics such as electricity, dynamics, thermodynamics, and, most notably, in ether, the material postulated at the end of the 19^{th} century as a medium pervading space and transmitting the electromagnetic radiation. He is best known for calculating the rate at which energy is radiated from a charged particle (Larmor law); for explaining the splitting of spectral lines by a magnetic field; and for the Larmor equation $\omega = \gamma B$, where ω is the angular frequency of a precessing proton, γ the gyromagnetic constant, and B the magnetic field.

LAUE, Max von (1879–1960)

German physicist, educated at the University of Strassbourg where he studied mathematics, physics and chemistry, University of Göttingen and University of Berlin where he received his doctorate in physics in 1903. He the worked for two years at the University of Göttingen, four years at the Institute for Theoretical Physics in Berlin, and three years at the University of Munich, before starting his series of Professorships in Physics in 1912 at the University of Zürich, 1914 at the University of Frankfurt, 1916 at the University of Würzburg and 1919 at the University of Berlin from which he retired in 1943.

Von Laue is best known for his discovery in 1912 of the diffraction of x rays on crystals. Since the wavelength of x rays was assumed to be of the order of interatomic separation in crystals, he surmised that crystalline structures behave like diffraction gratings for x rays. Von Laue's hypothesis was proven correct experimentally and established the wave nature of x rays and the regular internal structure of crystals. The crystalline structure essentially forms a three-dimensional grating, presenting a formidable problem to analyze. *William L. Bragg* proposed a simple solution to this problem now referred to as the Bragg equation. Von Laue also made notable contributions to the field of superconductivity where he collaborated with Hans Meissner who with Robert Ochsenfeld established that, when a superconductor in the presence of a magnetic field is cooled below a critical temperature, all of the magnetic flux is expelled from the interior of the sample.

The 1914 Nobel Prize in Physics was awarded to von Laue "*for his discovery of the diffraction of x rays by crystals.*"

LAUTERBUR, Paul Christian (1929–2007)

American chemist, educated at the Case Institute of Technology in Cleveland (B.Sc. in chemistry in 1951) and University of Pittsburgh (Ph.D. in chemistry in 1962). His first academic position was at Stony Brook University as Associate Professor and from 1969 until 1985 as Professor of Chemistry. From 1985 until 1990 he was Professor of Chemistry at the University of Illinois at Chicago and since 1985 he is Professor and Director of the Biomedical MR Laboratory at the University of Illinois at Urbana-Champaign.

Being trained in nuclear magnetic resonance (NMR), Lauterbur started his academic career in this area. However, in the early 1970s when investigating proton NMR relaxation times of various tissues obtained from tumor-bearing rats, he observed large and consistent differences in relaxation times from various parts of the sacrificed animals. Some researchers were speculating that relaxation time measurements might supplement or replace the observations of cell structure in tissues by pathologists but Lauterbur objected to the invasive nature of the procedure. He surmised that there may be a way to locate the precise origin of the NMR signals in complex objects, and thus non-invasively form an image of their distribution in two or even three dimensions. He developed the method of creating a two dimensional image by introducing gradients into the NMR magnetic field, analyzing the characteristics of the emitted radio waves, and determining the location of their source. To allay fears by the general public of everything nuclear, the NMR imaging became known as magnetic resonance imaging or MRI.

Lauterbur shared the 2003 Nobel Prize in Medicine with *Peter Mansfield* "*for their discoveries concerning magnetic resonance imaging.*"

LAWRENCE, Ernest Orlando (1900–1958)

American physicist, educated at the University of South Dakota (B.A. in chemistry in 1922), University of Minnesota (M.A. in chemistry in 1923) and Yale University (Ph.D. in physics in 1925). He first worked at Yale as research fellow and Assistant Professor of Physics and was appointed Associate Professor at the University of California at Berkeley in 1928 and Professor of Physics in 1930. In 1936 he was appointed Director of the University's Radiation Laboratory and remained in these posts until his death in 1958.

The reputation of the Berkeley Physics department as an eminent world-class center of physics is largely based on Lawrence's efforts. He was not only an excellent physicist, he was also an excellent research leader, director of large-scale physics projects, and government advisor. Lawrence is best known for his invention of the cyclotron (in 1930), a cyclic accelerator that accelerates heavy charged particles to high kinetic energies for use in producing nuclear reactions in targets or for use in cancer therapy. During World War II Lawrence worked on the Manhattan project developing the atomic fission bomb. His research interests were also in the use of radiation in biology and medicine.

In 1939 Lawrence was awarded the Nobel Prize in Physics "*for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements.*" Lawrence's name is honored by Lawrence Berkeley Laboratory in Berkeley, Lawrence Livermore National Laboratory in Livermore, California, and lawrencium, an artificial element with an atomic number 103.

LICHTENBERG, Georg Christoph (1742–1799)

German physicist and philosopher, educated at the University of Göttingen, where he also spent his whole professional life, from 1769 until 1785 as Assistant Professor of Physics and from 1785 until his death in 1799 as Professor of Physics.

In addition to physics, Lichtenberg taught many related subjects and was also an active researcher in many areas, most notably astronomy, chemistry, and mathematics. His most prominent research was in electricity and in 1777 he found that discharge of static electricity may form intriguing patters in a layer of dust, thereby discovering the basic principles of modern photocopying machines and xeroradiography. High voltage electrical discharges on the surface or inside of insulating materials often result in distinctive patterns that are referred to as Lichtenberg figures or "trees" in honor of their discoverer.

Lichtenberg is credited with suggesting that Euclid's axioms may not be the only basis for a valid geometry and his speculation was proven correct in the 1970s when *Benoit B. Mandelbrot*, a Polish-American mathematician, introduced the techniques of fractal geometry. Coincidentally, these techniques also produce patterns that are now referred to as Lichtenberg patterns.

Lichtenberg was also known as a philosopher who critically examined a range of philosophical questions and arrived at intriguing, interesting and often humorous conclusions. Many consider him the greatest German aphorist and his "Waste Books" contain many aphorisms and witticisms that are still relevant to modern societies.

LORENTZ, Hendrik Antoon (1853–1928)

Dutch physicist, educated at the University of Leiden where he obtained a B.Sc. degree in mathematics and physics in 1871 and a doctorate in physics in 1875. In 1878 he was appointed to the Chair of Theoretical Physics at the University of Leiden and he stayed in Leiden his whole professional life.

Lorentz made numerous contributions to various areas of physics but is best known for his efforts to develop a single theory to unify electricity, magnetism and light. He postulated that atoms were composed of charged particles and that atoms emitted light following oscillations of these charged particles inside the atom. Lorentz further postulated that a strong magnetic field would affect these oscillations and thus the wavelength of the emitted light. In 1896 Pieter Zeeman, a student of Lorentz, demonstrated the effect now known as the Zeeman effect. In 1904 Lorentz proposed a set of equations that relate the spatial and temporal coordinates for two systems moving at a large constant velocity with respect to each other. The equations are now called the Lorentz transformations and their prediction of increase in mass, shortening of length, and time dilation formed the basis of *Albert Einstein*'s special theory of relativity.

In 1902 Lorentz and Zeeman shared the Nobel Prize in Physics *"in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena."*

MANDELBROT, Benoit (born in 1924)

Polish-born American mathematician, educated in France at the École Polytechnique in Paris and the California Institute of Technology (Caltech) in Pasadena. Mandelbrot received his doctorate in mathematics from the University of Paris in 1952. From 1949 until 1957 he was on staff at the Centre National de la Recherche Scientifique. In 1958 he joined the research staff at the IBM T. J. Watson Research Center in Yorktown Heights, New York and he remained with the IBM until his retirement in 1987 when he became Professor of Mathematical Sciences at Yale University.

Mandelbrot is best known as the founder of fractal geometry, a modern invention in contrast to the 2000 years old Euclidean geometry. He is also credited with coining the term "fractal." Man-made objects usually follow Euclidean geometry shapes, while objects in nature generally follow more complex rules designs defined by iterative or recursive algorithms. The most striking feature of fractal geometry is the self-similarity of objects or phenomena, implying that the fractal contains smaller components that replicate the whole fractal when magnified. In theory the fractal is composed of an infinite number of ever diminishing components, all of the same shape.

Mandelbrot discovered that self-similarity is a universal property that underlies the complex fractal shapes, illustrated its behavior mathematically and founded a completely new methodology for analyzing these complex systems. His name is now identified with a particular set of complex numbers which generate a type of fractal with very attractive properties (Mandelbrot Set).

MANSFIELD, Peter (born in 1933)

British physicist, educated at the Queen Mary College in London where he obtained his B.Sc. in physics in 1959 and doctorate in physics in 1962. He spent 1962–1964 as research associate at the University of Illinois in Urbana and 1964–1978 as lecturer and reader at the University of Nottingham. In 1979 he was appointed Professor of Physics at the University of Nottingham and since 1994 he is Emeritus Professor of Physics at the University of Nottingham.

Mansfield's doctoral thesis was on the physics of nuclear magnetic resonance (NMR), at the time used for studies of chemical structure, and he spent the 1960s perfecting his understanding of NMR techniques. In the early 1970s Mansfield began studies in the use of NMR for imaging and developed magnetic field gradient techniques for producing two-dimensional images in arbitrary planes through a human body. The term "nuclear" was dropped from NMR imaging and the technique is now referred to as magnetic resonance imaging or MRI. Mansfield is also credited with developing the MRI protocol called the "echo planar imaging" which in comparison to standard techniques allows a much faster acquisition of images and makes functional MRI (*f*MRI) possible.

Mansfield shared the 2003 Nobel Prize in Medicine and Physiology with *Paul C. Lauterbur* "*for their discoveries concerning magnetic resonance imaging.*"

MARSDEN, Ernest (1889–1970)

New Zealand-born physicist who made a remarkable contribution to science in New Zealand and England. He studied physics at the University of Manchester and as a student of Ernest Rutherford, in collaboration with Hans Geiger, carried out the α-particle scattering experiments that inspired Rutherford to propose the atomic model, currently known as the Rutherford-Bohr model of the atom. In 1914 he returned to New Zealand to become Professor of Physics at Victoria University in Wellington. In addition to scientific work, he became involved with public service and helped in setting up the New Zealand Department of Scientific and Industrial Research. During World War II, he became involved with radar technology in defense work and in 1947 he was elected president of the Royal Society of New Zealand. He there returned to London as New Zealand's scientific liaison officer and "ambassador" for New Zealand science. In 1954 he retired to New Zealand and remained active on various advisory committees as well as in radiation research until his death in 1970.

MAXWELL, James Clerk (1831–1879)

Scottish mathematician and theoretical physicist, educated at the University of Edinburgh (1847–1850) and Trinity College of Cambridge University. From 1856–1860 he held the position of Chair of Natural Philosophy of Marischal College of Aberdeen University and from 1860–1865 he was Chair of Natural Philosophy at King's College in London where he established a regular contact with Michael Faraday.

In 1865 Maxwell resigned his position at King's College and for the following five years held no academic appointments. In 1871 he became the first Cavendish Professor of Physics at Cambridge and was put in charge of developing the Cavendish Laboratory. He remained at Cavendish until his death in 1879.

While at King;s College, Maxwell made his most important advances in the theory of electromagnetism and developed the famous set of four Maxwell equations, demonstrating that electricity, magnetism and light are all derived from electromagnetic field. His work on electromagnetic theory is considered of the same importance as Newton's work in classical mechanics and Einstein's work in relativistic mechanics.

Maxwell also worked on the kinetic theory of gases and in 1866 derived the Maxwellian distribution describing the fraction of gas molecules moving at a specified velocity at a given temperature. Together with Willard Gibbs and Ludwig Boltzmaun Maxwell is credited with developing statistical mechanics and paving the way for quantum mechanics and relativistic mechanics.

MEITNER, Lise (1878–1968)

Austrian-born physicist who studied physics at the University of Vienna and was strongly influenced in her vision of physics by Ludwig Boltzmann, a leading theoretical physicist of the time. In 1907 Meitner moved to Berlin to work with *Max Planck* and at the University of Berlin she started a life-long friendship and professional association with radiochemist *Otto Hahn*. At the Berlin University both Meitner and Hahn were appointed as scientific associates and progressed through academic ranks to attain positions of professor.

During her early days in Berlin, Meitner discovered the element protactinium with atomic number $Z = 91$ and also discovered, two years before Auger, the non-radiative atomic transitions that are now referred to as the Auger effect. Meitner became the first female physics professor in Germany but, despite her reputation as an excellent physicist, she, like many other Jewish scientists, had to leave Germany during the 1930s. She moved to Stockholm and left behind in Berlin her long-term collaborator and friend *Otto Hahn*, who at that time was working with *Friedrich Strassmann*, an analytical chemist, on studies of uranium bombardment with neutrons. Their experiments, similarly to those reported by Irene Joliot-Curie and Pavle Savic were yielding surprising results suggesting that in neutron bombardment uranium was splitting into smaller atoms with atomic masses approximately half of that of uranium. In a letter Hahn described the uranium disintegration by neutron bombardment to Meitner in Stockholm and she, in collaboration with Otto Frisch, succeeded in providing a theoretical explanation for the uranium splitting and coined the term nuclear fission to name the process.

The 1944 Nobel Prize in Chemistry was awarded to Hahn "*for the discovery of the nuclear fission.*" The Nobel Committee unfortunately ignored the contributions by Strassmann, Meitner and Frisch to the theoretical understanding of the nuclear fission process. Most texts dealing with the history of nuclear fission now recognize the four scientists: Hahn, Strassmann, Meitner, and Frisch as the discoverers of the fission process.

Despite several problems that occurred with recognizing Meitner's contributions to modern physics, her scientific work certainly was appreciated and is given the same ranking in importance as that of Marie Curie. In 1966 Meitner together with Hahn and Strassmann shared the prestigious Enrico Fermi Award. In honor of Meitner's contributions to modern physics the element with atomic number 109 was named meitnerium (Mt).

MENDELEEV, Dmitri Ivanovič (1834–1907)

Russian physical chemist, educated at the University of St. Petersburg where he obtained his M.A. in chemistry in 1856 and doctorate in chemistry in 1865. The years between 1859 and 1861 Mendeleev spent studying in Paris and Heidelberg. He worked as Professor of Chemistry at the Technical Institute of St. Petersburg and the University of St. Petersburg from 1862 until 1890 when he retired from his academic posts for political reasons. From 1893 until his death in 1907 he was Director of the Bureau of Weights and Measures in St. Petersburg.

While Mendeleev made contributions in many areas of general chemistry as well as physical chemistry and was an excellent teacher, he is best known for his 1869 discovery of the Periodic Law and the development of the Periodic Table of Elements. Until his time elements were distinguished from one another by only one basic characteristic, the atomic mass, as proposed by John Dalton in 1805. By arranging the 63 then-known elements by atomic mass as well as similarities in their chemical properties, Mendeleev obtained a table consisting of horizontal rows or periods and vertical columns or groups. He noticed several gaps in his Table of Elements and predicted that they represented elements not yet discovered. Shortly afterwards elements gallium, germanium and scandium were discovered filling three gaps in the table, thereby confirming the validity of Mendeleev's Periodic Table of Elements. Mendeleev's table of more than a century ago is very similar to the modern 21^{st} century Periodic Table, except that the 111 elements of the modern periodic table are arranged according to their atomic number Z in contrast to Mendeleev's table in which the 63 known elements were organized according to atomic mass. To honor Mendeleev's work the element with atomic number Z of 101 is called mendelevium.

MILLIKAN, Robert Andrews (1868–1952)

American physicist, educated at Oberlin College (Ohio) and Columbia University in New York where he received a doctorate in physics in 1895. He then spent a year at the universities of Berlin and Götingen, before accepting a position at the University of Chicago in 1896. By 1910 he was Professor of Physics and remained in Chicago until 1921 when he was appointed Director of the Norman Bridge Laboratory of Physics at the California Institute of Technology (Caltech) in Pasadena. He retired in 1946.

Millikan was a gifted teacher and experimental physicist. During his early years at Chicago he authored and coauthored many physics textbooks to help and simplify the teaching of physics. As a scientist he made many important discoveries in electricity, optics and molecular physics. His earliest and best known success was the accurate determination, in 1910, of the electron charge with the "falling-drop method" now commonly referred to as the Millikan experiment. He also verified experimentally the Einstein's photoelectric effect equation and made the first direct photoelectric determination of Planck's quantum constant h.

The 1923 Nobel Prize in Physics was awarded to Millikan "*for his work on the elementary charge of electricity and on the photoelectric effect.*"

MØLLER, Christian (1904–1980)

Danish theoretical physicist, educated at the University of Copenhagen where he first studied mathematics and then theoretical physics. In 1929 he obtained his M.Sc. degree and in 1933 his doctorate under Niels Bohr on passage of fast electrons through matter. He first worked as lecturer at the Bohr institute in Copenhagen and from 1943 until retirement in 1975 he was Professor of Mathematical Physics at the University of Copenhagen.

Møller began his theoretical physics work in nuclear and high-energy physics and was influenced by the many eminent physicists who were visiting the Bohr institute during the 1930s, such as George Gamow, Nevill Mott, and Yoshio Nishima. He made important contributions in nuclear and high-energy physics problems combined with the theory of relativity, most notably in alpha decay, α-particle scattering, electron-positron theory and meson theory of nuclear forces. He is best known for his work on electron scattering on atomic orbital electrons which in his honor is termed Møller scattering.

MÖSSBAUER, Rudolf Ludwig (born in 1929)

German physicist, educated at the Technische Hochschule (Technical University) in Munich, where he received his doctorate in physics in 1958, after carrying out the experimental portion of his thesis work in Heidelberg at the Institute for Physics of the Max Planck Institute for Medical Research. During 1959 Mössbauer worked as scientific assistant at the Technical University in Munich and from 1960 until 1962 as Professor of Physics at the California Institute of Technology (Caltech) in Pasadena. In 1962 he returned to the Technical Institute in Munich as Professor of Experimental Physics and stayed there his whole professional career except for the period 1972–1977 which he spent in Grenoble as the Director of the Max von Laue Institute.

Mössbauer is best known for his 1957 discovery of recoil-free gamma ray resonance absorption; a nuclear effect that is named after him and was used to verify *Albert Einstein*'s theory of relativity and to measure the magnetic field of atomic nuclei. The Mössbauer effect involves the emission and absorption of gamma rays by atomic nuclei. When a free excited nucleus emits a gamma photon, the nucleus recoils in order to conserve momentum. The nuclear recoil uses up a minute portion of the decay energy, so that the shift in the emitted photon energy prevents the absorption of the photon by another target nucleus. While working on his doctorate thesis in Heidelberg, Mössbauer discovered that by fixing emitting and absorbing nuclei into a crystal lattice, the whole lattice gets involved in the recoil process, minimizing the recoil energy loss and creating an overlap between emission and absorption lines thereby enabling the resonant photon absorption process and creating an extremely sensitive detector of photon energy shifts.

Mössbauer received many awards and honorable degrees for his discovery; most notably, he shared with Robert Hofstadter the 1961 Nobel Prize in Physics *"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name."* Hofstadter received his share of the 1961 Nobel Prize for his pioneering studies of electron scattering in atomic nuclei.

MOSELEY, Henry Gwen Jeffreys (1887–1915)

British physicist, educated at the University of Oxford where he graduated in 1910. He began his professional career at the University of Manchester as lecturer in physics and research assistant under *Ernest Rutherford*.

Based on work by *Charles Barkla* who discovered characteristic x rays and work of the team of *William Bragg* and *Lawrence Bragg* who studied x-ray diffraction, Moseley undertook in 1913 a study of the K and L characteristic x rays emitted by then-known elements from aluminum to gold. He found that the square root of the frequencies of the emitted characteristic x-ray lines plotted against a suitably chosen integer Z yielded straight lines. Z was subsequently identified as the number of positive charges (protons) and the number of electrons in an atom and is now referred to as the atomic number Z. Moseley noticed gaps in his plots that corresponded to atomic numbers Z of 43, 61, and 75. The elements with $Z = 43$ (technetium) and $Z = 61$ (promethium) do not occur naturally but were produced artificially years later. The $Z = 75$ element (rhenium) is rare and was discovered only in 1925. Moseley thus found that the atomic number of an element can be deduced from the element's characteristic spectrum (non-destructive testing). He also established that the periodic table of elements should be arranged according to the atomic number Z rather than according to the atomic mass number A as was common at his time.

There is no question that Moseley during a short time of two years produced results that were very important for the development of atomic and quantum physics and were clearly on the level worthy of Nobel Prize. Unfortunately, he perished during World War I shortly after starting his professional career in physics.

MOTT, Nevill Francis (1905–1996)

British physicist, educated at Clifton College in Bristol and St. John's College in Cambridge where he studied mathematics and physics, received a baccalaureate degree in 1927, and carried out his first work in theoretical physics studying scattering of electrons on nuclei. During 1928 he continued his physics studies under Niels Bohr in Copenhagen and Max Born in Göttingen. He spent the 1929–30 academic year as lecturer in Manchester where William L. Bragg introduced him to solid atate physics. In 1930 Mott returned to Cambridge, obtained his M.Sc. degree in Physics, and continued his work on particle scattering on atoms and nuclei in Rutherford's laboratory. His contributions to collision theory are recognized by the description of electron–nucleus scattering as Mott scattering.

The period from 1933 to 1954 Mott spent in Bristol, first as Professor of Theoretical Physics and from 1948 as Chairman of the Physics Department. His work concentrated on solid state physics and resulted in many important publications and several books. In 1954 Mott became Cavendish Professor of Physics at Cambridge. He continued his work in solid state physics, concentrating on amorphous semiconductors and producing research for which he shared the 1977 Nobel Prize in Physics with Philip W. Anderson and John H. Van Vleck "*for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems*".

In addition to his contributions to experimental and theoretical physics, Mott has also taken a leading role in science education reform in the U.K. and served on many committees that dealt with science education.

NISHINA, Yoshio (1890–1951)

Japanese physicist, educated at the University of Tokyo where he graduated in 1918. He worked three years as an assistant at the University of Tokyo and then spent several years in Europe: 1921–1923 at the University of Cambridge with *Ernest Rutherford* and 1923–1928 at the University of Copenhagen with *Niels Bohr*. From 1928 to 1948 he worked at the University of Tokyo.

Nishina is best known internationally for his collaboration with *Oskar Klein* on the cross section for Compton scattering in 1928 (Klein-Nishina formula). Upon return to Japan from Europe, Nishina introduced the study of nuclear and high-energy physics in Japan and trained many young Japanese physicists in the nuclear field. During World War II Nishina was the central figure in the Japanese atomic weapons program that was competing with the American Manhattan project and using the same thermal uranium enrichment technique as the Americans. The race was tight; however, the compartmentalization of the Japanese nuclear weapons program over competing ambitions of the army, air force and the navy gave the Americans a definite advantage and eventual win in the nuclear weapons competition that resulted in the atomic bombs over Hiroshima and Nagasaki and Japanese immediate surrender.

PAULI, Wolfgang (1900–1958)

Austrian-born physicist, educated at the University of Munich where he obtained his doctorate in physics in 1921. He spent one year at the University of Göttingen and one year at the University of Copenhagen before accepting a lecturer position at the University of Hamburg (1923–1928). From 1928 to 1958 he held an appointment of Professor of Theoretical Physics at the Eidgenössische Technische Hochschule in Zürich in Zürich. From 1940 to 1946 Pauli was a visiting professor at the Institute for Advanced Study in Princeton.

Pauli is known as an extremely gifted physicist of his time. He is best remembered for enunciating the existence of the neutrino in 1930 and for introducing the exclusion principle to govern the states of atomic electrons in general. The exclusion principle is now known as the Pauli Principle and contains three components. The first component states that no two electrons can be at the same place at the same time. The second component states that atomic electrons are characterized by four quantum numbers: principal, orbital, magnetic and spin. The third component states that no two electrons in an atom can occupy a state that is described by exactly the same set of the four quantum numbers. The exclusion principle was subsequently expanded to other electronic and fermionic systems, such as molecules and solids.

The 1945 Nobel Prize in Physics was awarded to Pauli *"for his discovery of the Exclusion Principle, also called the Pauli Principle."*

PLANCK, Max Karl Ernst (1858–1947)

German physicist, educated at the University of Berlin and University of Munich where he received his doctorate in physics in 1879. He worked as Assistant Professor at the University of Munich from 1880 until 1885, then Associate Professor at the University of Kiel until 1889 and Professor of Physics at the University of Berlin until his retirement in 1926.

Most of Planck's work was on the subject of thermodynamics in general and studies of entropy and second law of thermodynamics in particular. He was keenly interested in the blackbody problem and the inability of classical mechanics to predict the blackbody spectral distribution. Planck studied the blackbody spectrum in depth and concluded that it must be electromagnetic in nature. In contrast to classical equations that were formulated for blackbody radiation by Wien and Rayleigh, with Wien's equation working only at high frequencies and Rayleigh's working only a low frequencies, Planck formulated an equation that predicted accurately the whole range of applicable frequencies and is now known as Planck's equation for blackbody radiation. The derivation was based on the revolutionary idea that the energy emitted by a resonator can only take on discrete values or quanta, with the quantum energy ε equal to $h\nu$, where ν is the frequency and h a universal constant now referred to as the Planck's constant. Planck's idea of quantization has been successfully applied to the photoelectric effect by Albert Einstein and to the atomic model by Niels Bohr.

In 1918 Planck was awarded the Nobel Prize in Physics *"in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta."* In addition to Planck's constant and Planck's formula, Planck's name and work are honored with the Max Planck Medal that is awarded annually as the highest distinction by the German Physical Society (Deutsche Physikalische Gesellschaft) and the Max Planck Society for the Advancement of Science that supports basic research at 80 research institutes focusing on research in biology, medicine, chemistry, physics, technology and humanities.

POYNTING, John Henry (1852–1914)

British physicist, born in Monton near Manchester and educated at Owens College in Manchester (B.Sc. in 1876) and Trinity College in Cambridge (Sc.D in 1887). He started his academic career in Manchester (1876–1878) where he met J.J. Thomson with whom he completed "A Textbook of Physics." In 1878 he became a Fellow of Trinity College in Cambridge and for two years worked in Cavendish Laboratory under J.C. Maxwell. In 1880 he moved to the University of Birmingham as professor of physics and stayed there for the rest of his professional life.

Poynting was an excellent theoretical as well as experimental physicist. His greatest discovery was the Poynting theorem in electromagnetism from which comes the defintion of the Poynting vector. He is also remembered for many other contributions to physics, such as an accurate measurement of Newton's gravitational constant; determination of the mean density of the Earth; discovery of the Poynting-Robertson effect (small particles in the orbit about Sun spiral into the Sun); and method for determining absolute temperature of celestial objects.

The Poynting theorem deals with the conservation of energy for the electromagnetic field and can be derived from the Lorentz force in conjuction with Maxwell's equations. The Poynting vector represents the energy flow through a given area for electromagnetic field and is usually written as a vector product $\mathbf{S} = \boldsymbol{\mathcal{E}} \times \boldsymbol{\mathcal{B}}/\mu_0$ where $\boldsymbol{\mathcal{E}}$ is the electric field, $\boldsymbol{\mathcal{B}}$ the magnetic field, and μ_0 the permeability of vacuum.

Poynting was held in high esteem by his peers and received numerous awards for his work. He was President of Physiccal Society and was elected Fellow of the Royal Society. In 1905 he received the Royal Medal from the Royal Society.

PURCELL, Edward Mills (1912–1997)

American physicist, educated at Purdue University in Indiana where he received his Bachelor's degree in electrical engineering in 1933 and Harvard where he received his doctorate in physics in 1938. After serving for two years as lecturer of physics at Harvard, he worked at the Massachusetts Institute of Technology on development of new microwave techniques. In 1945 Purcell returned to Harvard as Associate Professor of Physics and became Professor of Physics in 1949.

Purcell is best known for his 1946 discovery of nuclear magnetic resonance (NMR) with his students Robert Pound and Henry C. Torrey. NMR offers an elegant and precise way of determining chemical structure and properties of materials and is widely used not only in physics and chemistry but also in medicine where, through the method of magnetic resonance imaging (MRI), it provides non-invasive means to image internal organs and tissues of patients.

In 1952 Purcell shared the Nobel Prize in Physics with *Felix Bloch* "*for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith.*"

RAYLEIGH, John William Strutt (1842–1919)

English mathematician and physicist who studied mathematics at the Trinity College in Cambridge. Being from an affluent family he set up his physics laboratory at home and made many contributions to applied mathematics and physics from his home laboratory. From 1879 to 1884 Rayleigh was Professor of Experimental Physics and Head of the Cavendish Laboratory at Cambridge, succeeding James Clark Maxwell. From 1887 to 1905 he was Professor of Natural Philosophy at the Royal Institution in London.

Rayleigh was a gifted researcher and made important contributions to all branches of physics known at his time, having worked in optics, acoustics, mechanics, thermodynamics, and electromagnetism. He is best known for explaining that the blue color of the sky arises from the scattering of light by dust particles in air and for relating the degree of light scattering to the wavelength of light (Rayleigh scattering). He also accurately defined the resolving power of a diffraction grating; established standards of electrical resistance, current, and electromotive force; discovered argon; and derived an equation describing the distribution of wavelengths in blackbody radiation (the equation applied only in the limit of large wavelengths).

In 1904 Rayleigh was awarded the Nobel Prize in Physics *"for his investigations of the densities of the most important gases and for his discovery of the noble gas argon in connection with these studies."* He discovered argon together with William

Ramsey who obtained the 1904 Nobel Prize in Chemistry for his contribution to the discovery.

RICHARDSON, Owen Willans (1879–1959)

British physicist, educated at Trinity College in Cambridge from where he graduated in 1990 as a student of Joseph J. Thomson at the Cavendish Laboratory. He was appointed Professor of Physics at Princeton University in the United States in 1906 but in 1914 returned to England to become Professor of Physics at King's College of the University of London.

Richardson is best known for his work on thermionic emission of electrons from hot metallic objects that enabled the development of radio and television tubes as well as modern x-ray (Coolidge) tubes. He discovered the equation that relates the rate of electron emission to the absolute temperature of the metal. The equation is now referred to as the Richardson's law or the Richardson-Dushman equation.

In 1928 Richardson was awarded the Nobel Prize in Physics "*for his work on the thermionic phenomenon and especially for the law that is named after him.*"

RÖNTGEN, Wilhelm Conrad (1845–1923)

German physicist, educated at the University of Utrecht in Holland and University of Zürich where he obtained his doctorate in physics in 1869. He worked as academic physicist at several German universities before accepting a position of Chair of Physics at the University of Giessen in 1979. From 1888 until 1900 he was Chair of Physics at the University of Würzburg and from 1900 until 1920 he was Chair of Physics at the University of Munich.

Röntgen was active in many areas of thermodynamics, mechanics and electricity but his notable research in these areas was eclipsed by his accidental discovery in 1895 of "a new kind of ray." The discovery occurred when Röntgen was studying cathode rays (now known as electrons, following the work of Joseph J. Thomson) in a Crookes tube, a fairly mundane and common experiment in physics departments at the end of the 19-th century. He noticed that, when his energized Crookes tube was enclosed in a sealed black and light-tight envelope, a paper plate covered with barium platinocianide, a known fluorescent material, became fluorescent despite being far removed from the discharge tube. Röntgen concluded that he discovered an unknown type of radiation, much more penetrating than visible light and produced when cathode rays strike a material object inside the Crookes tube. He named the new radiation x rays and the term is generaly used around the World. However, in certain countries x rays are often called Röntgen rays. In 1912 *Max von Laue* showed with his crystal diffraction experiments that x rays are electromagnetic radiation similar to visible light but of much smaller wavelength. In tribute to Röntgen's contributions to modern physics the element with the atomic number 111 was named röntgenium (Rg).

In 1901 the first Nobel Prize in Physics was awarded to Röntgen *"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him."*

RUTHERFORD, Ernest (1871–1937)

New Zealand-born nuclear physicist, educated at the Canterbury College in Christchurch, New Zealand (B.Sc. in mathematics and physical science in 1894) and at the Cavendish Laboratory of the Trinity College in Cambridge. He received his science doctorate from the University of New Zealand in 1901. Rutherford was one of the most illustrious physicists of all time and his professional career consists of three distinct periods: as MacDonald Professor of Physics at McGill University in Montreal (1898–1907); as Langworthy Professor of Physics at the University of Manchester (1908–1919); and as Cavendish Professor of Physics at the Cavendish Laboratory of Trinity College in Cambridge (1919–1937).

With the exception of his early work on magnetic properties of iron exposed to high frequency oscillations, Rutherford's career was intimately involved with the advent and growth of nuclear physics. Nature provided Rutherford with α particles, an important tool for probing the atom, and he used the tool in most of his exciting discoveries that revolutionized physics in particular and science in general.

Before moving to McGill in 1898, Rutherford worked with *Joseph J. Thomson* at the Cavendish Laboratory on detection of the just-discovered x rays (*Wilhelm Röntgen* in 1895) through studies of electrical conduction of gases caused by x-ray ionization of air. He then turned his attention to the just-discovered radiation emanating from uranium (*Henri Becquerel* in 1896) and radium (*Pierre Curie* and *Marie Curie* in 1898) and established that uranium radiation consists of at least two components, each of particulate nature but with different penetrating powers. He coined the names α and β particles for the two components.

During his 10 years at McGill, Rutherford published 80 research papers, many of them in collaboration with *Frederick Soddy*, a chemist who came to McGill from Oxford in 1900. Rutherford discovered the radon gas as well as gamma rays and speculated that the gamma rays were similar in nature to x rays. In collaboration with Soddy he described the transmutation of radioactive elements as a spontaneous disintegration of atoms and defined the half-life of a radioactive substance as the time it takes for its activity to drop to half of its original value. He noted that all atomic disintegrations were characterized by emissions of one or more of three kinds of rays: α, β, and γ.

During the Manchester period Rutherford determined that α particles were helium ions. He guided Hans Geiger and Ernest Marsden through the now-famous α particle scattering experiment. Based on the experimental results Rutherford in 1911 proposed a revolutionary model of the atom which was known to have a size of the order of 10^{-10} m. He proposed that most of the atomic mass is concentrated in a miniscule nucleus with a size of the order of 10^{-15} m) and that the atomic electrons are distributed in a cloud around the nucleus. In 1913 *Niels Bohr* expanded Rutherford's nuclear atomic model by introducing the idea of the quantization of electrons' angular momenta and the resulting model is now called the Rutherford-Bohr atomic model. During his last year at Manchester, Rutherford discovered that nuclei of nitrogen, when bombarded with α particles, artificially disintegrate and produce protons in the process. Rutherford was thus first in achieving artificial transmutation of an element through a nuclear reaction.

During the Cambridge period Rutherford collaborated with many world-renowned physicists such as John Cocroft and Ernest Walton in designing a proton accelerator now called the Cocroft-Walton machine, and with *James Chadwick* in discovering the neutron in 1932. Rutherford's contributions to modern physics are honored with the element of atomic number 104 which was named rutherfordium (Rf).

In 1908 Rutherford was awarded the Nobel Prize in Chemistry *"for his investigations into the disintegration of the elements and the chemistry of radioactive substances."*

RYDBERG, Johannes (1854–1919)

Swedish physicist, educated at Lund University. He obtained his Ph.D. in mathematics in 1879 but worked all his professional life as a physicist at Lund University where he became Professor of Physics and Chairman of the Physics department.

Rydberg is best known for his discovery of a mathematical expression that gives the wavenumbers of spectral lines for various elements and includes a constant that is now referred to as the Rydberg constant $\left(R_\infty = 109\,737\ \text{cm}^{-1}\right)$. In honor of Rydberg's work in physics the absolute value of the ground state energy of the hydrogen atom is referred to as the Rydberg energy ($E_\text{R} = 13.61\ \text{eV}$).

SCHRÖDINGER, Erwin (1887–1961)

Austrian physicist, educated at the University of Vienna where he received his doctorate in Physics in 1910. He served in the military during World War I and after the war moved through several short-term academic positions until in 1921 he accepted a Chair in Theoretical Physics at the University of Zürich. In 1927 he moved to the University of Berlin as Planck's successor. The rise of Hitler in 1933 convinced Schrödinger to leave Germany. After spending a year at Princeton University, he accepted a post at the University of Graz in his native Austria. The German annexation of Austria in 1938 forced him to move again, this time to the Institute for Advanced Studies in Dublin where he stayed until his retirement in 1955.

Schrödinger made many contributions to several areas of theoretical physics, however, he is best known for introducing wave mechanics into quantum mechanics. Quantum mechanics deals with motion and interactions of particles on an atomic scale and its main attribute is that it accounts for the discreteness (quantization) of physical quantities in contrast to classical mechanics in which physical quantities are assumed continuous. Examples of quantization were introduced by *Max Planck* who in 1900 postulated that oscillators in his blackbody emission theory can possess only certain quantized energies; *Albert Einstein* who in 1905 postulated that electromagnetic radiation exists only in discrete packets called photons; and *Niels Bohr* who in 1913 introduced the quantization of angular momenta of atomic orbital electrons. In addition, *Louis de Broglie* in 1924 introduced the concept of wave-particle duality.

Schrödinger's wave mechanics is based on the so-called Schrödinger's wave equation, a partial differential equation that describes the evolution over time of the wave function of a physical system. Schrödinger and other physicists have shown that many quantum mechanical problems can be solved by means of the Schrödinger equation. The best known examples are: finite square well potential; infinite square well potential; potential step; simple harmonic oscillator; and hydrogen atom.

In 1933 Schrödinger shared the Nobel Prize in Physics with *Paul A.M. Dirac "for the discovery of new productive forms of atomic theory."*

SEGRÈ, Emilio Gino (1905–1989)

Italian-born American nuclear physicist, educated at the University of Rome, where he received his doctorate in physics as Enrico Fermi's first graduate student in 1928. In 1929 he worked as assistant at the University of Rome and spent the years 1930–1931 with Otto Stern in Hamburg and Pieter Heman in Amsterdam. In 1932 he became Assistant Professor of Physics at the University of Rome and in 1936 he was appointed Director of the Physics Laboratory at the University of Palermo. In 1938 Segrè came to Berkeley University, first as research associate then as physics lecturer. From 1943 until 1946 he was a group leader in the Los Alamos Laboratory of the Manhattan Project and from 1946 until 1972 he held an appointment of Professor of Physics at Berkeley. In 1974 he was appointed Professor of Physics at the University of Rome.

Segrè is best known for his participation with Enrico Fermi in neutron experiments bombarding uranium-238 with neutrons thereby creating several elements heavier than uranium. They also discovered thermal neutrons and must have unwittingly triggered uranium-235 fission during their experimentation. It was Otto Hahn and colleagues, however, who at about the same time discovered and explained nuclear fission. In 1937 Segrè discovered technetium, the first man-made element not found in nature and, as it subsequently turned out, of great importance to medical physics in general and nuclear medicine in particular. At Berkeley Segrè discovered plutonium-239 and established that it was fissionable just like uranium-235. Segrè made many other important contributions to nuclear physics and high-energy physics and, most notably, in collaboration with Owen Chamberlain discovered the antiproton. Segrè and Chamberlain shared the 1959 Nobel Prize in Physics "*for their discovery of the antiproton.*"

SELTZER, Stephen Michael (born in 1940)

American physicist, educated at the Virginia Polytechnic Institute where he received his B.S. in physics in 1962 and at the University of Maryland, College Park where he received his M.Sc. in physics in 1973. In 1962 he joined the Radiation Theory Section at the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST), and has spent his professional career there, becoming the Director of the Photon and Charged-Particle Data Center at NIST in 1988 and the Leader of the Radiation Interactions and Dosimetry Group in 1994. He joined the International Commission on Radiation Units and Measurements (ICRU) in 1997.

Seltzer worked with *Martin Berger* on the development of Monte Carlo codes for coupled electron-photon transport in bulk media, including the transport-theoretical methods and algorithms used, and the interaction cross-section information for these radiations. Their ETRAN codes, underlying algorithms and cross-section data have been incorporated in most of the current radiation-transport Monte Carlo codes. Seltzer was instrumental in the development of extensive data for the production of bremsstrahlung by electrons (and positrons), electron and positron stopping powers, and a recent database of photon energy-transfer and energy-absorption coefficients. His earlier work included applications of Monte Carlo calculations to problems in space science, detector response, and space shielding, which led to the development of the SHIELDOSE code used for routine assessments of absorbed dose within spacecraft.

SIEGBAHN, Karl Manne Georg (1886–1978)

Swedish physicist, educated at the University of Lund where he obtained his Doctorate in Physics in 1911. From 1907 to 1923 he lectured in physics at the University of Lund, first as Assistant to Professor J. R. Rydberg, from 1911 to 1915 as Lecturer in Physics, and from 1915 to 1923 as Professor of Physics. In 1923 he moved to the University of Uppsala where he stayed as Professor of Physics until 1937 when he became a Research Professor of Experimental Physics and the first Director of the Physics Department of the Nobel Institute of the Royal Swedish Academy of Sciences in Stockholm. He remained with the Academy till 1975 when he retired.

Siegbahn's main contribution to physics was in the area of x-ray spectroscopy and covered both the experimental and theoretical aspects. He made many discoveries related to x-ray emission spectra from various target materials and also developed equipment and techniques for accurate measurement of x-ray wavelengths. He built his own x-ray spectrometers, produced numerous diamond-ruled glass diffraction gratings for his spectrometers, and measured x-ray wavelengths of many target elements to high precision using energetic electrons to excite the characteristic spectral emission lines.

To honor Siegbahn's significant contributions to x-ray spectroscopy the notation for x-ray spectral lines that are characteristic to elements is referred to as Siegbahn's notation. The notation has been in use for many decades and only recently the International Union of Pure and Applied Chemistry (IUPAC) proposed a new notation referred to as the IUPAC notation which is deemed more practical and is slated to replace the existing Siegbahn notation.

In 1924 Siegbahn received the Nobel Prize in Physics *"for discoveries and research in the field of x-ray spectroscopy."*

SODDY, Frederick (1877–1956)

British chemist, educated at Morton College in Oxford where he received his degree in chemistry in 1898. After graduation he spent two years as research assistant in Oxford, then went to McGill University in Montreal where he worked with *Ernest Rutherford* on radioactivity. In 1902 Soddy returned to England to work with William Ramsay at the University College in London. He then served as lecturer in physical chemistry at the University of Glasgow (1910–1914) and Professor of Chemistry at the University of Aberdeen (1914–1919). His last appointment was from 1919 until 1936 as Lees Professor of Chemistry at Oxford University.

Soddy is best known for his work in the physical and chemical aspects of radioactivity. He learned the basics of radioactivity with *Ernest Rutherford* at McGill University and then collaborated with William Ramsay at the University College. With Rutherford he confirmed the hypothesis by *Marie Curie* that radioactive decay was an atomic rather than chemical process, postulated that helium is a decay product of uranium, and formulated the radioactive disintegration law. With Ramsay he confirmed that the alpha particle was doubly ionized helium atom. Soddy's Glasgow period was his most productive period during which he enunciated the so-called displacement law and introduced the concept of isotopes. The displacement law states that emission of an alpha particle from a radioactive element causes the element to transmutate into a new element that moves back two places in the Periodic Table of Element. The concept of isotopes states that certain elements exist in two or more forms that differ in atomic mass but are chemically indistinguishable.

Soddy was awarded the 1921 Nobel Prize in Chemistry "*for his contributions to our knowledge of the chemistry of radioactive substances, and his investigations into the origin and nature of isotopes.*"

STERN, Otto (1888–1969)

German-born physicist educated in physical chemistry at the University of Breslau where he received his doctorate in 1912. He worked with *Albert Einstein* at the University of Prague and at the University of Zürich before becoming an Assistant Professor at the University of Frankfurt in 1914. During 1921–1922 he was an Associate Professor of Theoretical Physics at the University of Rostock and in 1923 he was appointed Professor of Physical Chemistry at the University of Hamburg. He remained in Hamburg until 1933 when he moved to the United States to become a Professor of Physics at the Carnegie Institute of Technology in Pittsburgh.

Stern is best known for the development of the molecular beam epitaxy, a technique that deposits one or more pure materials onto a single crystal wafer forming a perfect crystal; discovery of spin quantization in 1922 with *Walther Gerlach*; measurement of atomic magnetic moments; demonstration of the wave nature of atoms and molecules; and discovery of proton's magnetic moment.

Stern was awarded the 1943 Nobel Prize in Physics *"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton."*

STRASSMANN, Friedrich Wilhelm (1902–1980)

German physical chemist, educated at the Technical University in Hannover where he received his doctorate in 1929. He worked as an analytical chemist at the Kaiser Wilhelm Institute for Chemistry in Berlin from 1934 until 1945. In 1946 Strassmann became Professor of Inorganic Chemistry at the University of Mainz. From 1945 to 1953 he was Director of the Chemistry department at the Max Planck Institute.

Strassmann is best known for his collaboration with Otto Hahn and Lise Meitner on experiments that in 1938 lead to the discovery of neutron induced fission of uranium atom. Strassmann's expertise in analytical chemistry helped with discovery of the light elements produced in the fission of uranium atoms. In 1966 the nuclear fission work by Hahn, Strassmann and Meitner was recognized with the Enrico Fermi Award.

SZILÁRD Leó (1898–1964)

Hungarian born American physicist, educated in engineering first at the Budapest Technical University and at the "Technische Hochschule" in Berlin. After the basic training in engineering he switched to physics and received his Ph.D. in Physics in 1923 from the Humboldt University in Berlin. He worked as physics instructor and inventor at the University of Berlin. In 1933 he moved to Britain where he worked till 1938 on various nuclear physics and engineering projects in London and Oxford. His main interests during that time were the practical use of atomic energy and the nuclear chain reaction process. He received a British patent for proposing that if any neutron-driven process released more neutrons than the number required to start it, an expanding nuclear chain reaction would result in a similar fashion to chain reactions known in chemistry.

In 1938 Szilárd moved to Columbia University in New York City where he was soon joined by Enrico Fermi who moved to the U.S. from Italy. In 1939 Szilárd and Fermi learned about nuclear fission experiment carried out by Hahn and Strassmann and concluded that uranium would be a good material for sustaining a chain reaction through the fission process and neutron multiplication.

The use of nuclear chain reaction for military purpose became obvious and Szilárd was instrumental in the creation of the Manhattan project whose purpose was to develop nuclear weapons for use in the World War II against Germany and Japan. In 1942 both Szilárd and Fermi moved to the University of Chicago and in December of 1942 they set off the first controlled nuclear chain reaction and subsequently many well-known theoretical and experimental physicists became involved with the project. Since uranium-235 was one of the two fissionable nuclides of choice (the other was plutonium) for the bomb, several laboratories around the U.S.A. were working on techniques for a physical separation of U-235 from the much more abundant U-238 in natural uranium. Atomic bombs became available for actual military use in 1945; they were used on Hiroshima and Nagasaki in Japan and are credited with accelerating the rapid surrender of Japan.

In 1955 Szilárd, with Enrico Fermi, received a patent for a nuclear fission reactor in which nuclear chain reactions are initiated, controlled, and sustained at a steady observable rate. These reactions are used today as source of power in nuclear power plants.

Szilárd was very conscious socially and had great concern for the social consequences of science. He believed that scientists must accept social responsibility for unexpected detrimental consequences of their discoveries. After the military use of the atomic bombs that caused enormous civilian casualties, Szilárd became a strong promoter of peaceful uses of atomic energy and control of nuclear weapons.

THOMSON, George Paget (1892–1975)

British physicist, educated in mathematics and physics at the Trinity College of the University of Cambridge. He spent the first world war years in the British army and after the war spent three years as lecturer at the Corpus Christi College in Cambridge. In 1922 he was appointed Professor of Natural Philosophy at the University of Aberdeen in Scotland and from 1930 until 1952 he held an appointment of Professor of Physics at the Imperial College of the University of London. From 1952 until 1962 he was Master of the Corpus Christi College in Cambridge.

In Aberdeen Thomson carried out his most notable work studying the passage of electrons through thin metallic foils and observing diffraction phenomena which suggested that electrons could behave as waves despite being particles. This observation confirmed Louis de Broglie's hypothesis of particle-wave duality surmising that particles should display properties of waves and that the product of the wavelength of the wave and momentum of the particle should equal to the Planck's quantum constant h. Clinton J. Davisson of Bell Labs in the United States noticed electron diffraction phenomena with a different kind of experiment.

In 1937 Thomson shared the Nobel Prize in Physics with Clinton J. Davisson "*for their experimental discovery of the diffraction of electrons by crystals.*"

THOMSON, Joseph John (1856–1940)

British physicist, educated in mathematical physics at the Owens College in Manchester and the Trinity College in Cambridge. In 1884 he was named Cavendish Professor of Experimental Physics at Cambridge and he remained associated with the Trinity College for the rest of his life.

In 1987 Thomson discovered the electron while studying the electric discharge in a high vacuum cathode ray tube. In 1904 he proposed a model of the atom as a sphere of positively charged matter in which negatively charged electrons are dispersed randomly ("plum-pudding model of the atom").

In 1906 Thomson received the Nobel Prize in Physics *"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases."* Thomson was also an excellent teacher and seven of his former students also won Nobel Prizes in Physics during their professional careers.

D

Roman Letter Symbols

A

a	acceleration; radius of atom; apex-vertex distance for a hyperbola; specific activity; annum (year)
a	year (annum)
$a_{\max}$	maximum specific activity
a_0	Bohr radius (0.5292 Å)
a_{TF}	Thomas-Fermi atomic radius
a_{theor}	theoretical specific activity
A	ampere (SI unit of current)
$\mathbf{A}$	vector function
A	atomic mass number; Richardson thermionic constant
Å	ångström (unit of length or distance: 10^{-10} m)
$\mathcal{A}$	activity
$\mathcal{A}_{\mathrm{D}}$	daughter activity
$\mathcal{A}_{\mathrm{P}}$	parent activity
$\mathcal{A}_{\mathrm{sat}}$	saturation activity
$\mathcal{A}_{\max}$	maximum activity

B

b	barn (unit of area: 10^{-24} cm^2)
b	impact parameter
$b_{\max}$	maximum impact parameter
$b_{\min}$	minimum impact parameter
B_{col}	atomic stopping number in collision stopping power
B	build-up factor in broad beam attenuation
$\mathcal{B}$	magnetic field
B	boron atom
B_{rad}	parameter in radiation stopping power
Bq	becquerel (SI unit of activity)

C

c	speed of light in vacuum (3×10^8 m/s)
c_n	speed of light in medium
C	coulomb (unit of electric charge); carbon atom
C_0	collision stopping power constant (0.3071 MeV $\cdot$ cm^2 /mol)
Ci	curie (old unit of activity: 3.7×10^{10} s^{-1} = 3.7×10^{10} Bq)
C_K	K-shell correction for stopping power
C_M	nuclear mass correction factor
C_υ	electric field correction factor

D

d	day, deuteron
d	distance; spacing
D	daughter nucleus
D	dose; characteristic distance in two-particle collision
$D_{\alpha-N}$	distance of closest approach (between α particle and nucleus)
D_{eff}	effective characteristic scattering distance
$D_{\alpha-N}$	effective characteristic scattering distance of closest approach between α particle and nucleus
D_{e-a}	effective characteristic scattering distance between electron and atom
D_{e-e}	effective characteristic distance between the electron and orbital electron
D_{e-N}	effective characteristic distance between electron and nucleus
D_{ex}	exit dose
D_s	surface dose

E

e	electron charge $\left(1.6\times10^{-19}\text{ C}\right)$
e^-	electron
e^+	positron
e	base of natural logarithm (2.7183. . .)
erf(x)	error function
eV	electron volt (unit of energy: 1.6×10^{-19} J)
$e\phi$	work function
E	energy
$\mathcal{E}$	electric field
E_{ab}	energy absorbed
$\overline{E}_{ab}$	mean energy absorbed
E_B	binding energy of electron in atom or neucleon in nucleus
E_{col}	energy lost through collisions
E_i	initial total energy of charged particle

$\mathcal{E}_{\text{in}}$	electric field for incident radiation
E_{K}	kinetic energy
$(E_{\text{K}})_0$	initial kinetic energy of charged particle
$(E_{\text{K}})_{\text{crit}}$	critical kinetic energy
$(E_{\text{K}})_{\text{D}}$	recoil kinetic energy of daughter
$(E_{\text{K}})_{\text{f}}$	final kinetic energy
$(E_{\text{K}})_{\text{i}}$	initial kinetic energy
$(E_{\text{K}})_{\text{IC}}$	kinetic energy of conversion electron
$(E_{\text{K}})_{\text{max}}$	maximum kinetic energy
$(E_{\text{K}})_{\text{n}}$	kinetic energy of incident neutron
$(E_{\text{K}})_{\text{thr}}$	threshold kinetic energy
E_{n}	allowed energy state (eigenvalue)
E_0	rest energy
$\mathcal{E}_{\text{out}}$	electric field for scattered radiation
E_{p}	barrier potential
E_{R}	Rydberg energy
E_{rad}	energy radiated by charged particle
E_{thr}	threshold energy
E_{tr}	energy transferred
$\overline{E}_{\text{tr}}$	average energy transferred
E_{v}	photon energy; energy of neutrino
$\overline{E}_{\text{tr}}^{\text{PP}}$	mean energy transferred from photons to charged particles in pair production
$\overline{E}_{\text{tr}}^{\text{C}}$	mean energy transferred from photons to electrons in Compton effect
$\overline{E}_{\text{tr}}^{\text{PE}}$	mean energy transferred from photons to electrons in photoeffect
E_β	energy of beta particle
$(E_\beta)_{\text{max}}$	maximum total energy of electron or positron in β decay
E_γ	energy of gamma photon
$(E_\gamma)_{\text{thr}}$	threshold energy for pair production
$(\mathcal{E}_{\text{z}})_0$	amplitude of electric field in uniform wave guide

F

f	function; theoretical activity fraction; branching fraction in radioactive decay
$f(x)$	function of independent variable x
$\overline{f}_{\text{PE}}$	mean fraction of energy transferred from photons to electrons in photoelectric effect
$\overline{f}_{\text{C}}$	mean fraction of energy transferred from photons to electrons in Compton effect
$(\overline{f}_{\text{C}})_{\text{max}}$	maximum energy transfer fraction in Compton effect

$\overline{f}_{\mathrm{PP}}$	mean fraction of energy transferred from photons to charged particles in pair production
$\overline{f}_{\mathrm{ab}}$	total mean energy absorption fraction
$\overline{f}_{\mathrm{tr}}$	total mean energy transfer fraction
f_{spin}	spin correction factor
f_{recoil}	recoil correction factor
fm	femtometer $\left(10^{-15}\ \mathrm{m}\right)$
F	fluorine
F	force
F_{coul}	Coulomb force
$F(K)$	form factor
$F(x,Z)$	atomic form factor
F_{KN}	Klein–Nishina form factor
F_{L}	Lorentz force
F_{n}	neutron kerma factor
F^{+}	stopping power function for positrons
F^{-}	stopping power function for electrons

G

g	gram (unit of mass: 10^{-3} kg)
$\overline{g}$	mean radiation fraction
$\overline{g}_{\mathrm{A}}$	mean in-flight radiation fraction
$\overline{g}_{\mathrm{B}}$	mean bremsstrahlung fraction
$\overline{g}_{\mathrm{i}}$	mean impulse ionization fraction
G	granddaughter nucleus
G	Newtonian gravitational constant
Gy	gray (SI unit of kerma and dose: 1 J/kg)

H

h	Planck constant $\left(6.626\times10^{-34}\ \mathrm{J\cdot s}\right)$, hour
h	hour (1 h = 60 min = 3600 s)
H	hydrogen
H	equivalent dose; hamiltonian operator
Hz	unit of frequency $\left(\mathrm{s}^{-1}\right)$
$\hbar$	reduced Planck constant ($h/2\pi$)

I

I	electric current; mean ionization/excitation potential; beam intensity; radiation intensity
I_0	Initial photon beam intensity

J

j	current density; quantum number in spin-orbit interaction
J	joule (SI unit of energy)
$J_m(x)$	Bessel function of order m

K

k	wave number, free space wave number, Boltzmann constant, effective neutron multiplication factor in fission chain reaction
k_g	wave guide wave number (propagation coefficient)
kg	kilogram (SI unit of mass)
$k\,(K_\alpha)$	wave number for K_α transition
kVp	kilovolt peak (in x-ray tubes)
k^*	ratio σ_P/σ_D in neutron activation
$\mathbf{k}_i$	initial wave vector
$\mathbf{k}_j$	final wave vector
K	$n = 1$ allowed shell (orbit) in an atom; Kelvin temperature; potassium
$\mathbf{K}$	wave vector
K	kerma; capture constant in disk-loaded waveguide
K_{col}	collision kerma
K_{rad}	radiation kerma
K_α	characteristic transition from L shell to K shell

L

l	length
L	$n = 2$ allowed shell (orbit) in an atom
L	angular momentum
$\mathbf{L}$	angular momentum vector
ℓ	orbital quantum number; distance; path length

M

m	meter (SI unit of length or distance)
m	mass; magnetic quantum number; decay factor in parent-daughter-granddaughter decay; activation factor in nuclear activation; integer in Bragg relationship
m_e	electron rest mass $\left(0.5110\ \text{MeV}/c^2\right)$
m_{e^-}	electron rest mass
m_{e^+}	positron rest mass
m_ℓ	magnetic quantum number
m_n	neutron rest mass $\left(939.6\ \text{MeV}/c^2\right)$

m_0	rest mass of particle
m_p	proton rest mass $(938.3\ \mathrm{MeV}/c^2)$
m_α	rest mass of α particle
$m(\upsilon)$	relativistic mass m at velocity υ
m^*	modified activation factor
M	$n = 3$ allowed shell (orbit) in an atom
$\mathbf{M}_\mathrm{if}$	matrix element
M	mass of heavy nucleus
M_u	molar mass constant
MeV	megaeletron volt (unit of energy: 10^6 eV)
MHz	megahertz (unit of frequency: 10^6 Hz)
MV	megavoltage (in linacs)
$M(Z, A)$	nuclear mass in atomic mass units
$\mathcal{M}(Z, A)$	atomic mass in atomic mass units
Mu	muonium

N

n	neutron
nm	nanometer (unit of length or distance: 10^{-9} m)
n	unit vector
n	principal quantum number
$n^\square$	number of atoms per volume
N	$n = 4$ allowed shell (orbit) in an atom; nitrogen, Newton (SI unit of force)
$N_\mathrm{m}(x)$	Neumann function (Bessel function of second kind) of order m
N	number of radioactive nuclei; number of experiments in central limit theorem; number or monoenergetic electrons in medium
N_a	number of atoms
N_A	Avogadro number $(6.022\times10^{23}\ \mathrm{atom/mol})$
N_e	number of electrons
N_t/m	number of specific nuclei per unit mass of tissue

O

O	oxygen
OER	oxygen enhancement ratio

P

p	proton
p	momentum
p_e	electron momentum
p_ν	photon momentum
$\mathbf{p}_\mathrm{i}$	initial particle momentum vector
$\mathbf{p}_\mathrm{f}$	final particle momentum vector

P	parent nucleus
P	power; probability
$\overline{P}$	mean power
$\mathrm{P_a}$	pascal, SI derived unit of pressure ($1\ \mathrm{P_a} = 1\ N/m^2$)
P_j	probability for photoelectric effect, if it occurs, to occur in the j subshell
$P(\varepsilon, Z)$	pair production function
Ps	positronium
P_K	fraction of photoelectric interactions that occur in the K-shell
$P(x)$	probability density function

Q

q	charge
Q	charge; nuclear reaction energy; Q value
$\overline{Q}$	expectation (mean) value of physical quantity Q
$[Q]$	operator associated with the physical quantity Q
Q_EC	decay energy (Q value) for electron capture
Q_IC	decay energy (Q value) for internal conversion
Q_α	decay energy (Q value) for alpha decay
Q_β	decay energy (Q value) for beta decay
$Q(x)$	standard cumulative distribution function

R

r	radius vector; separation between two interacting particles, radius of curvature
$\mathbf{r}$	radius vector
rad	old unit of absorbed dose (100 erg/g); radian
rem	old unit of equivalent dose
r_e	classical electron radius (2.818 fm)
r_n	radius of the n-th allowed Bohr orbit
$\overline{r}$	average electron radius
R	roentgen (unit of exposure: $2.58\times10^{-4}\ \mathrm{C/kg_{air}}$)
RBE	relative biological effectiveness
R	radial wave function; radius (of nucleus); reaction rate; distance of closest approach
$\overline{R}$	mean range
R_CSDA	continuous slowing down approximation range
R_H	Rydberg constant for hydrogen $\left(109678\ \mathrm{cm}^{-1}\right)$
R_max	maximum penetration depth
R_0	nuclear radius constant
$R_{\alpha-\mathrm{N}}$	distance of closest approach between the α particle and nucleus in a non-direct hit collision
R_∞	Rydberg constant assuming an infinite nuclear mass $\left(109737\ \mathrm{cm}^{-1}\right)$
R_{50}	depth of the 50 % percentage depth dose in water for electron beam

S

s	second (unit of time)
s	spin quantum number
S	mass stopping power
$\mathbf{S}$	Poynting vector
$\overline{S}$	mean total mass stopping power
S_{col}	mass collision stopping power
$\overline{S}_{col}$	mean collision stopping power
S_{in}	Poynting vector of incident radiation
$\overline{S}_{in}$	mean Poynting vector of incident radiation
S_{out}	Poynting vector of scattered radiation
$\overline{S}_{out}$	mean Poynting vector of scattered radiation
S_{rad}	mass radiation stopping power
S_{tot}	total mass stopping power
Sv	sievert (SI unit of equivalent dose)
$S(x, Z)$	incoherent scattering function

T

t	triton
t	time; thickness of absorber in mass scattering power
t_{max}	characteristic time in nuclear decay series or nuclear activation
$t_{1/2}$	half-life
T	temperature; linear scattering power; temporal function
T/ρ	mass scattering power
TE	transverse electric mode
TM	transverse magnetic mode
torr	non-SI unit of pressure defined as 1/760 of a standard atmosphere (1 torr = 1 mm Hg)

U

u	unified atomic mass constant $\left(931.5\ \text{MeV}/c^2\right)$
u	particle velocity after collision; EM field density
U	uranium atom
U	applied potential

V

υ	velocity
υ_{el}	electron velocity
υ_{thr}	threshold velocity in Čerenkov effect

υ_{en}	velocity of energy flow
υ_{gr}	group velocity
υ_{n}	velocity of electron in n-th allowed orbit
υ_{ph}	phase velocity
υ_{α}	velocity of α particle
V	volt (unit of potential difference); potential operator
V	volume; potential energy
V_{N}	nuclear potential
$V_{\mathrm{TF}}(r)$	Thomas-Fermi potential
V_{FNS}	potential energy for finite nuclear size
V_{Yuk}	Yukawa potential
$\mathcal{V}$	volume
ν	variance

W

w_{R}	radiation weighting factor
w_{C}	relative weight of Compton effect
w_{PE}	relative weight of photoelectric effect
w_{PP}	relative weight of pair production
W	transmitted particle in weak interaction; tungsten atom
W_{el}	electric energy stored per unit length
W_{if}	transition (reaction) rate
W_{mag}	magnetic energy stored per unit length
W	watt (unit of power)

X

x	momentum transfer variable $(x = \sin(\theta/2)/\lambda)$; normalized time $x = t/t_{1/2}$; horizontal axis in 2D and 3D Cartesian coordinate system; coordinate in Cartesian coordinate system; abscissa axis
x_{f}	particle final position
x_{i}	particle initial position
x_0	target thickness
x_{01}	first zero of the zeroth order Bessel function ($x_{01} = 2.405$)
$\overline{x}$	mean free path; mean value of variable x
$(x_{\mathrm{D}})_{\mathrm{max}}$	maximum normalized characteristic time of the daughter
$x_{1/10}$	tenth value layer
$x_{1/2}$	half-value layer
${}^{A}_{Z}\mathrm{X}$	nucleus with symbol X, atomic mass number A and atomic number Z
X	exposure
X_0	target thickness; radiation length
$\overline{X}_{\mathrm{PE}}(\mathrm{j})$	mean fluorescence emission energy

Y

y	vertical axis in 2D Cartesian coordinate system; coordinate in Cartesian coordinate system; ordinate axis
Y	radiation yield; activation yield
y_{P}	normalized activity
$(y_{\mathrm{D}})_{\max}$	maximum normalized daughter activity
Y_{D}	radioactivation yield of the daughter
$Y\left[(E_{\mathrm{K}})_0, Z\right]$	radiation yield
y_{P}	normalized parent activity

Z

z	atomic number of the projectile; depth in phantom; coordinate in cartesian coordinate system; applicate axis
$z_{\max}$	depth of dose maximum
Z	atomic number
Z_{eff}	effective atomic number
Z^{o}	transmitted particle in weak interaction

E

Greek Letter Symbols

$\boldsymbol{\alpha}$

α	fine structure constant (1/137); ratio $\sigma_{\mathrm{P}}/\sigma_{\mathrm{D}}$; nucleus of helium atom (alpha particle)
α_{IC}	internal conversion factor

$\boldsymbol{\beta}$

β	normalized particle velocity (v/c)
β^{+}	beta plus particle (positron)
β^{-}	beta minus particle (electron)

$\boldsymbol{\gamma}$

γ	photon originating in a nuclear transition; ratio of total to rest energy of a particle; ratio of total to rest mass of a particle

$\boldsymbol{\delta}$

δ	polarization (density effect) correction for stopping power; delta particle (electron); duty cycle for linear accelerators
Δ	energy threshold for restricted stopping power

$\boldsymbol{\varepsilon}$

ε	eccentricity of hyperbola; normalized photon energy: $\varepsilon = h\nu/(m_{\mathrm{e}}c^2)$; Planck energy
ε^{*}	ratio $\lambda_{\mathrm{D}}^{*}/\lambda_{\mathrm{D}}$ in nuclear activation
ε_0	electric constant (electric permittivity of vacuum): 8.85×10^{-12} $\mathrm{A\cdot s/(V\cdot m)}$

$\boldsymbol{\theta}$

θ scattering angle for a single scattering event; scattering angle of projectile in projectile/target collision; scattering angle of photon in Compton and Rayleigh scattering
$\overline{\theta^2}$ mean square scattering angle for single scattering
θ_{cer} Čerenkov characteristic angle
$\theta_{\max}$ characteristic angle in bremsstrahlung production; maximum scattering angle
$\theta_{\min}$ minimum scattering angle
θ_{R} characteristic angle for Rayleigh scattering
Θ scattering angle for multiple scattering
$\overline{\Theta^2}$ mean square scattering angle for multiple scattering

$\boldsymbol{\eta}$

η pair production parameter; maximum energy transfer fraction in nuclear collision; energy boundary between hard and soft collision; fluorescence efficiency

$\boldsymbol{\kappa}$

κ linear attenuation coefficient for pair production
${}_{\mathrm{a}}\kappa$ atomic attenuation coefficient for pair production
κ/ρ mass attenuation coefficient for pair production

$\boldsymbol{\lambda}$

λ wavelength; separation constant; decay constant; de Broglie wavelength of particle
λ_{C} Compton wavelength
$(\lambda)_{\mathrm{c}}$ cutoff wavelength in uniform waveguide
λ_{D} decay constant of daughter
λ_{D}^* modified decay constant
$\lambda_{\min}$ Duane-Hunt short wavelength cut-off
λ_{P} decay constant of parent
Λ separation constant

$\boldsymbol{\mu}$

μ linear attenuation coefficient; reduced mass
μ_{ab} linear energy absorption coefficient
μ_{eff} effective attenuation coefficient
μ_{H} reduced mass of hydrogen atom
μ_{m} mass attenuation coefficient
μ_{tr} linear energy transfer coefficient
μ/ρ mass attenuation coefficient

μ_0	magnetic constant (magnetic permeability of vacuum): $4\pi\times10^{-7}$ $(\mathrm{V}\cdot\mathrm{s})/(\mathrm{A}\cdot\mathrm{m})$
(μ_{ab}/ρ)	mass energy absorption coefficient
(μ_{tr}/ρ)	mass energy transfer coefficient
$_{\mathrm{a}}\mu$	atomic attenuation coefficient
$_{\mathrm{e}}\mu$	electronic attenuation coefficient
$\mu\mathrm{m}$	unit of length or distance (10^{-6} m)

$\boldsymbol{\nu}$

ν	frequency
ν_{eq}	photon frequency at which the atomic cross sections for Rayleigh scattering and Compton scattering are equal
ν_{e}	electronic neutrino
ν_{orb}	orbital frequency
ν_{trans}	transition frequency
ν_{μ}	muonic neutrino

$\boldsymbol{\xi}$

ξ	ratio between daughter and parent activities at time t; Thomas-Fermi atomic radius constant; absorption edge parameter in photoelectric effect
ξ_j	absorption edge parameter for subshell j

$\boldsymbol{\pi}$

π	pi meson (pion)
π^+	positive pi meson (pion)
π^-	negative pi meson (pion)

$\boldsymbol{\rho}$

ρ	density; energy density
$\rho(E_{\mathrm{f}})$	density of final states

$\boldsymbol{\sigma}$

σ	cross section; linear attenuation coefficient; standard deviation
σ_{rad}	cross section for emission of bremsstrahlung
σ_{C}	Compton cross section (attenuation coefficient)
$\sigma_{\mathrm{C}}^{\mathrm{KN}}$	Klein–Nishina cross section for Compton effect
$_{\mathrm{a}}\sigma_{\mathrm{C}}$	atomic attenuation coefficient (cross section) for Compton effect
$_{\mathrm{a}}\sigma_{\mathrm{R}}$	atomic attenuation coefficient (cross section) for Rayleigh scattering
$_{\mathrm{a}}\sigma_{\mathrm{Th}}$	atomic attenuation coefficient (cross section) for Thomson scattering
$_{\mathrm{e}}\sigma_{\mathrm{C}}$	electronic attenuation coefficient for Compton effect
σ_{D}	daughter cross section in particle radioactivation

σ_{R}	Rayleigh cross section (linear attenuation coefficient)
σ_{Ruth}	cross section for Rutherford scattering
σ_{Th}	Thomson cross section (linear attenuation coefficient)
${}_{\mathrm{a}}\sigma$	atomic cross section (in cm^2/atom)
${}_{\mathrm{e}}\sigma$	electronic cross section (in cm^2/electron)
$[\sigma(z)]^2$	spatial spread of electron pencil beam

τ

τ	linear attenuation coefficient for photoelectric effect; normalized electron kinetic energy; mean (average) life
${}_{\mathrm{a}}\tau$	atomic attenuation coefficient for photoelectric effect
τ/ρ	mass attenuation coefficient for photoelectric effect

ϕ

ϕ	angle between radius vector and axis of symmetry on a hyperbola; recoil angle of the target in projectile/target collision; neutron recoil angle in elastic scattering on nucleus; recoil angle of the electron in Compton scattering
φ	particle fluence
$\dot{\varphi}$	particle fluence rate

χ

χ	homogeneity factor

ψ

ψ	wavefunction (eigenfunction) depending on spatial coordinates; energy fluence
Ψ	wavefunction depending on spatial and temporal coordinates

ω

ω	fluorescence yield; angular frequency
ω_{c}	cutoff angular frequency in accelerating waveguide
ω_{cyc}	cyclotron frequency
ω_{K}	fluorescence yield for K-shell transition
Ω	solid angle

F

Acronyms

AAPM	American Association of Physicists in Medicine
ACMP	American College of Physicists in Medicine
ACR	American College of Radiology
AFOMP	Asia-Oceania Federation of Organizations for Medical Physics
ALFIM	Associaçåo Latino-americana de Fisica Medica
ART	Adaptive radiotherapy
BNCT	Boron Neutron capture therapy
BNL	Brookhaven National Laboratory
CAMPEP	Commission on Accreditation of Medical Physics Educational Programs
CCPM	Canadian College of Physicists in Medicine
CODATA	Committee on Data for Science and Technology
CPA	Charged particle activation
CPE	Charged particle equilibrium
CSDA	Continuous slowing down approximation
CT	Computerized tomography
CNT	Carbon nanotube
DT	Deuterium-tritium
EC	Electron capture
EFOMP	European Federation of Organisations of Medical Physics
EM	Electromagnetic
EGS	Electron-gamma shower
EE	Exoelectron emission
FAMPO	Federation of African Medical Physics Organizations
FDG	Fluoro-deoxy-glucose
FE	Field emission
FNS	Finite nuclear size
FWHM	Full width at half maximum
HVL	Half value layer
HPA	Hospital Physicists' Association

IAEA	International Atomic Energy Agency
IC	Internal conversion
ICRP	International Commission on Radiation Protection
ICRU	International Commission on Radiation Units and Measurements
IGRT	Image guided radiotherapy
IMRT	Intensity modulated radiotherapy
IOMP	International Organisation of Medical Physics
IP	Ionization potential
KN	Klein-Nishina
LET	Linear energy transfer
LINAC	Linear accelerator
MC	Monte Carlo
MEFOMP	Middle East Federation of Organizations for Medical Physics
MFP	Mean free path
MLC	Multi leaf collimator
MOC	Maintenance of certification
MRI	Magnetic resonance imaging
MV	Megavoltage
NA	Nuclear activation
NDS	Nuclear data section
NIST	National Institute of Standards and Technology
NNDC	National Nuclear Data Center
NRC	National Research Council
NTCP	Normal tissue complication probability
OER	Oxygen enhancement ratio
PE	Photoelectric
PET	Positron emission tomography
PP	Pair production
RBE	Relative biological effectiveness
RF	Radiofrequency
RT	Radiotherapy
SAD	Source axis distance
SF	Spontaneous fission
SI	Système International
SEAFOMP	Southeast Asian Federation for Medical Physics
SLAC	Stanford Linear Accelerator Center
SRA	Synchrotron radiation angioplasty
STP	Standard temperature and pressure
TCP	Tumor control probability
TVL	Tenth value layer
TE	Transverse electric
TM	Transverse magnetic
UK	United Kingdom
US	Ultrasound

G

Electronic Databases of Interest in Nuclear and Medical Physics

Atomic Weights and Isotopic Compositions

J.S. Coursey, D.J. Schwab, and R.A. Dragoset

The atomic weights are available for elements 1 through 112, 114, and 116, and isotopic compositions or abundances are given when appropriate.

www.physics.nist.gov/PhysRefData/Compositions/index.html

Bibliography of Photon Attenuation Measurements

J. H. Hubbell

This bibliography contains papers (1907–1995) reporting absolute measurements of photon (XUV, X-ray, gamma-ray, bremsstrahlung) total interaction cross sections or attenuation coefficients for the elements and some compounds used in a variety of medical, industrial, defense, and scientific applications. The energy range covered is from 10 eV to 13.5 GeV.

www.physics.nist.gov/PhysRefData/photoncs/html/attencoef.html

Elemental Data Index and Periodic Table of Elements

M. A. Zucker, A. R. Kishore, R. Sukumar, and R. A. Dragoset

The Elemental Data Index provides access to the holdings of NIST Physics Laboratory online data organized by element. It is intended to simplify the process of retrieving online scientific data for a specific element.

www.physics.nist.gov/PhysRefData/Elements/cover.html

Fundamental Physical Constants

CODATA

CODATA, the Committee on Data for Science and Technology, is an interdisciplinary scientific committee of the International Council for Science (ICSU), which works to improve the quality, reliability, management and accessibility of data of importance to all fields of science and technology. The CODATA committee was established in 1966 with its secretariat housed at 51, Boulevard de Montmorency, 75016 Paris, France. It provides scientists and engineers with access to international data activities for increased awareness, direct cooperation and new knowledge. The committee was established to promote and encourage, on a world-wide basis, the compilation, evaluation, and dissemination of reliable numerical data of importance to science and technology. Today 23 countries are members, and 14 International Scientific Unions have assigned liaison delegates.

www.codata.org

Fundamental Physical Constants

The NIST Reference on Constants, Units, and Uncertainty.

www.physics.nist.gov/cuu/constants/

Ground Levels and Ionization Energies for the Neutral Atoms

W. C. Martin, A. Musgrove, S. Kotochigova, and J. E. Sansonetti

This table gives the principal ionization energies (in eV) for the neutral atoms from hydrogen ($Z = 1$) through rutherfordium ($Z = 104$). The spectroscopy notations for the electron configurations and term names for the ground levels are also included.

www.physics.nist.gov/PhysRefData/IonEnergy/ionEnergy.html

International System of Units (SI)

The NIST Reference on Constants, Units, and Uncertainty

The SI system of units is founded on seven SI base units for seven base quantities that are assumed to be mutually independent. The SI base units as well as many examples of derived units are given.

www.physics.nist.gov/cuu/Units/units.html

Mathematica

Wolfram MathWorld

Wolfram MathWorld™ is web's most extensive mathematical resource, provided as a free service to the world's mathematics and internet communities as part of a commitment to education and educational outreach by Wolfram Research, makers of Mathematica, an extensive technical and scientific software. Assembled during the past decade by Eric W. Weisstein, MathWorld emerged as a nexus of mathematical information in mathematics and educational communities. The technology behind MathWorld is heavily based on Mathematica created by Stephen Wolfram. In addition to being indispensable in the derivation, validation, and visualization of MathWorld's content, Mathematica is used to build the website itself, taking advantage of its advanced mathematical typesetting and data-processing capabilities.

mathworld.wolfram.com

Nuclear Data

National Nuclear Data Center

The National Nuclear Data Center (NNDC) of the *Brookhaven National Laboratory* (BNL) in the USA developed a software product (NuDat 2) that allows users to search and plot nuclear structure and nuclear decay data interactively. The program provides an interface between web users and several databases containing nuclear structure, nuclear decay and some neutron-induced nuclear reaction information. Using NuDat 2, it is possible to search for nuclear level properties (energy, half-life, spin-parity), gamma-ray information (energy, intensity, multipolarity, coincidences), radiation information following nuclear decay (energy, intensity, dose), and neutron-induced reaction data from the BNL-325 book (thermal cross section and resonance integral). The information provided by NuDat 2 can be seen in tables, level schemes and an interactive chart of nuclei. The software provides three different search forms: one for levels and gammas, a second one for decay-related information, and a third one for searching the Nuclear Wallet Cards file.

www.nndc.bnl.gov

Nuclear Data Services

International Atomic Energy Agency (IAEA)

The Nuclear Data Section (NDS) of the *International Atomic Energy Agency* (IAEA) of Vienna, Austria maintains several major databases as well as nuclear databases and files, such as: ENDF – evaluated nuclear reaction cross section libraries; ENSDF – evaluated nuclear structure and decay data; EXFOR – experimental nuclear reaction data; CINDA – neutron reaction data bibliography; NSR – nuclear science references; NuDat 2.0 – selected evaluated nuclear data; Wallet cards – ground and metastable state properties; Masses 2003 – atomic mass evaluation data file; Thermal neutron capture gamma rays; Q-values and Thresholds.

www-nds.iaea.or.at

Nuclear Energy Agency Data Bank

Organisation for Economic Cooperation and Development (OECD)

The nuclear energy agency data bank of the Organization for Economic Cooperation and Development (OECD) maintains a nuclear database containing general information, evaluated nuclear reaction data, format manuals, preprocessed reaction data, atomic masses, and computer codes.

www.nea.fr/html/databank/

Nucleonica

European Commission: Joint Research Centre

Nucleonica is a new nuclear science web portal from the European Commission's Joint Research Centre. The portal provides a customizable, integrated environment and collaboration platform for the nuclear sciences using the latest internet "Web 2.0" dynamic technology. It is aimed at professionals, academics and students working with radionuclides in fields as diverse as the life sciences, the earth sciences, and the more traditional disciplines such as nuclear power, health physics and radiation protection, nuclear and radiochemistry, and astrophysics. It is also used as a knowledge management tool to preserve nuclear knowledge built up over many decades by creating modern web-based versions of so-called legacy computer codes. Nucleonica also publishes and distributes the Karlsruhe Nuklidkarte (Karlsruhe Chart of the Nuclides).

www.nucleonica.net/unc.aspx

Photon Cross Sections Database: XCOM

M.J. Berger, J.H. Hubbell, S.M. Seltzer, J. S. Coursey, and D. S. Zucker

A web database is provided which can be used to calculate photon cross sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients, for any element, compound or mixture ($Z \leq 100$) at energies from 1 keV to 100 GeV.

www.physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html

Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions

M.J. Berger, J.S. Coursey, and M.A. Zucker

The databases ESTAR, PSTAR, and ASTAR calculate stopping-power and range tables for electrons, protons, or helium ions, according to methods described in ICRU Reports 37 and 49. Stopping-power and range tables can be calculated for electrons in any user-specified material and for protons and helium ions in 74 materials.

www.physics.nist.gov/PhysRefData/Star/Text/contents.html

X-Ray Form Factor, Attenuation, and Scattering Tables

C.T. Chantler, K. Olsen, R.A. Dragoset, A.R. Kishore, S.A. Kotochigova, and D.S. Zucker

Detailed Tabulation of Atomic Form Factors, Photoelectric Absorption and Scattering Cross Section, and Mass Attenuation Coefficients for Z from 1 to 92. The primary interactions of x-rays with isolated atoms from $Z = 1$ (hydrogen) to $Z = 92$ (uranium) are described and computed within a self-consistent Dirac-Hartree-Fock framework. The results are provided over the energy range from either 1 or 10 eV to 433 keV, depending on the atom. Self-consistent values of the $f1$ and $f2$ components of the atomic scattering factors are tabulated, together with the photoelectric attenuation coefficient τ/ρ and the K-shell component τ_K/ρ, the scattering attenuation coefficient σ/ρ (coh + inc), the mass attenuation coefficient μ/ρ, and the linear attenuation coefficient μ, as functions of energy and wavelength.

www.physics.nist.gov/PhysRefData/FFast/Text/cover.html

X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients

J. H. Hubbell and S. M. Seltzer

Tables and graphs of the photon mass attenuation coefficient μ/ρ and the mass energy-absorption coefficient μ_{en}/ρ are presented for all elements from $Z = 1$ to $Z = 92$, and for 48 compounds and mixtures of radiological interest. The tables cover energies of the photon (X-ray, gamma ray, bremsstrahlung) from 1 keV to 20 MeV.

www.physics.nist.gov/PhysRefData/XrayMassCoef/cover.html

X-ray Transition Energies

R.D. Deslattes, E.G. Kessler Jr., P. Indelicato, L. de Billy, E. Lindroth, J. Anton, J.S. Coursey, D.J. Schwab, K. Olsen, and R.A. Dragoset

This X-ray transition table provides the energies and wavelengths for the K and L transitions connecting energy levels having principal quantum numbers $n = 1$, 2, 3, and 4. The elements covered include $Z = 10$, neon to $Z = 100$, fermium. There are two unique features of this database: (1) all experimental values are on a scale consistent with the International System of measurement (the SI) and the numerical values are determined using constants from the Recommended Values of the Fundamental Physical Constants: 1998 and (2) accurate theoretical estimates are included for all transitions.

www.physics.nist.gov/PhysRefData/XrayTrans/index.html

H

International Organizations

whose mission statements fully or partially address radiation protection, use of ionizing radiation in medicine, and promotion of medical physics:

American Association of Physicists in Medicine (AAPM)
College Park, MD, USA — www.aapm.org

Asia-Oceania Federation of Organizations for Medical Physics (AFOMP) — www.afomp.org

European Federation of Organizations for Medical Physics (EFOMP)
York, UK — www.efomp.org

European Society for Therapeutic Radiology and Oncology (ESTRO)
Brussels, Belgium — www.estro.be

International Atomic Energy Agency (IAEA)
Vienna, Austria — www.iaea.org

International Commission on Radiological Protection (ICRP)
Stockholm. Sweden — www.icrp.org

International Commission on Radiation Units and Measurements (ICRU)
Bethesda, Maryland, USA — www.icru.org

International Electrotechnical Commission (IEC)
Geneva, Switzerland — www.iec.org

International Organisation for Standardization (ISO)
Geneva, Switzerland — www.iso.org

International Organisation for Medical Physics (IOMP)
www.iomp.org

International Radiation Protection Association (IRPA)
Fontenay-aux-Roses, France — www.irpa,net

International Society of Radiology (ISR)
Bethesda, Maryland, USA — www.isradiology.org

Pan American Health Organisation (PAHO)
Washington, D.C., USA — www.paho.org

Radiological Society of North America (RSNA)
Oak Brook, IL, USA — www.rsna.org

World Health Organization (WHO)
Geneva, Switzerland — www.who.int

I

Nobel Prizes for Research in X Rays

	Year	Field	Scientists and Justification for Nobel Prize
(1)	1901	Physics	**Wilhelm Conrad ROENTGEN** *"for his discovery of the remarkable rays subsequently named after him"*
(2)	1914	Physics	**Max von LAUE** *"for his discovery of the diffraction of x rays by crystals"*
(3)	1915	Physics	**William Henry BRAGG and William Lawrence BRAGG** *"for their services in the analysis of crystal structure by means of X rays"*
(4)	1917	Physics	**Charles Glover BARKLA** *"for his discovery of the characteristic Roentgen radiation of the elements"*
(5)	1924	Physics	**Karl Manne Georg SIEGBAHN** *"for discoveries and research in the field of x-ray spectroscopy"*
(6)	1927	Physics	**Arthur Holly COMPTON** *"for the discovery of the effect that bears his name"*
(7)	1936	Chemistry	**Peter J.W. DEBYE** *"for his contributions to our knowledge of molecular structure through his investigations on dipole moments and on the diffraction of X-rays and electrons in gases"*

(8)	1962	Chemistry	**Max Ferdinand PERUTZ and John Cowdery KENDREW** *"for their studies of the structures of globular proteins"*
(9)	1962	Medicine	**Francis CRICK, James WATSON, and Maurice WILKINS** *"for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material"*
(10)	1979	Medicine	**A. McLeod CORMACK and G. Newbold HOUNSFIELD** *"for the development of computer assisted tomography"*
(11)	1981	Physics	**Kai M. SIEGBAHN** *"for his contribution to the development of high-resolution electron spectroscopy"*
(12)	1985	Chemistry	**Herbert A. HAUPTMAN and Jerome KARLE** *"for their outstanding achievements in the development of direct methods for the determination of crystal structures"*
(13)	1988	Chemistry	**Johann DEISENHOFER, Robert HUBER and Hartmut MICHEL** *"for the determination of the three dimensional structure of a photosynthetic reaction centre"*
(14)	2002	Physics	**Raymond DAVIS, Jr., Masatoshi KOSHIBA, Riccardo GIACCONI** *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos and discovery of cosmic X-ray sources"*

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