Note Added in Proof (Chapter 1)

Since the completion of this review, a number of important advances has been made in the field of atomic physics in heavy-ion reactions at energies near the Coulomb barrier (cf. Section 7). An up to date presentation related to this subject can be found in (Me 84).

$K$-hole production in 7.5 MeV/u $U + U$ collisions has been studied by Meyerhof and collaborators (St 84) as a function of the $Q$-value. According to the predictions of Figure 7.2b the vacancy rate should strongly decrease as a function of delay time. Since such an effect indeed has been observed experimentally, one may hope to obtain information on the magnitude of delay times and their relation to the energy loss in deep inelastic nuclear collisions. The data show indications that the delay time is underestimated by conventional reaction models.

Similarly, the energy spectra of electrons and positrons in deep inelastic nuclear collisions leading to nuclear fission have been studied (Ba 83). In general agreement with theoretical expectations, cf. Figure 7.6b, the slopes of the observed spectra are clearly steeper than those originating from elastic scattering events. The data are not yet, however, fully consistent with detailed coupled-channel calculations (Mü 84) based on friction models for the deep inelastic reaction.

The first observations of narrow line structures in the spectrum of positrons emitted in very heavy collision systems have been impressively corroborated and extended by two experimental groups working at the GSI accelerator (Darmstadt). Striking line structures have been observed in $U + U$, $U + Th$ and $U + U$ collisions by the EPOS group (Sch 83). The first two systems also were studied by the Munich group (C I 84) with similar results. Convincing evidence has been compiled by both groups which seems to rule out a trivial explanation of the effect in terms of conversion of $\gamma$-lines. The expected accompanying line structures in the electron or $\gamma$-ray spectrum are not observed. Furthermore the width of the positron line and its angular distribution strongly hint that the source of the positron emission moves with center-of-mass system. The most convincing interpretation of these facts assumes that in a small fraction of all collisions a combined nuclear system ("giant nucleus") is formed for up to $\approx 10^{-19}$ s (Re 81b, Mü 83).

Inspired by the experimental evidence attempts have been undertaken to go beyond the phenomenological analysis of the positron line in terms of a classical time delay picture. The fully quantal theory and its semiclassical limit have been discussed in (He 83a). To obtain a workable description one may start from quantum mechanical scattering theory and introduce two regions in the radial coordinate $R$. For large distances the nuclei do not interact and the semiclassical treatment is appropriate. In the interior region atomic excitations may be neglected while the nuclear scattering is described
by the nuclear $S$-matrix. This leads to a factorization of the excitation amplitudes (To 84, He 84b). Averaging over the spread of the beam energy, it turns out that the electronic excitation is determined by the nuclear autocorrelation function (To 83).

Using an expression for the autocorrelation function motivated by the statistical model for nuclear reactions, Tomoda and Weidenmüller could qualitatively reproduce the line structure in the positron spectrum. This is not surprising, since it can be shown (Re 83) that such a description is completely equivalent to the semiclassical picture of a nuclear time delay employed earlier (Re 81b). The lifetime distribution function $\rho(T)$, cf. equation (7.9), is given by the Fourier transform of the nuclear autocorrelation function.

In an attempt to understand the mechanism behind reactions with long delay times, the heavy-ion internuclear potential has been examined. Seiwert et al. (Rh 83) predict that in system like $^{238}U + ^{244}Cm$ the potential under favourable conditions (head-on-head orientation of the deformed nuclei to minimize Coulomb repulsion) should exhibit a pocket. Based on this result Heinz et al. (He 83b), (He 84a,b) constructed a simple reaction model assuming the presence of several rotational bands of resonance states in a potential pocket. The autocorrelation function and its Fourier transform, the distribution of reaction times, could be calculated analytically. The positron emission spectra resulting from delayed collisions exhibit a narrow positron line (He 83b). The effect has a narrow excitation function (He 84a) centered at the top of the barrier, since only here the required long-lived resonance levels can be excited with sufficient probability. To get a quantitative description of the process, the incorporation of inelastic mechanisms will be required. These may also lead to additional structure in the positron spectrum due to the conversion of nuclear excitations during the lifetime of the combined nuclear system (Re 81b, Mü 83).

At the time of writing no completely satisfactory understanding of the “positron line” has been achieved, in particular the weak dependence of its position on the charge of the colliding system is not understood. Nevertheless, there is much evidence that indeed the phenomenon is connected with the supercritical vacuum of QED discussed in Section 2. At the same time this means that remarkably long lived “giant” nuclear systems with $Z > 180$ have been observed. The study of these objects probably will reveal surprising facts about nuclear properties far off the domain of stable elements.

References to the Note Added in Proof

Joachim Reinhardt and Walter Greiner


(St 84) Ch. Stoller, M. Nessi, E. Morenzoni, W. Wölfli, W. E. Meyerhof, J. D. Molitoris, E. Grosse, and Ch. Michel, to be published.


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