Mechanism for electron-positron pair production in heavy-ion collisions

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It is hypothesized that peaks in the cross section for the production of electron-positron pairs in collisions of heavy ions are interference effects stemming from the Coulomb field.

In the course of experiments on the scattering of heavy ions which have been carried out by various research groups on the UNILAC accelerator (FRG), anomalous structure was found in the spectra of the emitted positrons and correlated electron-positron pairs (see Refs. 1 and 2 and the bibliographies there). The numerous, fairly narrow peaks have gone several years without adequate explanation.[3]

It has been established experimentally that these peaks arise not only when the total charge of the interacting nuclei is $Z > 173$ (e.g., U + U) but also when Z is below the critical value (e.g., Pb + Pb). For this reason, the phenomenon cannot be attributed to a spontaneous production of positrons.[4,5] The positions of the peaks in the cross section are essentially independent of Z, although there is some tendency for the energies of the peaks to decrease with decreasing Z. The relative height of the peaks is at maximum for pairs whose emission direction are separated by an angle of 180°.

Pair production obviously occurs under the strong influence of the external Coulomb electromagnetic field, giving rise to analogies with other effects which occur in external fields. Relatively recent work established theoretically that the cross sections for various elementary processes oscillate if the processes occur in an external field.[6–8] One such process is the two-photon production of electron-positron pairs, which was analyzed in most detail in Ref. 8, where the external field was chosen to be a uniform crossed field. It was shown that the cross section for fields which are weak in comparison with the critical field ($F \ll F_0$) effectively breaks up into a monotonic part and an oscillatory part. The formation length for the monotonic part is on the order of the electron de Broglie wavelength, while that for the oscillatory part is on the order of $(F_0/F)\lambda$. The oscillatory part stems from the electrons and positrons which are emitted in opposite directions along the electric field (in the c.m. frame); it disappears when the external field is turned off. The oscillatory part can be calculated through an analytic continuation of the expression for the cross section for below-threshold pair production. All this is very reminiscent of an effect which was recognized a long time ago in solid state physics: the Franz-Keldysh effect. There is the distinction, however, that in the case at hand the role of a Fermi surface is played by the boundary of the physical region for the process in the absence of an external field.

On the basis of a comparison of the results outlined above with experimental data, one might hypothesize that the peaks of interest here are of a purely electromagnetic

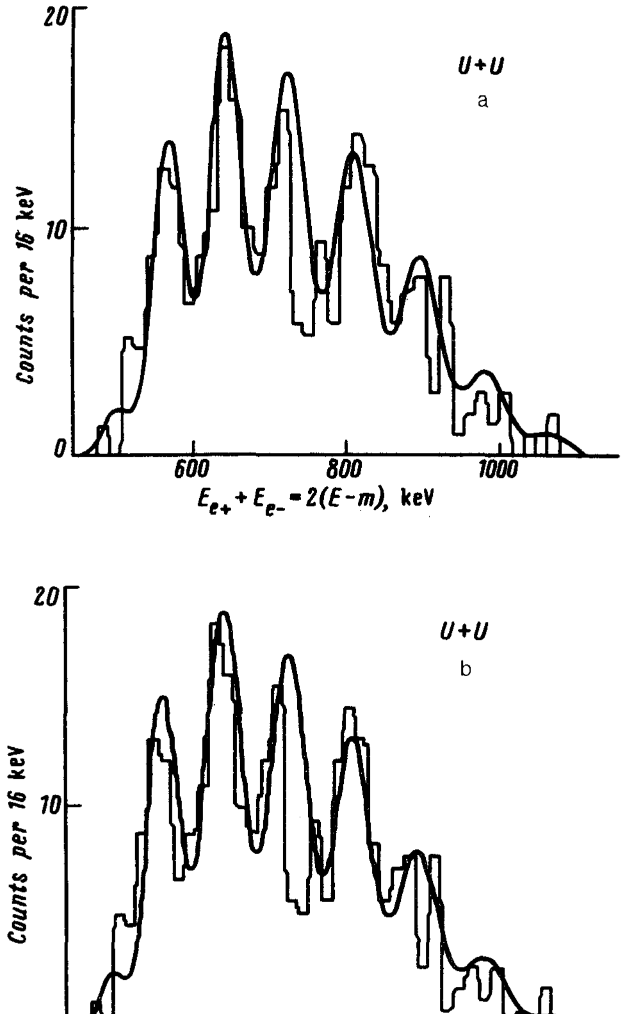

FIG. 1. Comparison of the experimental data of Refs. 1 and 2 on U + U scattering with a curve of $(1 + T)$, modulated by the experimental envelope. (a) $Z_0 = Z = 184$, $N = 38$; (b) $Z_0 = Z = 184$, $N = 40$.

origin, and one might suggest a model for evaluating the oscillatory part of the cross section or, more precisely, for determining the positions of the peaks.

Let us assume that the production of electrons and positrons results primarily from an interaction of two photon-like quasiparticles (photons) which arise in the course of the collision of the nuclei. Clearly, photons with energies sufficient for pair production are emitted predominantly at the time of closest approach of the nuclei. It is thus sufficient to examine the electrons and positrons which have zero angular momenta and which are formed in the interaction of photons for which the c.m. frame coincides with the c.m. frame of the ion-atom system. The oscillatory part of the probability for pair production at a distance r from the nucleus is written in the form $W = W_0 W_1 W_{e-} W_{e+}$, where W_0 is the probability for the production of photons with the necessary characteristics, W_1 is the probability for the production of a virtual pair, and W_{e-} and W_{e+} are the probabilities for the escape of the electron and positron from the field-filled region. Obviously, oscillations could be caused only by the quantity $W_{e-} W_{e+}$. Since exact calculation of this quantity is exceedingly complicated, we consider a very simple model: In the region in which the pairs are produced, the external potential is $(eZ_0/r)(Z_0 \leqslant Z)$. In the semiclassical approximation we can then write

$$W_{e+} = -\sin[J(r)], \tag{1}$$

where

$$J(r) = 2 \int_{r_1}^{r} [(E + \frac{\alpha Z_0}{r} - \frac{\alpha Z_0}{x})^2 - m^2]^{1/2} dx. \tag{2}$$

Here E is the energy of the interacting photons, $r_1 = \alpha Z_0(E - m + \alpha Z_0/r)^{-1}$, e and m are the charge and mass of an electron, α is the fine-structure constant, and $\hbar = c = 1$. Expression (1) is an analytic continuation of the probability for the escape of a positron from under the Coulomb barriers into the region $E > m$. Unfortunately, we cannot write equally simple recipes for W_{e-}, so we use some heuristic considerations. The only parameter with the dimensionality of a length, which is pertinent to below-threshold pair production, is the screening radius (R) of the quasi-ion which is formed in the scattering process. It is reasonable to choose $W_{e-} \sim \Theta(r - R)$. Although this choice could be debated, the results found below do justify it to some extent. To estimate R, we use the expression[9]

$$R = \frac{2^{1/3}}{\alpha m}(Z - N)^{2/3}[(\frac{1}{2} + \frac{1}{\pi})Z + (\frac{1}{2} - \frac{1}{\pi})N]^{-1}, \tag{3}$$

where N is the degree of ionization of the accelerator beam. Integrating $W_{e+} W_{e-}$ over r (since we have $mR \gg 1$, we can use the stationary-phase method), we find

$$\sigma_{osc} \sim T = -[\frac{\partial J(R)}{\partial (mR)}]^{-1} \cos[J(R)]. \tag{4}$$

Since R depends only very weakly on Z in the region of interest here, the energies of the peaks for different systems will differ only slightly. For example, as we go from U + U to U + Pb, we would expect the peaks to shift an average ~ 10 keV toward lower energies; this expectation agrees with the data available. One advantage of this model is that it can be tested experimentally. Since R depends significantly on N, one could test the validity of our hypothesis by varying the degree of ionization of the beam or by comparing the results for asymmetric systems such as U + Ta and Ta + U.

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