Nature of the narrow energy peak of positrons produced in heavy-ion collisions

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Some of the positrons may be temporarily captured by an open resonator formed between two repulsive Coulomb centers and undergo an adiabatic cooling as the nuclei fly apart. This suggestion agrees qualitatively with experiment.

The advent of heavy-ion accelerators has recently made it possible to observe collisions in which a vacancy in the electron states deepest along the energy scale reaches the lower continuum, and a positron is produced when this vacancy is filled.[1] The most paradoxical aspect of the spectrum of these positrons is a relatively narrow peak ($\sim$80 keV wide) at $\sim$250 kV, whose position and width depend only slightly on the charges of the nuclei. At first glance, the width of this peak would seem to contradict the energy-time uncertainty relation: The collision time is 10^{-18} s, from which we would conclude $\Delta E \geqslant 250$ keV, but this figure is several times the observed value. Attempts to explain this contradiction have been constructed on hypotheses regarding an "adhesion" of the nuclei for a certain time interval[2] and even the existence of a new elementary particle.[3]

We would like to point out a less exotic possible explanation for this experimental result. The positron which is produced is in the field of two nuclei—in the simplest approximation—two repulsive Coulomb centers. In the semiclassical approximation such centers could be thought of as constituting an open resonator: A particle moving

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between the centers along the axis joining their nuclei might undergo an oscillatory motion, being reflected from each of the centers alternately. Admittedly, the stability condition is not satisfied here, and the quality of this resonator is low. Nevertheless, some of the positrons might be captured in a "laser" mode of this sort, and as the nuclei fly apart the energy of the positrons might decrease "adiabatically," and the time spent by the positrons near the nuclei might increase severalfold. As a result, we might expect to see the appearance of a comparatively narrow peak against the background of the broad "normal" spectrum of positrons, on the low-energy slope of this spectrum. Such an observation would agree with experiment.

These considerations can only point us in a general direction, however, since the semiclassical approximation on which they are based is not valid in this case. We nevertheless know that the semiclassical approach often yields some fairly good results at small quantum numbers, despite the fact that it is formally inapplicable.

A more accurate theoretical approach to the problem is possible, because in the nonrelativistic problem of the motion of a particle in the field of two Coulomb centers it is possible to separate variables in the spheroidal coordinates ζ, η, φ. The physical meaning here is that the energies corresponding to motion along the quasiangular (η) and quasiradial (ζ) variables are separately conserved: An exchange between these two energies would necessarily involve a disruption of the separation of variables in the real problem because of relativistic corrections, motion of the nuclei, the final dimensions of the nuclei, and so forth.

There is accordingly the possibility that the spectrum of the emitted positrons is related to the mathematical problem of the spectrum of a charged particle in the field of two repulsive Coulomb centers. At nuclear charges on the order of 100, the problem is of course very relativistic (and the separation of the variables breaks down), but in the case of a positron (in contrast with an electron) we could expect that the nonrelativistic approximation would still be fairly good, since the repulsion would keep the positron from approaching the nuclei, and the velocity of the positron would be well below the velocity of light, especially near the axis joining the nuclei.

Although the motion of a particle in the field of two Coulomb centers has been the subject of a formidable list of studies, the case of two repulsive centers has been almost completely ignored, since it does not have the bound states which have been the center of attention. The complex values of the energies of the quasistationary and virtual ("antibonding") states can be calculated as functions of the distance between the nuclei, R, by the method of chained fractions,[4] which is also valid in problems in which the parameters have complex values. Figure 1 shows results calculated for two identical unit repulsive centers, in atomic units. The real values of the energy E_0 are plotted upward along the ordinate axis, while the imaginary values $\Gamma/2$—the level widths—are plotted downward. The dashed line shows the potential energy $E = 4/R$, at the saddle point, halfway between the nuclei. It is physically obvious that the quasistationary terms should lie above this curve, and this is indeed what we find. The classification of terms is not completely unambiguous; it is determined here by the initial bound state in the problem $z_1 = 1$, $z_2 = e^{i\phi}$ as ϕ varies smoothly from π to 0. We pursue the scaling to $z = 92$ ($U^{+92} + U^{+92}$) and calculate the positron spectrum,

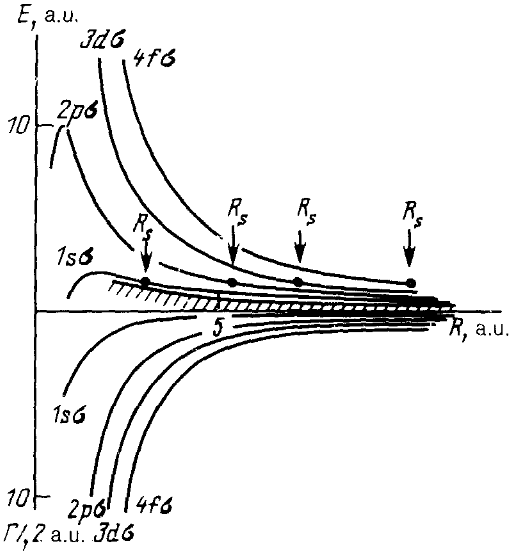

FIG. 1. Results calculated on the energies and widths of the quasistationary states in the (pe^6+p) problem as functions of the distance between the nuclei, R. Hatching—potential energy at the saddle point halfway between the nuclei; R—distance out to which the quasistationary state survives at the actual velocity at which the nuclei fly apart.

allowing for the change in the energy and width as the nuclei fly apart, in accordance with the adiabatic formula[5]

$$\frac{dP(E)}{dE} \sim \frac{1}{V} C^2(E) \left| \frac{dR(E)}{dE} \right| \exp\left(-2\int^{E} dE' \frac{\mathrm{Im}R(E')}{V}\right),$$

where V is the velocity, $R(E)$ is the function which is the inverse of the term $E(R)$, and $C(E)$ is the state density in the continuum.[5] We find the result shown by the dashed line in Fig. 2. We take the initial value of $R_{\min}$ to be 18 fm: the distance of

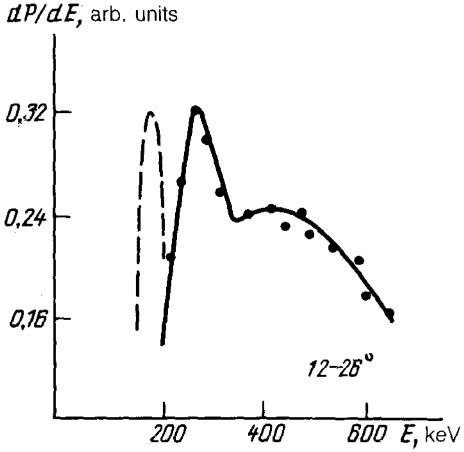

FIG. 2. Positron spectrum in $U^{238}+U^{238}$ collisions at a collision energy of 5.7 MeV/nucleon; the scattering angle is 12°–26°. Filled circles—experimental data[1]; dashed line—results of the present calculations, shown in arbitrary units (normalized to the height of the experimental peak).

closest approach for the typical energy $E = 5.7$ meV/nucleon and a scattering angle $\sim 30°$. At very small values of R, the wave function of the positron apparently behaves as a spreading wave packet, which determines the extent to which the various quasistationary states are populated. We suggest that this population is sufficient to explain the absolute magnitude of the observed peak, especially since the shape of the peak is essentially independent of which state is assumed to be populated, and the peak may be formed by several quasistationary states, rather than by a single one. The distance R out to which the quasistationary state will survive as the nuclei fly apart is shown in Fig. 1 for the $1s\delta$, $2p\delta$, and $3d\delta$ terms. For these terms, the value of R is seen to correspond to approximately identical values of E_0. The solid line in this figure is the experimental positron spectrum. We have not evaluated the probabilites for the capture of the positron into various states, so the heights of the calculated peaks have been normalized to the experimental data. It should be noted that as z is varied by several units, the positions of the quasistationary terms vary only slightly (on the order of the ratio $\Delta z/z$), in contrast with the position of an electron state with respect to the lower continuum: The latter determines the very sharp z dependence of the positron production probability itself. The suggestion that the positron production mechanism, which depends very strongly on z, is one mechanism, while the mechanism by which the positron energy spectrum is shaped—which depends only weakly on z—is a different mechanism, agrees completely with the experimental data. The proposed mechanism for the formation of the narrow peak leads to a predominant emission of positrons in the direction perpendicular to the orientation of the axis joining the nuclei after the collision. This prediction can be tested in coincidence experiments.

Comparison with the experimental data shows that the quality factor of the positron resonator is in fact "too good" in our approximation: The calculated peak is narrower than the experimental peak and lies at a lower energy. A slight increase in the term width Γ broadens the peak and reduces the "adiabatic cooling" of the positrons, i.e., improves the agreement. Incorporating relativistic effects, the finite size of the nuclei, the rotation of the axis joining the nuclei, and so forth, will—by disrupting the separation of variables—apparently act in specifically this direction.

Our calculations do not touch on the region of very small values of R, much smaller than, say, 1000 fm (the equivalent D_0 at $z = 1$). However, our primary result is that if a positron survives near the nuclei by some mechanism up to this time, then the observed energy peak will subsequently be shaped by specifically the mechanism of capture and cooling by an open resonator.

We will not discuss here some recent experiments on the correlation in the emission of electrons and positrons which were stimulated by the hypothesized existence of a new elementary particle: the axion. We simply note that quasistationary states in the field of two Coulomb centers with roughly the same energies will also exist for an electron.[5]

It can thus be concluded that the mechanism proposed here is fairly plausible and deserves further study.

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