Anomalous Positron Peak in Heavy-Ion Collisions

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We explore the possibility of whether the anomalous positron peak observed recently in heavy-ion experiments may be due to a polyelectron complex $(e^+e^+e^-)$. The decay of such a complex with the emission of a photon leads to a positron with a kinetic energy of 341 keV, which coincides with the recently observed anomalous positron peak to within the experimental error. The hypothesis of a polyelectron complex may also explain other features of the phenomenon.

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Recently, an anomalous positron peak has been observed in heavy-ion collisions involving systems with a combined charge of $Z \geqslant 163$ at a bombarding energy close to the Coulomb barrier.[1-4] The positron peak lies at an energy[3] of 336 ± 10 keV in the center-of-mass system and has a width of about 75 keV. The energy of the peak appears to be insensitive to all the projectile and target combinations involving Th, U, and Cm,[3] and also appears in the collision of Ta on Th.[4] The latter case involves a system with $Z = 163$ which is below the supercritical field of $Z_{\mathrm{cr}} \sim 173$. Such a feature suggests a common source that is nonnuclear in nature. Attention is turned to the search for a particle or a complex which may be formed in these collisions. The entity should give rise to a positron of 336 keV in its two-body decay mode. It should be produced in both a supercritical field and a subsupercritical field. Finally, as nuclear reaction takes place within 10^{-21} sec and the positron is detected within the time resolution of the apparatus, the entity should have a mean life much longer than 10^{-21} sec but much shorter than 10^{-10} sec.

It has been suggested[5,6] that this positron peak may arise from a neutral pseudoscalar particle (axion) which decays into e^+ and e^-. Reference 5 proposed an axion which couples to the leptons with a coupling constant allowed by the uncertainty in the *g*-factor measurement. The coupling of this axion to quarks is not standard. On the other hand, Ref. 6 proposed that any axion which may arise must come from the coupling of the axion to the nuclear hadronic current.

I would like to point out an interesting coincidence of the positron energy in the decay of a polyelectron complex $(e^+e^+e^-)$ and the energy of the anomalous positron peak. In the decay of $(e^+e^+e^-) \rightarrow e^+ + \gamma$, the kinetic energy T of the positron and the photon energy E_γ can be calculated. Neglecting the mutual interaction of the electron and the positrons, which is small in comparison with the rest mass of the complex, one finds that a two-body decay of $(e^+e^+e^-) \rightarrow e^+ + \gamma$ produces a positron with a kinetic energy of $T = 340.66$ keV and a photon of 681.3 keV. The kinetic energy of the positron coincides with the energy of the observed anomalous positron peak of 336 ± 10 keV, within the experimental error. Such a coincidence merits further theoretical and experimental investigations. The polyelectron complex can be an unbound or a (very weakly) bound system. Both possibilities will be explored in turn.

It is worth noting that *in the presence of a strong field, there are positron single-particle states which are bound and localized near the nucleus.* This is due to the relativistic effect of an effective attraction at short distances even though the electromagnetic interaction is repulsive.[7] From the Dirac equation, one knows that these positron states have the same wave functions as those of the electron states (except for an interchange of the labels of the G and F components and the corresponding orbital angular momenta). The eigenenergies of these states are equal and opposite to those of the corresponding electron states (Fig. 1). As the field strength increases, the eigenenergies of these states rise and the wave functions are pulled closer to the center. When the eigenenergies exceed m_e, however, the positron states have a finite probability to penetrate a potential barrier to escape to infinity and become resonance states.

As is well known, a stable vacuum is the state with the lowest energy constructed by filling all the negative-energy electron single-particle states.[9,10] In the quasielastic collision of two nuclei, the initial vacuum is characterized by the occupation of all the negative-energy electron continuum states. This vacuum is the proper reference with respect to which subsequent dynamics is described. When two nuclei with a combined nuclear charge $Z > 150$ are brought in contact with each other, there are bound electron single-particle states whose energies dive down below $\epsilon = 0$ [Fig. 1(a)], and the vacuum changes its nature. It is now characterized by the occupation of not only the negative-energy electron continuum states but also those negative-energy electron bound states which dive down below $\epsilon = 0$. If the electron states are completely empty before they dive below $\epsilon = 0$, then, with respect to the initial vacuum, the configuration of the lowest-energy state of the system at the moment of

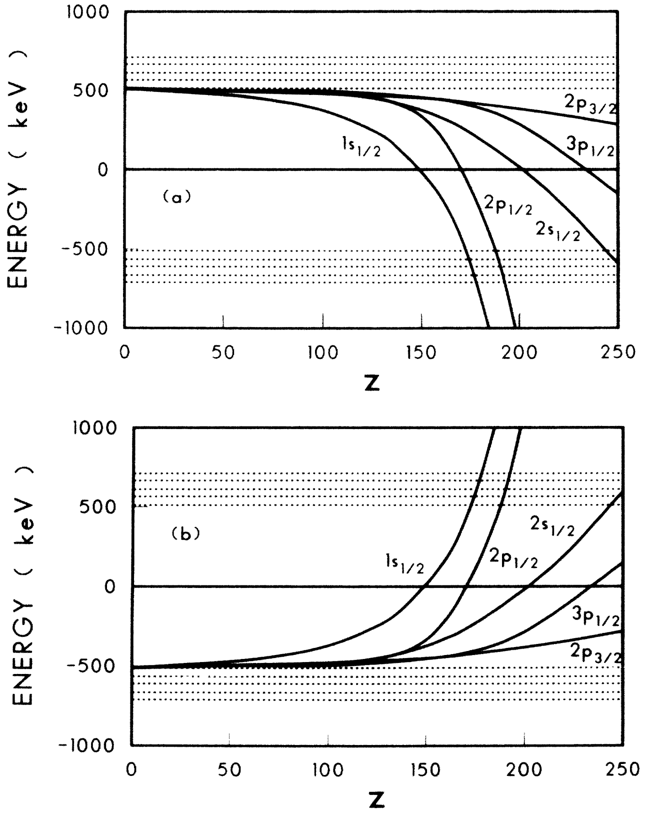

FIG. 1. (a) Some of the electron single-particle states as a function of the nuclear charge (Ref. 8). (b) Some of the positron single-particle states as inferred from (a). The discrete states are shown as solid curves and the continuum as dotted lines.

closest approach consists predominantly of electron-positron pairs where the electrons occupy the negative-energy electron states while the positrons occupy the corresponding positive-energy bound single-particle states [Fig. 1(b)] with their wave functions extending only a few hundred fermis from the center. In fact, simple analysis shows that the state with a dominant two-pair component is lower than the state with no particles by many tens of kiloelectronvolts.[11]

In heavy-ion quasielastic collisions involving a combined charge of $Z \geqslant 150$, the dynamical process may lead to a shakeoff of both electrons in the $1s_{1/2}$ orbital. As the dynamics proceed, the $1s_{1/2}$ electron state dives down below $\epsilon = 0$. There is a change of nature of the vacuum and the system may settle down to the lowest-energy state containing two electron-positron pairs in bound single-particle states. As the positron production is associated with quasielastic nuclear collisions, we consider the colliding nuclei to separate from each other at a time 10^{-21} sec after touching. The underlying strong Coulomb field confining the electron-positron pairs is suddenly removed as the nuclei recede farther out. For two receding nuclei approximately equal in charge (which are the experimental cases considered), the two electron-positron pairs can remain essentially at rest in the center-of-mass system and disperse freely outward. After the two nuclei are well separated, one of the electron-positron pairs can annihilate in the presence of another positron in its vicinity. As the mutual interaction is small compared with the electron rest mass and the confining Coulomb potential and the departed nuclei are no longer present, the decay energetics can be estimated by use of only the rest masses. A decay of $(e^+e^+e^-) \rightarrow e^+ + \gamma$ will lead to a positron with an energy of 341 keV. We shall see later that the mean life of such a $(e^+e^+e^-)$ complex falls within the correct range prescribed by the experiment. If this is the proper description, then, as the energy of the $1s_{1/2}$ electron bound state dives below $\epsilon = 0$ even before the field strength becomes supercritical, the process can occur in a subsupercritical field with $Z \geqslant 150$, such as in the collision of Ta with Th.[4] It appears that a compact, unbound $(e^+e^+e^-)$ complex can explain many of the peculiar features associated with the positron peak. Although the scenario is physically reasonable, it nevertheless must yet be worked out quantitatively in detail to find out whether it is the correct description.

I note in passing that in this description, bound positrons produced by electron shakeoff may show up as positrons essentially at rest in the center-of-mass system after the colliding nuclei recede to infinity. I also expect the occurrence of the complementary process of $(e^-e^-e^+) \rightarrow e^- + \gamma$ in which a pair of electrons near the nucleus and one of the positrons in their vicinity decay into an electron with an energy of 341 keV and a photon of 681 keV.

The other alternative explanation of the anomalous positron peak as arising from a bound polyelectron complex can also be explored but there may be questions concerning its branching probabilities and production mechanism. Wheeler[12] first predicted the existence of polyelectron systems of electrons and positrons bound together to form stable or metastable entities. The trielectron system P^{++-} is a very weakly bound leptonic complex[12,13] consisting of two positrons and one electron, bounded by 0.3266 eV against dissociation into positronium and a positron, and by 7.129 eV against dissociation into three particles. Its charge-conjugate partner P^{--+} has been observed experimentally.[14] The decay mode $P^{--+} \rightarrow e^- + 2\gamma$ has been observed[15] with a mean life of $\tau_{2\gamma} = (0.478 \pm 0.020) \times 10^{-9}$ sec which agrees with theoretical calculations.[16] The decay mode $P^{++-} \rightarrow e^+ + \gamma$ is allowed.[12,17,18] A recent calculation[17] gives a mean life for the one-photon decay of $\tau_{1\gamma} = 11.4$ sec and a branching ratio of $1\gamma/2\gamma$

$=4.2\times10^{-11}$. Thus, if the positron line arises from the bound P^{++-}, it will be accompanied by a large production of γ rays of 0.511 MeV. The small width for one-photon decay may make it unlikely that P^{++-} is the source of the positron peak.

What is the mean lifetime for the compact, unbound $(e^+e^+e^-)$ complex? I note that the small width for the one-photon decay of P^{++-} is due to the large separation (of the order of 10^5 fm) between the electron and the positrons. In the case of the compact, unbound $(e^+e^+e^-)$ complex produced in a strong field discussed previously, the separation between the electron and the positrons is of the order of 10^2 fm. The decay rate for the emission of two photons is proportional to the particle density when the relative coordinate of a positron and an electron is zero[16] and goes as (length scale)$^{-3}$. The decay rate for the emission of one photon is proportional to the particle density when the relative coordinates of both the like particles and the unlike particles are the same[17] and goes as (length scale)$^{-6}$. By comparing the length scales of the compact, unbound $(e^+e^+e^-)$ system with the very weakly bound, large P^{++-} system, one finds that the mean life for two-photon decay of the compact, unbound $(e^+e^+e^-)$ complex is $\tau_{2\gamma}\sim0.478\times10^{-9}\times(10^3)^{-3}$ sec $\sim5\times10^{-19}$ sec and the mean life for the one-photon decay is $\tau_{1\gamma}\sim11.4\times(10^3)^{-6}$ sec $\sim11\times10^{-18}$ sec. The branching ratio $1\gamma/2\gamma$ is of the order of 10^{-1}. The mean life of the compact, unbound polyelectron complex $(e^+e^+e^-)$ is much longer than 10^{-21} sec and much shorter than 10^{-10} sec as is necessarily the case to explain the anomalous positron peak.

We can make a rough estimate of the production cross section based on the assumption of a compact $(e^+e^+e^-)$ complex. The production arises from having two holes in the electron K shell. The probability of production of one hole is about $\frac{1}{10}$,[19] and the probability of production of two holes is about $\frac{1}{10}$ of the probability of production of one hole. The branching $1\gamma/2\gamma$ gives another factor of $\frac{1}{10}$. We can estimate the probability for the production of the anomalous positron peak to be about $\frac{1}{100}$ of that for the production of a single K-electron hole which leads to the broad positron peak in the background. In consequence, the cross section for the production of the anomalous positron peak should be roughly $\frac{1}{100}$ of the cross section for the production of all positrons. The experimental ratio of the yield of the anomalous positron to the yield of all the positrons is approximately $\frac{1}{20}$ for U on U and is slightly higher for other target and projectile combinations. This estimated ratio compares favorably with the experimental ratio, in order of magnitude.

It is an experimental question of whether the polyelectron complex $(e^+e^+e^-)$ plays any role in the origin of the anomalous positron peak. It is necessary to search for the 0.681-MeV γ line in coincidence with the anomalous positron peak to test whether the positron arises from a two-body decay of $(e^+e^+e^-)$. One should also search for positrons at rest in the center-of-mass system. Supplementary investigations should be carried out to study the production of the charge-conjugate partner $(e^-e^-e^+)$ which is expected to be produced and can decay into an electron of 0.341 MeV and a γ ray of 0.681 MeV.

In conclusion, in exploring whether a compact, unbound $(e^+e^+e^-)$ complex may be the source of the anomalous positron peak, we find good agreement of the positron energies, the existence of compact bound positron states which may lead to the possibility of production of the entity for both supercritical and subsupercritical fields with $Z\geqslant150$, and the correct range of mean lifetime. These observations provide encouraging hints for further experimental and theoretical investigations.

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