Production of New Particles in Heavy-Ion Collisions

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Experimentally observed sharp lines in the positron-emission spectra resulting from low-energy heavy-ion collisions are interpreted in terms of the production and subsequent decay of a neutral, pseudoscalar particle. This particle has a mass of about 1.6 MeV and a lifetime of about 1.3×10^{-13} sec.

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Some time ago Peccei and Quinn postulated[1] a global U(1) symmetry to suppress *CP*-nonconserving instanton effects in quantum chromodynamics. Subsequently, Weinberg[2] and Wilczek[3] noted that, as a consequence of the breaking of this U(1) symmetry, a new pseudoscalar neutral boson (axion) should exist. However, efforts to observe such particles have proved unsuccessful.[4]

Independently it has been recognized[5] that electron-positron pairs would be excited nonperturbatively from the vacuum in low-energy collisions of heavy ions with a combined charge greater than $Z > 173$. Also, motivated by theoretical studies of Greiner and collaborators,[6] sharp lines in the positron emission spectra were experimentally identified.[7] These positrons are emitted from the center of mass of the heavy-ion system, and it has been suggested that the peaks originate from a long-lived superheavy nuclear complex.[8] Our present understanding of such nuclear systems requires that the energy of the peak and the cross section associated with the peak change considerably from system to system. Experimentally the systems U+U, U+Cm, Cm+Th, and U+Th have been investigated, and the resulting peaks occur at approximately the same positron kinetic energy of 300 keV with widths less than about 70 keV and with integrated cross sections of about 200 μb.[9]

In this Letter we propose an alternative explanation for these sharp lines in terms of the production and subsequent decay of a neutral pseudoscalar particle and investigate if such a particle can be identified with the axion. We assume a standard pseudoscalar interaction Lagrangean for the coupling of this particle to the electrons and the positrons,

$$\mathscr{L}_{\text{int}} = g\bar{\psi}_e \gamma_5 \psi_e \phi_a, \tag{1}$$

where g is a free parameter. If we assume their production in the heavy-ion collision with a mass greater than twice the electron mass, they would decay with some probability into electron-positron pairs. These positrons, together with those produced directly from the strong electrodynamics, would give rise to the experimental yield. If the lifetime of such a particle is much greater than the heavy-ion reaction time, about 10^{-21} sec, the positron differential cross section resulting from its decay can be given by

$$d\sigma/dE = \sigma_{cl}\, dN/dE, \tag{2}$$

where E is the total positron energy and $\sigma_{cl} \approx \pi R_D^2$ is the characteristic heavy-ion cross section for positron production. The strong electromagnetic fields principally occur for the central collisions. Thus, we use $R_D \approx 20$ fm which gives $\sigma_{cl} \approx 12.6$ b. The energy distribution of the emitted positrons is denoted by dN/dE. Let $F(\mathbf{k})$ be the normalized probability for producing a new particle with momentum between $|\mathbf{k}|$ and $|\mathbf{k}| + d|\mathbf{k}|$. In our work we assume that they decay isotropically with $F(\mathbf{k}) = F(|\mathbf{k}|)$. We have

$$dN/dE = [4\pi m_a M_a/(m_a^2 - 4m_e^2)^{1/2}] \int_{|\mathbf{k}_-|}^{|\mathbf{k}_+|} d|\mathbf{k}|\, |\mathbf{k}| F(|\mathbf{k}|) \theta(E_a - E), \tag{3}$$

where

$$|\mathbf{k}_\pm| = (m_a^2/2m_e^2) E (1 - 4m_a^2/m_e^2)^{1/2} \pm (E^2 - m_e^2)^{1/2}. \tag{4}$$

Here, m_a and E_a are the mass and the total energy of the new particle, respectively. The number of these produced during the heavy-ion reaction (multiplicity) is M_a. Given our lack of detailed knowledge as to the mechanisms producing such particles during these collisions, we take $F(|\mathbf{k}|)$ as

$$F(|\mathbf{k}|) \propto |\mathbf{k}|^2 \exp[-|\mathbf{k}|^2/K^2]. \tag{5}$$

In Eqs. (2)–(5) m_a and K were adjusted to fit the experimental peak energy (300 keV) and width (70 keV), and M_a was adjusted to fit the integrated experimental cross section (200 μb), giving $m_a = 3.2 m_e$, $K = 0.1 m_e c$, and $M_a \sim 2.6 \times 10^{-5}$ particle per reaction. The calculated differential cross section is shown in Fig. 1(a), and the function $F(|\mathbf{k}|)$ is shown in Fig. 1(b) (solid line).

In obtaining these results, we have assumed that the coupling constant g is sufficiently small that the lifetime of the new particle is long compared to the heavy-ion reaction time, but short compared to the time of flight to the positron detectors. Under these conditions, and for a wide range of values for g, most of the particles will decay into electron-positron pairs with a resulting energy spectrum which does not depend on g. However, we should note that such particles which interact with electrons via the Lagrangean in Eq. (1) will contribute in general to the magnetic properties of matter, and specifically to the anomalous magnetic moment of the electron. For a mass $m_a = 3.2 m_e$, we find that their contribution to the electron g factor is approximately $5 \times 10^{-3} g^2$. Thus, existing highly accurate g-factor measurements[10] set a limit on the value of the coupling constant. Combining these data with recent theoretical work,[11] we plot the maximum allowed value of g^2 vs m_a in Fig. 2. The shaded area denotes the allowed combinations of the mass and the coupling constant. Consequently, we conclude that $g \sim 10^{-4}$, which gives us a lifetime of $\tau \sim 10^{-13}$ sec.

Numerical methods have been developed to compute the electron-positron pair production during slow heavy-ion collisions.[5,12] These methods yield reasonable results for the inclusive production of on-shell electrons and positrons, and can be applied to estimate the production of these new particles in first-order perturbation theory. The resulting inclusive singles distribution of produced particles is

$$D(\mathbf{k}) = \sum_{\mathbf{p},\mathbf{q}} \delta_{\mathbf{k},\mathbf{p}+\mathbf{q}} \left(\frac{dN_+}{d\mathbf{p}} \right) \left(\frac{dN_-}{d\mathbf{q}} \right), \tag{6}$$

where $dN_+/d\mathbf{p}$ and $dN_-/d\mathbf{q}$ are the differential numbers of positrons and electrons calculated with the methods of Ref. 12. In our first-order calculation, the multiplicity is related to the mean number of pairs produced during the collision by g^2, and is approximately 10^{-10} particle per heavy-ion reaction. The distribution function $D(|\mathbf{k}|)$ is shown in Fig. 1(b) as the dashed curve and is significantly different from the solid curve given by Eq. (5). However, we should note that during the heavy-ion collisions we are considering, electromagnetic processes are strongly time dependent and

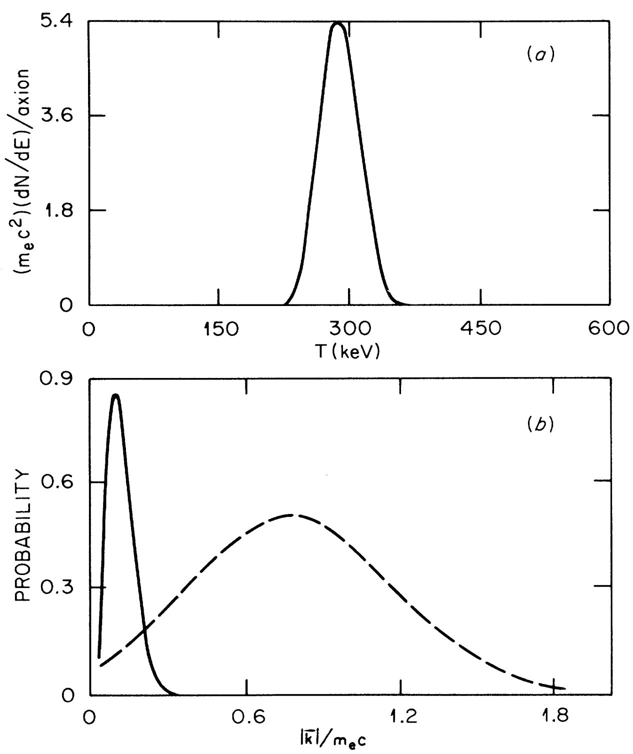

FIG. 1. (a) The differential number of emitted positrons in the center-of-mass frame during low-energy U+U, U+Cm, and Cm+Th collisions, Eq. (3), as a function of the kinetic energy of the outgoing positron. (b) The normalized probability for production of a particle with momentum between $|\mathbf{k}|$ and $|\mathbf{k}| + d|\mathbf{k}|$ in a heavy-ion collision. The solid curve results from Eq. (5) with parameters adjusted to fit the heavy-ion data; the dashed curve results from calculations using Eq. (6) and the methods of Ref. 12, and is multiplied by 250 for the purposes of plotting; m_e denotes the electron mass.

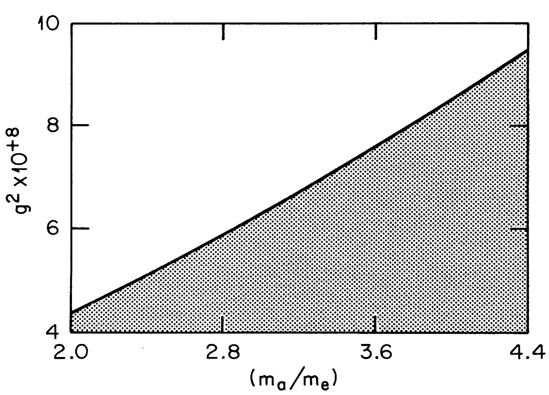

FIG. 2. Solid curve: The coupling constant g^2 vs possible values of the mass m_a in units of the electron mass m_e, assuming the maximum contribution allowed by the current experimental limits to the electron g factor. The shaded region denotes all possible combinations of mass and coupling constant which are consistent with the measurements.

nonperturbative. All orders of the lepton-antilepton, lepton-photon, and photon-photon interactions can contribute on an equal footing to the production of these particles. Thus, nonperturbative methods are needed to calculate the production reliably. Such calculations are of a complexity beyond the scope of the present work and will be reported elsewhere.

One might be tempted to identify this new particle with the standard axion. However, we should emphasize that the modeling of heavy-ion data determines the coupling of such new particles only to leptons [cf. Eq. (1)], with no information as to the possibility of hadronic coupling. If one chooses to identify this particle with the standard axion or other particles introduced in a similar way, its coupling to quarks is fixed as well. Furthermore, one could argue that the existence of a new particle with a mass and lifetime as given above would already be ruled out from the existing negative results from axion search experiments. In particular, those experiments looking for the electron-positron decay of axions are also sensitive to decays of other such particles.

Two experiments have directly searched for this decay mode. Calaprice *et al.*[13] rule out axions or any other particles interacting via the Lagrangean (1) with

$$m_e (G_F\sqrt{2})^{1/2}/g > 0.3.$$

Similarly, Faissner *et al.*[14] conclude that such particles with a lifetime greater than 10^{-9} sec are not allowed. Both results are consistent with our analysis.

The existence of such neutral, light particles has profound astrophysical implications,[15,16] especially on our understanding of stellar evolution. In particular, their emission can cause substantial energy loss from red-giant stars. Our parameter values are consistent with the limits on m_a and g required for the stability of such stars.[17]

The coupling of the standard axion to leptons and quarks is given by[2,3,17]

$$\mathscr{L}_{\rm int} = 2^{1/4} G_F^{1/2} \phi_a \left(\tan\lambda \sum_{\substack{Q=2/3 \\ \text{quarks}}} m_i \bar{\psi}_i \gamma_5 \psi_i + \cot\lambda \sum_{\substack{Q=-1/3 \\ \text{quarks}}} m_j \bar{\psi}_j \gamma_5 \psi_j + \cot\lambda \sum_{\substack{Q=-1 \\ \text{leptons}}} m_k \bar{\psi}_k \gamma_5 \psi_k \right). \quad (7)$$

Comparing Eq. (7) with Eq. (1) and using $g^2 = 10^{-8}$, we find $\cot\lambda = 49.0$ and $X \equiv \tan\lambda = 2.05 \times 10^{-2}$. The production rate of axions in radiative decays of heavy vector mesons,[3]

$$\Gamma(V \to \alpha + \gamma)/\Gamma(V \to \mu^+ + \mu^-) \approx (G_F m_q^2/\sqrt{2}\pi\alpha) y^2, \quad (8)$$

where V is the vector meson composed of quarks of mass m_q and $y = \tan\lambda$ $(\cot\lambda)$ for charge $\frac{2}{3}$ $(-\frac{1}{3})$ quarks, is expected to be substantial because of the available energy for the axions. For the J/ψ decay we find this ratio to be $\sim 3.2 \times 10^{-8}$, which is consistent with the Crystal Ball experiment,[18] $R(J/\psi \to a + \gamma) < 10^{-6}$. However, the values of our parameters predict the branching ratio for the upsilon to be $R(\Upsilon \to a + \gamma) \sim 17$, which is inconsistent with the present experimental limits.[19] We conclude that the particle produced in heavy-ion collisions cannot be the standard axion.

We would like to state two experimental tests to confirm the validity of our interpretation of the heavy-ion reaction data. First, in the heavy-ion reaction it is desirable to measure the yield versus the invariant mass by detection of electrons and positrons in coincidence. In such an experiment the yield as a function of invariant mass is expected to have a very narrow peak whose maximum value must be consistent with the multiplicity quoted earlier. Also, the energy distribution of the electrons measured in coincidence with the positrons should be similar to the sharp positron peak. Finally, it would be possible to observe axions directly in electron-positron collisions in the appropriate energy range. Since such experiments are presently in progress,[20] a detailed investigation of this process will be published separately.

To conclude, we would like to stress that our interpretation of the heavy-ion data results in the parameters of new particles which are presently consistent with all known experimental and theoretical limits.

Note added.—Since the present Letter was submitted, another paper[21] has appeared discussing this subject but with somewhat different conclusions.

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