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PHENOMENOLOGY OF NEW PARTICLE PRODUCTION
IN HEAVY-ION COLLISIONS*

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ABSTRACT

It is shown that the existence of sharp lines in the positron emission spectra observed in low-energy heavy-ion collisions is consistent with the production and subsequent decay of a neutral, pseudoscalar particle with a mass of about 1.6 MeV and a lifetime of about 10^{-13} sec.

INTRODUCTION

Binding energies of the electronic states in atoms are known to increase with the nuclear charge Z . At a critical charge $Z_c \approx 173$, the $1s$ state dives into the negative energy continuum. Consequently, it was suggested¹ some time ago that positrons would be emitted non-perturbatively from the vacuum in low-energy collisions of heavy ions with a combined charge greater than 173. The spectra of positrons emitted from the center of mass of the heavy-ion system have been experimentally studied; in particular, some sharp lines were identified.²

Numerical methods have been developed to solve the time-dependent Dirac equation in the presence of strong electromagnetic fields,^{1,3} and it has been shown that if a small fraction of the collisions leads to a nuclear reaction with a very long time delay, then one would expect to see such peaks. A possible mechanism to obtain such a delay time has been advanced by Greiner and co-workers.⁴ They suggest that the potential between heavy ions has a pocket, and when the system hits this pocket, quasimolecular nuclear configurations with a lifetime of 10^{-20} sec or more are formed. However, our present understanding of such systems requires that the energy of the peak and the cross section associated with the peak change considerably from system to system. For the five systems $U+Cm$, $U+U$, $Th+U$, $Th+Cm$, and $Th-Th$ experimentally studied so far, the sharp lines in the positron emission spectra occur at approximately the same positron kinetic energy of 300 KeV with integrated cross sections of about 200 μb and with widths less than approximately 70 KeV.⁵ In the following, another possibility for the existence of these sharp peaks will be elucidated. It will be shown that production and subsequent decay of a new neutral, pseudoscalar particle⁶ is a viable

alternative explanation to the formation of a long-lived superheavy nuclear complex.

DECAY MECHANISM

A standard pseudoscalar interaction Lagrangian will be assumed for the coupling of the new particle to the positrons and electrons

$$\mathcal{L}_{\text{int}} = g \bar{\psi}_e \gamma_5 \psi_e \phi_a. \quad (1)$$

The interaction strength g and the mass of the new particle, m_a , are taken to be free parameters to be fixed by data. If m_a is greater than twice the electron mass, then the two-photon decays of this new particle are suppressed and the dominant decay mode is into electron-positron pairs. Such positrons coming from the decay of the new particle, together with those produced directly by the strong electromagnetic field, give the experimental spectrum.

Let us assume that the lifetime of this particle is much longer than the heavy-ion reaction time which is about 10^{-21} sec. Under this assumption, which will be justified by the consistency of the final results, the positron differential cross section resulting from the decay of such a particle can be written as

$$\frac{d\sigma}{dE} = \sigma_{c1} \frac{dN}{dE} \quad (2)$$

where E is the total positron energy and dN/dE is the energy distribution of the emitted positrons. The characteristic heavy-ion cross section for positron production, σ_{c1} , sets the scale for the yield in Eq. (2). Since strong fields occur mostly in the central collisions, the characteristic interaction length is taken to be $R_D \approx 20$ fm which gives $\sigma_{c1} \approx \pi R_D^2 \approx 12.6$ b. Let $F(\vec{k})$ be the normalized probability for such a particle coming out of the interaction region with momentum between $|\vec{k}|$ and $|\vec{k}| + d|\vec{k}|$. Assuming the new particle decays isotropically into electron-positron pairs, $F(\vec{k}) = F(|\vec{k}|)$, one gets⁶

$$\frac{dN}{dE} = \frac{4\pi m_a \mathcal{M}_a}{\sqrt{m_a^2 - 4m_e^2}} \int_{|\vec{k}_-|}^{|\vec{k}_+|} d|\vec{k}| |\vec{k}| F(|\vec{k}|) \theta(E_a - E), \quad (3a)$$

with

$$|\vec{k}_{\pm}| = \frac{m_a^2}{2m_e^2} \left| E \sqrt{1 - \frac{4m_e^2}{m_a^2}} \pm \sqrt{E^2 - m_e^2} \right|, \quad (3b)$$

where E_a and $\mathcal{M}_a$ are the total energy and the multiplicity of the produced new particles. Since there essentially are three data points (position, cross section, and the width of the peak), one can

fit only three parameters in Eq. (3). Choosing two of these parameters to be the mass m_a and the multiplicity $\mathcal{M}_a$, one is forced to take a one-parameter function for $F(|\vec{k}|)$. We have made the analytically convenient choice

$$F(|\vec{k}|) \propto |\vec{k}|^2 \exp[-|\vec{k}|^2/\kappa^2], \quad (4)$$

where the free parameter κ characterizes the momentum of this particle. The mass m_a and the multiplicity $\mathcal{M}_a$ are adjusted to fit the experimental peak energy (300 KeV) and the integrated cross section (200 μb) respectively giving $m_a \approx 3.2 m_e$ and $\mathcal{M}_a \sim 10^{-5}$ new particles per heavy-ion reaction.⁶ The width of the peak (70 KeV) is the order of experimental resolution. When adjusted to fit this width, the momentum κ is found to be $0.1 m_e c$. The calculated cross section is shown in Fig. (1a) and the function $F(|\vec{k}|)$ is shown by a solid line in Fig. (1b).

In principle, the coupling strengths of this new particle to electrons, g_e , to up quarks, g_u , and to down quarks, g_d , need not be the same. Consequently, even if we make a model for the production mechanism of such particles during heavy-ion collisions, we would not be able to deduce g uniquely from the phenomenologically determined multiplicity, $\mathcal{M}_a \sim 10^{-5}$. However, the assumptions made in the previous paragraphs would fail unless the lifetime of this particle is longer than the heavy-ion reaction time (10^{-21} sec) but is shorter than the time of flight to the positron detectors (10^{-9} sec). Assuming electron-positron decay is the dominant mode, the lifetime of this particle is

$$\tau = \frac{\hbar}{\Gamma} \quad (5a)$$

where

$$\Gamma = \frac{g^2}{8\pi} \sqrt{m_a^2 - 4m_e^2}. \quad (5b)$$

Consequently, the above restrictions on the lifetime restrict the coupling strength to electrons and positrons to be $10^{-7} < g < 10^{-1}$.

Such particles interacting with electrons and positrons via the Lagrangian in Eq. (1) would contribute to the anomalous magnetic moment of electron. For a mass $m_a \approx 3.2 m_e \approx 1.6 \text{ MeV}$, the contribution to the electron g -factor is⁶ $\sim 5 \times 10^{-3} g^2$. Hence, the current state of the art g -2 measurements further restrict the value of the coupling constant g . Combining these data with the Q.E.D. calculations,⁷ the maximum allowed values of g^2 versus m_a are plotted in Fig. 2. The shaded area denotes the allowed values. Based on this figure, in the rest of this analysis we will take $g \sim 10^{-4}$ which yields a lifetime of $\tau \sim 10^{-13}$ sec.

Sometime ago, it was observed⁸ that a global $U(1)$ symmetry would suppress CP-violating instanton effects in quantum chromodynamics. As a consequence of breaking this $U(1)$ invariance, a new neutral

Fig. 1. (a) dN/dE per particle as calculated in Eq. (3a). (b) $F(|\vec{k}|)$ of Eq. (4) (solid line) and $250 D(|\vec{k}|)$ of Eq. (6) (dashed line).

pseudoscalar boson, called the axion,⁹ should exist. So far, no such particles have been observed. In the next section, we will demonstrate that the particle we introduce is not the standard axion. However at this point, one might ask if the existence of such a particle can be ruled out using the existing negative results from the axion search experiments. Since most of those experiments looking for the electron-positron decay mode would be sensitive not only to axions, but also to other pseudoscalar particles in this mass range, one would expect that our new particle, introduced to explain the heavy-ion data, could already be ruled out. Two such experiments have been performed. Calaprice *et al.* searched¹⁰ for the decay of the 12.7-MeV state in ^{12}C by the pseudoscalar particle emission to ^8Be . A model-independent analysis of their result does not rule out

Fig. 2. The values of g^2 and m_a allowed by the anomalous magnetic moment of electrons (shaded area).

the possibility $g \sim 10^{-4}$. In another experiment, Faissner *et al.*¹¹ conclude that such particles with a lifetime less than 10^{-9} sec are not ruled out.

The existence of such particles would also have astrophysical implications, particularly for our understanding of stellar evolution. Emission of neutral particles can cause substantial energy loss from red giant stars. The values $m_a = 1.6$ MeV and $g \sim 10^{-4}$ are consistent with the limits on m_a and g required for the stability of those stars.¹²

PRODUCTION MECHANISMS

So far, we have only studied the decay of this particle. Using the numerical techniques developed in Ref. 3 to calculate pair production during slow heavy-ion collisions, we can try estimating the distribution function $F(\vec{k})$. In the first approximation, let us neglect the nuclear contributions and estimate the production of this particle using first-order perturbation theory. The resulting inclusive singles distribution for the neutral particles is

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

where $(dN_+/d\vec{p})$ and $(dN_-/d\vec{q})$ are the differential number of positrons and electrons respectively computed using the techniques of Ref. 3. Since we are performing a first-order calculation, multiplicity is proportional to the mean number of pairs given in Eq. (6) with a proportionality factor g^2 . We find the multiplicity to be about 10^{-10} neutral particles per collision. The function $D(|\vec{k}|)$ is given in Fig. 1b as the dashed curve, where it is multiplied by a factor of 250 for plotting purposes. We conclude that nuclear processes and/or non-perturbative electromagnetic processes must contribute very significantly to the production of such particles.

Up to this point, very little has been said about the coupling of this new, neutral pseudoscalar particle to quarks. Let us assume that its coupling to a particular quark q has the same form as in the Lagrangian of Eq. (1), with g replaced by a different parameter g_q . The vector meson V , composed of the quark q and its antiquark $\bar{q}$, would decay into this new particle and a photon. For a vector meson, the ratio of the radiative decay width to that of decay width into u^+u^- pairs is given by¹³

$$\frac{\Gamma(V \rightarrow a + \gamma)}{\Gamma(V \rightarrow u^+ + u^-)} = \frac{g_q^2}{2\pi\alpha} \left(1 - \frac{m_a^2}{m_V^2} \right) \quad (7)$$

where m_V is the mass of the vector meson. For the decay of J/ψ the bound on this ratio is¹⁴ $\text{BR}(J/\psi \rightarrow a + \gamma) < 10^{-6}$, and for the decay of T it is¹⁵ $\text{BR}(T \rightarrow a + \gamma) < 10^{-4}$. These numbers limit the coupling strength of this particle to the charmed and bottom quarks as $g_c < 10^{-4}$ and $g_b < 10^{-3}$.

Using g_c and g_b determined above, one can easily demonstrate that this particle is not the standard axion. For the standard axion, one has⁹

$$\frac{g_e}{g_b} = \frac{m_e}{m_b}, \quad (8)$$

where m_b is the mass of the bottom quark (~ 4.5 GeV). For $g_e \sim 10^{-4}$, Eq. (1) predicts $g_b \sim 0.9$, which clearly violates the experimental limit in the previous paragraph. Since there is no other evidence for the standard axion model, it would be more surprising than otherwise if it explained the heavy-ion data.

CONCLUSIONS

We have shown that the experimentally observed positron emission spectra are consistent with the production and subsequent decay of a neutral, pseudoscalar particle whose mass and the coupling strength are consistent with all presently known experimental and theoretical limits. Moreover, we have demonstrated that if this particle exists, it is not the standard axion, and it must be produced by nuclear and/or non-perturbative electromagnetic processes.

It is, however, clear that those peaks observed in the positron emission spectra are not well understood theoretically. We would like to briefly summarize some of the other proposed explanations and suggest possible experimental tests.

A. Atomic Many-Electron Processes:¹⁶

The main problem in assessing this explanation is the lack of detailed many-body calculations addressing the question of positron emission. Such calculations should be available in the near future.

B. Long-Lived Superheavy Nuclear Systems:⁴

Nuclear molecules are well established in light nuclear systems.¹⁷ In principle, most detailed theoretical studies predict the existence of metastable, superheavy nuclei; a definitive experimental confirmation, however, is still lacking. The stability of such nuclei is intimately connected to the detailed nature of nuclear shell structure in the superheavy region and is presently not well known. Schematic calculations indicate that the position of a positron peak varies¹ between 200 KeV and 400 KeV for the systems considered, which is not experimentally observed. On the other hand, the experimental situation is somewhat ambiguous since two groups report peak energies which differ by many standard deviations for the same system.

C. Nuclear Pair Conversion:

The longitudinal part of the electromagnetic field can strongly induce transitions between two nuclear 0^+ states, producing electron-positron pairs. However, a detailed study of such processes has not been carried out to understand the relationship with the positron peak.

It is then very important to do further experiments to assess the validity of these different explanations. Several such investigations are possible:

a) Looking for the universal spike in a clearly subcritical system (one for which $Z_p + Z_T < 170$): The experimental observation of the peak in such systems may rule out the nuclear molecule hypothesis.

b) Experiments which probe higher $Z_p + Z_T$ systems: The availability of californium and einsteinium targets makes it feasible to study U+Cf ($Z_p + Z_T = 190$) and U+Es ($Z_p + Z_T = 191$) systems. Such studies would at least contribute to a better understanding of the nature of positron peaks.

c) Coincidence experiments: Positron measurements, in coincidence with heavy ions both in and out of the heavy-ion reaction plane would unambiguously determine the reference frame from which the positrons are emitted.

If either a new particle is produced, or if there is the pair conversion of a nuclear state, it should be possible to observe electrons in coincidence with positrons and heavy ions. In such an experiment, the yield as a function of invariant mass would give us information on the process of formation. In either case, the energy distribution of the electrons measured in coincidence with the positrons should give a peak similar to the positron yield.

d) Electron-positron collisions: It should be possible to unambiguously test the particle hypothesis by observing such particles

directly in electron-positron collisions. Since such experiments are in progress,¹⁸ an article including a detailed study of such processes is in preparation.¹⁹

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