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ON THE POSSIBILITY OF NEW PARTICLE PRODUCTION IN HEAVY-ION COLLISIONS*

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ON THE POSSIBILITY OF NEW PARTICLE PRODUCTION IN HEAVY-ION COLLISIONS*

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INTRODUCTION

Experimental identification of narrow peaks in the positron spectra emitted in the low-energy collisions of heavy ions¹⁻⁴ has brought many surprises. Such structures were predicted to be present when the collision leads to a long-lived nuclear complex.⁵ However, the observed Z-dependence of the peak energy and the cross section does not seem to be consistent with the hypothesis that quasimolecular nuclear configurations are formed. The 1s binding energy for those systems is expected to vary strongly with the total nuclear charge Z.⁶ Hence, when this binding energy exceeds twice the electron mass,⁷ the spontaneously created positron would have an energy strongly dependent on Z. Initial data¹⁻³ indicated that there is at least one constant peak energy for all the systems investigated, supercritical or subcritical. More recent measurements^{8,9} seem to unveil the existence of a multiple structure in the positron emission spectra, again with little Z-dependence.

In this talk, I consider an alternative hypothesis, namely two-body decay of a particle,^{10,11} which would explain the constancy of the peak energy. I also discuss the consequences of such a hypothesis and recent theoretical and experimental work motivated by it.

PHENOMENOLOGY OF PARTICLE PRODUCTION

I assume a pseudoscalar interaction Lagrangian of the form¹⁰

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

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where the interaction strength g_e , and the mass of the particle, m_a , are free parameters to be fitted by the data. One can repeat similar analyses for other types of the interactions,¹¹ but a pseudoscalar interaction suffices to illustrate the basic principles. For the purposes of the analysis which follows, the Lagrangian in Eq. (1) can be either elementary or effective. The mass of the particle is assumed to be greater than twice the electron mass, so that its dominant decay mechanism is into electron-positron pairs. Since these positrons are products of a two-body decay, they would yield sharp peaks in the experimental spectrum. This hypothesis has a built-in assumption about the lifetime of the particle. It must live longer than heavy-ion reaction time ($\sim 10^{-20}$ sec), but shorter than the time of flight to the positron detectors ($\sim 10^{-9}$ sec). So if a subsequent analysis yields a lifetime outside the above limits, this hypothesis should be discarded.

The peak at 300 keV positron kinetic energy has three pieces of information: its energy, width (< 70 keV), and the cross section ($\sim 200 \mu\text{b}$).³ The mass of the particle is adjusted to fit the peak energy, the production multiplicity to fit the integrated cross section, and the momentum to fit the width. One gets¹⁰ $m_a \approx 1.6\text{--}1.8$ MeV momenta with less than $0.1 m_{ec}$ with approximately 10^{-5} neutral particles being produced per reaction.

If we make a model for production, one can deduce the interaction strength g_e from the multiplicity quoted above. Given the lack of definitive models, we can extract limits on the interaction strength from the absence of this particle from other experimental observations. A particle interacting with electrons and positrons via the Lagrangian in Eq. (1) would contribute to various quantum electrodynamics processes. Here I consider the limits coming from the most thoroughly tested prediction of Q.E.D., the anomalous magnetic moment of electron.¹⁰ A similar analysis has been carried out for other Q.E.D. processes.^{12,13} For a particle with mass 1.6–1.8 MeV, the contribution to the anomalous magnetic moment is $\sim 5 \times 10^{-3} g_e^2$.¹⁰ Thus, combining very accurate recent measurements¹⁴ and theoretical work on higher order Q.E.D. corrections,¹⁵ one concludes that this contribution would not have been observed if $g_e \sim 10^{-4}$.¹⁰ Since this particle predominantly decays into electron-positron pairs, its lifetime can then be calculated to be $\sim 10^{-13}$ sec¹⁰ which is well within the previously mentioned bounds.

Light particles, even if they couple to matter very weakly, could carry away large amounts of energy from the stars and could have significant effects on other astrophysical processes. Now, using the constraints from red giant stars as an example, I illustrate that a particle, which would explain the heavy-ion data, would not contribute to the astrophysical processes. Light particles, if they directly couple to fermions as in Eq. (1), can be photoproduced in red giant stars and carry away energy. The observational bounds on energy loss is 100 ergs/gr-sec, and a significant portion of this could be due to the production of a particle if its mass is less than 5×10^2 keV.¹⁶ Obviously, this is much lighter than 1.8 MeV.

A crucial experiment to confirm the particle interpretation of heavy-ion data is to measure the yield versus invariant mass by detecting electrons and positrons in coincidence. This is a very difficult experiment. However, it has been observed that the positrons associated with the narrow peak are correlated with the simultaneous emission of electrons whose energy spectrum also contains a narrow peak at approximately the same energy and with the same width.^{8,17} For a detailed discussion of these experiments, I refer the reader to the other contributions to these Proceedings.^{8,9}

THE AXION HYPOTHESIS

The standard theory of strong interactions, quantum chromodynamics, does not necessarily have CP invariance, since gauge principle allows CP-violating terms. But there is, at present, no experimental evidence for CP violation in strong interaction physics. Sometime ago, it was observed¹⁸ that a global U(1) symmetry would suppress CP-violating instanton effects. As a consequence of breaking this U(1) invariance, one can introduce a neutral pseudo-scalar particle, called an axion.¹⁹ So far, all experiments trying to observe axions have failed. One then might be tempted to rule out the particle interpretation of heavy-ion data using the previous negative results from the axion search experiments. However, essentially all axion searches performed prior to 1986 are not sensitive to a particle decaying as fast as 10^{-13} sec.^{10,20,21} A summary of axion search experiments as of mid-1985 is presented in Fig. 1 which displays the possible window.

Fig. 1. A summary of world data for axion searches up to 1985 as presented by CHARM collaboration in Ref. 22. $F_x = 250 \times \text{GeV}$ and M_x is the axion mass. The shaded areas in the parameter space are excluded by the specified considerations. The CHARM collaboration data are from the 400-GeV proton beam dump experiment reported in Ref. 22. The black dot denotes the parameters of the particle which would explain the heavy-ion data.

In the standard axion model¹⁹ one introduces two Higgs doublets. The ratio of the vacuum expectation values of these two fields is denoted by X . If the generic Lagrangian in Eq. (1) represents the coupling of axion to electron, the interaction strength g_e can be related to X

$$X = m_e (G_F \sqrt{2})^{1/2} / g_e \quad (2)$$

where G_F is the Fermi constant. For an axion of mass 1.65 MeV, X is either 4.4×10^{-2} or 22 assuming three generations of quarks and taking the ratio of u and d quark current algebra masses to be 0.56. The latter X value yields too long a lifetime ($\sim 10^{-6}$ sec) to be compatible with experiments,¹⁰ while the former value gives a lifetime of about 10^{-12} sec, in agreement with the electron anomalous magnetic moment considerations.

As I enumerate in the next section, recent experiments and reanalyses of old data to accommodate the short axion lifetime still rules out the standard axion model. In particular, it was found out that if there is a neutral, pseudoscalar boson of mass 1.6 MeV, it should couple to light quarks more strongly than to heavy quarks. In the past year, a number of new models, taking this universality breaking into account, have been proposed.²³⁻²⁶ Again in the next section, I compare two of those models, those of Krauss and Wilczek²³ and of Peccei et al.²⁴ with the recent experiments.

RECENT PARTICLE SEARCH EXPERIMENTS

Radiative Upsilon Decays

A search for possible radiative decays of heavy vector mesons into light pseudoscalar particles is experimentally feasible since the monochromatic photons provide a clear signal. Let us consider a heavy vector meson composed of the quark q and its antiquark $\bar{q}$ and assume that this quark couples to the light particle via a pseudoscalar interaction Lagrangian similar to that in Eq. (1) with a coupling strength g_q . The ratio of the radiative decay width of the vector meson to the decay width into $\mu^+\mu^-$ pairs is given by²⁷

$$\frac{\Gamma(V \rightarrow \alpha + \gamma)}{\Gamma(V \rightarrow \mu^+ + \mu^-)} = \frac{g_q^2}{2\pi\alpha} \left(1 - \frac{m_a^2}{m_V^2} \right) \quad (3)$$

where m_V is the mass of the vector meson and the quantum chromodynamics corrections are neglected.

For the decay of Υ , Eq. (3) predicts

$$B[\Upsilon(1s) \rightarrow \gamma + a] \sim (2.7 \pm 0.7) \times 10^{-4} X^2 \quad (4)$$

in the standard axion model.¹⁹ Previous experimental searches looking for this decay reported null results,²⁸ but they have assumed that the axion escapes the detector region before decaying. However, axions with a lifetime of $\sim 10^{-13}$ sec would decay dominantly inside the detector. For $X = 0.04$, Eq. (4) gives a branching ratio of 0.16 ± 0.04 . Two searches for axions decaying into e^+e^- inside the detector were recently performed by groups using the CUSB²⁹ and CLEO³⁰ detectors. Both groups report an upper limit of $\sim 2 \times 10^{-3}$ for the branching ratio which conclusively excludes the possibility of short-lived axions within the original model.

One can, nevertheless, use Eq. (3) in conjunction with the above experimental results to obtain an upper limit on g_b .²¹ Those limits would be

consistent with the new axion models^{23,24} since in these models the couplings of the axion to heavy quarks are suppressed.

Electron Beam Dump Experiments

A recent search for neutral penetrating particles has been performed using a 2.5-GeV electron beam at the National Laboratory for High Energy Physics (KEK) in Japan.³¹ After the beam hits a tungsten target, the axions were supposed to penetrate a dump and to decay into e^+e^- pairs in a decay volume. Neutral particles are assumed to be produced by the Primakoff process by photons

$$\mathcal{L} = \frac{g_Y}{m_e} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi_a \quad (5)$$

as well as by bremsstrahlung from electrons (cf. Eq. (1)). A portion of the two-dimensional parameter space of $\alpha_e = g_e^2/4\pi$ and $\alpha_Y = g_Y^2/4\pi$ is excluded at the 90% confidence level³¹ assuming $m_a = 1.8$ MeV. In particular, neutral particles living longer than 10^{-12} sec are excluded for all values of g_e , when $\alpha_Y \geq 10^{-21}$. Also, when $g_Y = 0$, the interval $0.022 < X < 0.074$ is excluded for the standard axion model. Let me reiterate that a standard axion would require $X \sim 0.04$ to explain the heavy-ion data.

Nuclear M1 Transition Experiments

If there is enough energy, a neutral particle coupling to up and down quarks can be produced in nuclear transitions.³² This is an ideal situation in which to use perturbation theory since the relevant couplings are small. Furthermore, since a neutral, pseudoscalar particle acts like a "magnetic" photon,¹⁹ the emission of such a particle would follow the same selection rules as the magnetic transitions in nuclei.^{33,34} Consequently, one could look for the decay of a nuclear state by neutral particle emission in competition with, say, M1 transitions.

The decay of the 9.17-MeV $J^\pi=2^+$, $T=1$ state in ^{14}N has been recently investigated for this purpose.³⁵ This state decays into the $J^\pi=1^+$, $T=0$ ground state by an M1 transition with a branch of 85%.³⁶ Savage et al. measured the branching ratio of neutral particle emission decay to that of M1 transition by studying the angular correlation of e^+e^- pairs.³⁵ Assuming $m_a = 1.7$ MeV and a lifetime less than 10^{-11} sec, they obtain an upper limit of 4×10^{-4} for this branching ratio, as opposed to the standard axion model prediction of 0.55. Since this transition is isovector, the above result can also be used to provide an upper limit of 1.4×10^{-2} to the neutral particle-nucleon isovector coupling constant.

Other Limits from Nuclear e^+e^- Pair Measurements

Calaprice and his collaborators reanalyzed³⁷ early Brookhaven data³⁸ determining multipolarities of various nuclear electromagnetic transitions. In particular, they studied the decays of the 3.56-MeV 0^+ state in ^6Li , and the 7.03-MeV 2^+ state in ^{14}N by internal pair conversion to the ground states of these nuclei. They deduced the branching ratio of neutral particle emission decay to the e^+e^- pair emission decay to be less than 0.14 for ^6Li and less than 5 for ^{14}N . The standard axion,¹⁹ Krauss-Wilczek,²³ and Peccei et al.²⁴ models predict this ratio to be 7.2(300), 10(0), and 10(0) respectively for ^6Li (^{14}N). Thus, these two new axion models seem to be also ruled out.

NEUTRAL PARTICLE PRODUCTION MECHANISMS IN HEAVY-ION COLLISIONS

During the past year, considerable theoretical activity has been devoted to the investigation of various possible mechanisms to produce light, neutral particles in heavy-ion collisions.^{10,39-42} Generally, one assumes that the heavy-ion system generates a current $j(\vec{x},t)$ which is the source of the neutral particles. The resulting interaction Lagrangian

$$\mathcal{L}_{\text{int}} = \phi_\alpha j(\vec{x},t) \quad (6)$$

leads to an exactly solvable quantum field theory problem.⁴³ The momentum distribution, $F(\vec{k})$, of the produced particles is given by

$$F(\vec{k}) \sim e^{-\bar{n}} |j(\vec{k},\omega_k)|^2 / \omega_k \quad (7)$$

where $\omega_k = \sqrt{\vec{k}^2 + m_a^2}$, $\bar{n}$ is the average number of the particles produced, and

$$j(\vec{k},\omega_k) = \int d^4x j(\vec{x},t) \exp[i(\vec{k} \cdot \vec{x} - \omega_k t)]. \quad (8)$$

The function j was modeled in several ways. One possibility is to take¹⁰

$$j(k) \sim \sum_{\vec{p},\vec{q}} \delta_{\vec{k},\vec{p}+\vec{q}} \left(\frac{dN_+}{d\vec{p}} \right) \left(\frac{dN_-}{d\vec{q}} \right) \quad (9)$$

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. 44. Another possibility is to consider³⁹⁻⁴² effective pseudoscalar

$$j(\vec{x},t) \sim \vec{E} \cdot \vec{B} \quad (10a)$$

or scalar

$$j(\vec{x},t) \sim \vec{E}^2 - \vec{B}^2 \quad (10b)$$

couplings to the classical electromagnetic field of heavy ions.

One can unfold the experimental data directly to obtain the momentum distribution given in Eq. (7). This had been done in Ref. 10, and the distribution shown in Fig. 2b (solid line) was obtained. Probably the most salient feature of this figure is that the momentum spread is very small ($< 0.1 m_e c$). On the other hand, $F(k)$ obtained by substituting Eq. (9) into Eq. (7) is much broader (Fig. 2b, dashed line). Other authors³⁹⁻⁴² using the source terms given in Eq. (10), modeled along very different lines, arrive at a similar conclusion. Thus, the theory seems to fail in describing the production mechanism if indeed such particles are produced in heavy-ion collisions. However, at this conference it was reported⁸ that one can fold the broad distribution in Fig. 2 by the kinematical constraints of the experiment and obtain a rather sharp momentum spread.

COMPOSITE AND EXOTIC PARTICLES

So far, I have confined my discussion to the particles which are either elementary or with some possible structure which cannot be probed at these energies. A number of other possibilities were also considered concerning the creation of composite particles or exotic states which I will summarize very briefly.

Fig. 2. a) Differential number of positrons emitted in the heavy-ion collisions. b) Momentum distribution of the neutral particles required to fit the data (solid line) and obtained from Eqs. (7) and (9) (dashed line).

Wong suggested that a polyelectron complex ($e^+e^+e^-$) could be produced in heavy-ion collisions.⁴⁵ The decay of this complex into a positron and a photon would create a sharp positron line. However, the decay of such a complex is dominated by the two-photon mode $e^+e^+e^- \rightarrow e^+ + 2\gamma$. Indeed the branching ratio $\Gamma_{1\gamma}/\Gamma_{2\gamma}$ is calculated to be $\sim 10^{-11}$.⁴⁶ Consequently, if the positron peak with a cross section of $200 \mu\text{b}$ is due to the one-photon decay mode, most of the polyelectrons produced in heavy-ion collisions would decay through the two-photon mode yielding a total positron cross section of $\sim 200 \times 10^{11} \mu\text{b} = 2 \times 10^7$ barns. Such a situation is manifestly not realized in the experiments.

Celenza et al. suggested that these peaks could originate from the decay of nontopological solitons.⁴⁷ Other possible mechanisms might be due to a change in the vacuum structure of a Higgs field⁴⁸ or due to the existence of systems with highly localized and tightly bound states of several electron-positron pairs.⁴⁹ A detailed discussion of these subjects is given elsewhere in this volume.^{42,50}

CONCLUSIONS

Experimental data still seem to allow a neutral particle with mass $\sim 1.6 - 1.8 \text{ MeV}$ and a lifetime of $\sim 10^{-12} - 10^{-13} \text{ sec}$, but the situation might soon change. This particle is not the standard axion; the recent models proposed by Krauss-Wilczek and Peccei et al. also seem to be ruled out. Furthermore, if this particle is being produced in heavy-ion collisions, we do not know its production mechanism where the main difficulty appears to be obtaining the correct momentum spread.

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