Production Mechanisms for a New Neutral Particle below 2 MeV

Alan Chodos and L. C. R. Wijewardhana
Physics Department, Yale University, New Haven, Connecticut 06511
(Received 23 September 1985)

Recently observed e^+ kinetic-energy peaks at 336 ± 40 keV in several heavy-ion systems have suggested the existence of a particle ϕ decaying to e^+e^-. We construct a simple model of ϕ production by the electromagnetic field of the ions. It is not possible to produce ϕ at rest as the data require. If m_ϕ is just above $2m_e$, then a sharp peak in the e^+ kinetic energy can be obtained if the ϕ velocity is sharply peaked and nonzero. Our model suggests a mechanism for this via the formation of a resonance in the ionic system for which there is independent evidence.

PACS numbers: 14.80.Pb, 25.70.Gh

Recently, the energy distribution of positrons produced in scattering experiments involving two high-Z ions has been measured.[1,2] The data reveal an unexpected peak in the positron kinetic energy at 336 keV with a width of 70–80 keV. This peak is observed essentially at the same energy in six different systems (uranium, curium, and thorium colliding with each other in all possible combinations) and it has been suggested that this could be evidence for a new neutral particle ϕ decaying into an e^+e^- pair.[2,3]

In this paper we shall construct a simple dynamical model of ϕ production in the heavy-ion collision process. Our goal is to see whether such a model can account for the data, thereby lending credence to the idea that a particle is being observed. We do not address the question of whether the existence of such a particle can be made consistent with other phenomenological constraints (such as leptonic $g-2$, and the decay of various particles into ϕ).[3,4]

It has been argued in Ref. 2 that if a particle is responsible for the peak then the data strongly imply that the particle must have an appreciable amplitude to be produced at rest in the center of mass (c.m.) system of the two ions. Otherwise the peak would be obliterated by Doppler broadening. (There is negligible difference between the c.m. and the laboratory systems because their relative velocity is only $\frac{1}{20}c$.) We shall find, in the simplest version of our model, that the production amplitude is actually suppressed for small values of the c.m. momentum k of the ϕ, and we therefore cannot reproduce the observed peak. Another version of the model incorporates resonant behavior in the ion-ion system. Although we still find suppression at small k, we note that an alternative explanation of the peak is possible in which the ϕ is produced with a sharp nonzero value of k and then decays essentially at threshold into e^+e^-.

In our model, the heavy ions are assumed unaffected by the act of creation of the ϕ, which has a mass less than 2 MeV. The ions, as they collide, generate some sort of external current $j_{\text{ext}}(\mathbf{x},t)$ to which the ϕ can couple:

$$L_{\text{int}} = j_{\text{ext}}(x)\phi(x). \tag{1}$$

One is then dealing with the exactly solvable problem of a quantum field interacting with an external source. The average number of particles produced per collision is

$$\beta = \int [d^3k/(2\omega_k)(2\pi)^3]\,|\tilde{j}_{\text{ext}}(\mathbf{k},\omega)|^2, \tag{2a}$$

and the probability distribution for producing a single ϕ with momentum k is

$$P(k) = |\tilde{j}_{\text{ext}}(k)|^2 e^{-\beta}/2\omega_k(2\pi)^3, \tag{2b}$$

where

$$\tilde{j}_{\text{ext}}(k) = \int d^4x\, e^{-ikx} j_{\text{ext}}(x)$$

and

$$\omega_k^2 = \mathbf{k}^2 + m_\phi^2.$$

For definiteness, we take

$$j_{\text{ext}}(x) = g\mathbf{E}\cdot\mathbf{B}(x), \tag{3}$$

where $\mathbf{E}$ and $\mathbf{B}$ are the usual electric and magnetic fields, and g is a coupling constant with dimensions of inverse mass. This form is suggested by two considerations: (i) Because of the high Z and small impact parameter, the collision involves the generation of intense electromagnetic fields, so that electromagnetic production might well be what is observed; (ii) this particular coupling is natural if the ϕ turns out to be pseudoscalar. However, we stress that this choice is made only as a first guess.

To proceed, we assume that in the center-of-mass system one of the ions describes a trajectory $\mathbf{r}(t)$ and the other $-\mathbf{r}(t)$. (We ignore the possible mass difference between the two ions.) By conservation of angular momentum, $\mathbf{r}(t)$ is confined to a plane. It is straightforward to compute

$$\mathbf{E}\cdot\mathbf{B}(\mathbf{x},t) = (4Z_1Z_2e^2\gamma^2)\frac{\mathbf{x}\cdot\mathbf{r}\times\dot{\mathbf{r}}}{D^{3/2}}, \tag{4}$$

where

$$D=[\mathbf{x}-\mathbf{r}(t)]^2[\mathbf{x}+\mathbf{r}(t)]^2,$$

$$\gamma^2=(1-v^2)^{-1},\quad v^2=\dot{\mathbf{r}}\cdot\dot{\mathbf{r}}.$$

The most obvious trajectory to choose is that corresponding to Coulomb scattering. To simplify the analysis, we compute the production for rectilinear motion. This does not mean that a straight line is a good approximation to the actual trajectory (it certainly is not); rather, we are trying to obtain qualitatively correct results as simply as possible. Below we shall analyze a more realistic trajectory.

If we choose the z axis perpendicular to the plane of scattering, with the velocity along the x axis, we have

$$\mathbf{r}(t)=(vt,b,0).$$

Then, after some manipulations we obtain

$$\tilde{j}(k)=\frac{-i\pi k_z}{v}\int_{-1}^{1}d\omega\, e^{-ik_y b\omega}K_0(b\alpha(\omega)), \tag{5}$$

where

$$\alpha(\omega)=\left[\left(\frac{k_0^2}{v^2}+k_x^2\right)-2\frac{\omega k_0 k_x}{v}+(k_y^2+k_z^2)(1-\omega^2)\right]^{1/2},$$

and K_0 is the modified Bessel function. With this form, we can obtain all quantities of physical interest numerically on the computer. The factor of k_z in $\tilde{j}(k)$ arises because $\mathbf{E}\cdot\mathbf{B}(\mathbf{x},t)$ is odd under $z\to -z$. This leads to suppression of ϕ's produced with small momenta over and above the $|\mathbf{k}|^2$ that comes from the phase-space volume element. We shall comment on this further below.

At this point, there are two free parameters: the coupling g and the impact parameter b. By adjusting g we can clearly obtain whatever production rate we desire. The test of the model is whether one gets the observed rate with a "reasonable" value for g. If, for example, we conjecture that ϕ has something to do with the weak interactions, then the relevant mass scale is perhaps $M_W \simeq 100$ GeV, and since we are considering an electromagnetic coupling, there should also be a factor of (at least) $\alpha \simeq 10^{-2}$. Thus we would estimate $g \simeq 10^{-4}\ \mathrm{GeV}^{-1}$.

In the case at hand, the quoted differential production cross section $d\sigma_p/d\Omega = 10\ \mu\mathrm{b/sr}^2$. If we choose b to correspond to 90° Coulomb scattering in the center-of-mass system (even though the trajectory that we are actually computing with is a straight line) then, using the relation

$$d\sigma_p/d\Omega \simeq \beta\, d\sigma/d\Omega, \tag{6}$$

where β is given in Eq. (2), we find that $g \simeq 0.6\ \mathrm{GeV}^{-1}$, in disagreement with our previous estimate by about 4 orders of magnitude. Furthermore, we can compute the actual distribution of positron kinetic energy Q, using the formula

$$F(Q)=\mathrm{const}\times\int_{|k_-|}^{k_+}k\,dk\left[\int|\tilde{j}(k)|^2 d\Omega_k\right],$$

$$k_\pm=\tfrac{1}{2}m^{-2}[pm_\phi^2 \pm m_\phi E(m_\phi^2-4m^2)^{1/2}]. \tag{7}$$

E is the positron energy, p the magnitude of its momentum, and m its mass. The result is displayed in Fig. 1. The curve is clearly not peaked the way that the experimental distribution is. The reason for this is partly, as remarked above, that there is both phase-space and dynamical suppression of small ϕ momenta, and partly that the natural scale for ϕ momenta in the production process turns out to be on the order of m_ϕ, which is 1.7 MeV. It is possible to replace $\mathbf{E}\cdot\mathbf{B}$ by an even function of z, such as $\mathbf{E}^2-\mathbf{B}^2$, thereby eliminating the dynamical suppression factor k_z^2, but $\mathbf{E}^2-\mathbf{B}^2$ is more singular at short distances, and would require some cutoff procedure to exclude the centers of charge from the integration region.

We believe that the twin problems of (a) kinematical suppression of ϕ production at low $|\mathbf{k}^2|$ and (b) a natural tendency to produce ϕ's with $|\mathbf{k}|\sim m_\phi$ are indeed fairly general. This is borne out by results reported in Ref. 3 (see Fig. 1), where an attempt along quite different lines to calculate the distribution of ϕ momenta yields a curve that is much broader than the one required to fit the data.

We turn next to a different type of trajectory $\mathbf{r}(t)$ that is motivated by experimental evidence that the observed peak is associated with resonant behavior in the total center-of-mass energy of the ion-ion system. The most natural explanation for this is that when the two ions collide, the combination of nuclear and elec-

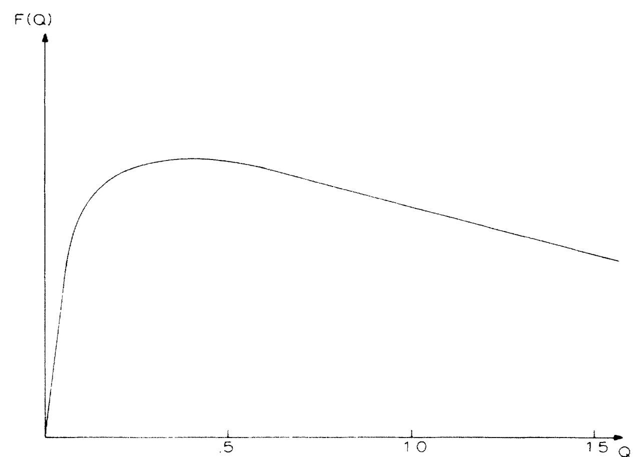

FIG. 1. Positron kinetic-energy distribution $F(Q)$ with arbitrary normalization, plotted against the kinetic energy Q measured in units of m_ϕ.

tromagnetic forces is such that a long-lived composite state is formed, and only when this state has been formed does appreciable ϕ production take place.

We model this situation as follows: We imagine that the two ions approach each other from infinity, with initial velocity v and impact parameter b. The angular momentum of the system is then $2Mvb$. (M is the mass of one of the ions.) When the ions just touch, they lock into a composite system, which we view as the two ions rotating about each other with angular frequency ω. The frequency ω is determined from conservation of angular momentum:

$$I\omega = 2Mvb, \tag{8}$$

where I is the total moment of inertia of the system. If we think of the ions as a pair of spheres of radius R rotating about their common point of tangency, then $I = \frac{14}{5}MR^2$. (Actually, this is at best a crude approximation, since the nuclei in question are rather deformed objects.) We thus have

$$\omega = \tfrac{5}{7}(b/R^2)v.$$

For $b \approx 1$ fm, $R \approx 8$ fm, and $v = \frac{1}{20}$, this gives $\omega = 110$ keV. We shall see below that experiment favors $\omega = 850$ keV. Given the level of our approximations, and the uncertainties in the correct values to take for b and R, we shall not worry too much about this discrepancy.

To study ϕ production, it is convenient to ignore the initial and final times during which the resonance is coming together and breaking up, and to pretend temporarily that this spinning system exists for all time. This will be a good approximation, if the resonance is sufficiently long-lived. Thus we take

$$\mathbf{r}(t) = R\,(\cos\omega t, \sin\omega t, 0).$$

One feature is immediately evident: Since $\mathbf{r}(t+2\pi/\omega) = \mathbf{r}(t)$, the Fourier transform must be a sum of δ functions:

$$\tilde{j}(k) = \sum_{n=-\infty}^{\infty} j_n(k)\delta(k_0 - n\omega). \tag{9}$$

Physical quantities [e.g., Eqs. (2a) and (2b)] are evaluated at $k_0 = \omega_k$, so that the $n \leqslant 0$ terms in the sum do not contribute. Furthermore, symmetry considerations show that $j_n = 0$ if n is odd. Thus we take

$$\tilde{j}(k) = \sum_{n=1}^{\infty} j_{2n}(\mathbf{k})\delta(k_0 - 2n\omega). \tag{10}$$

When we square this to get the relevant probabilities, we shall obtain

$$|\tilde{j}(k)|^2 = \left[\sum_{n=1}^{\infty} |j_{2n}(\mathbf{k})|^2 \delta(k_0 - 2n\omega)\right]\delta(0). \tag{11}$$

As usual, we imagine that the resonance really exists for t such that $-\frac{1}{2}T \leqslant t \leqslant \frac{1}{2}T$, and interpret $2\pi\delta(0) = T$. Thus our probability distributions will be proportional to the lifetime of the resonant state. The computation of β is more difficult than in the rectilinear case. We make the following approximations: (i) We keep only the $n = 1$ term in Eq. (11), and (ii) we note that kR is small for those k that contribute to the peak (since $R^{-1} \sim 25$ MeV) and we therefore keep only the leading kR behavior. This yields

$$\beta = (\gamma^2 e^2 Z_1 Z_2 \omega R)^2 (4\pi/945) k^3 (kR)^4 g^2 T. \tag{12}$$

To obtain a numerical value, we note that the Doppler broadening will be too large unless we have $k \leqslant 100$ keV. Setting $k = 100$ keV in Eq. (12), we obtain $\beta = 1.3 \times 10^{-14} g^2 T$ MeV^3. This number is too small by many orders of magnitude for any reasonable values of g^2 and T. The reason for this is that the $\mathbf{r}(t)$ that we have chosen generates a k^7 suppression factor which is much more severe than the purely k^2 kinematical suppression that one might expect.

Let us return to the fact that in our model of resonant production, the ϕ is produced with a discrete set of energies $k_0^{(n)} = 2n\omega$. (Of course, these spikes will be broadened by the finite resonance lifetime, but we neglect this here.) We can use this circumstance to explain the peak in the positron kinetic energy in a novel way. The object is to obtain a unique value for $|\mathbf{p}^*|$, which is the magnitude of the positron's momentum in the c.m. frame. Let us denote the positron's momentum in the ϕ rest frame by $\mathbf{p}$, and its energy by E, and write

$$\mathbf{p} = \mathbf{p}_\parallel + \mathbf{p}_\perp,$$

where $\mathbf{p}_\parallel$ is parallel to $\mathbf{k}$ (the ϕ's momentum in the c.m. frame) and $\mathbf{k}\cdot\mathbf{p}_\perp = 0$. Then $\mathbf{p}^* = \mathbf{p}_\perp + (\omega_k/m_\phi)\mathbf{p}_\parallel + (E/m_\phi)\mathbf{k}$. Because of the two-body kinematics, $|\mathbf{p}|$ is uniquely determined, so that $|\mathbf{p}^*|$ will be unique if $\mathbf{k} \simeq 0$ since then $\mathbf{p}^* \simeq \mathbf{p}$. This is the standard scenario that we have been considering so far. But if $|\mathbf{k}|$ is fixed dynamically, as in the present situation (at least it is restricted to certain well-separated discrete values), then if $\mathbf{p} \simeq 0$, $|\mathbf{p}^*| \simeq (m/m_\phi)|\mathbf{k}|$ will also be uniquely determined. Of course, for $\mathbf{p} \simeq 0$ we require that $m_\phi \simeq 2m = 1.022$ MeV, i.e., this possibility predicts quite a different mass for the ϕ than in the previous case.

The advantage of this scenario is that instead of $|\mathbf{k}| \simeq 0$ we have $|\mathbf{k}| \simeq 1.35$ MeV, and we thus avoid the kinematical suppression at $|\mathbf{k}| = 0$. The effect of this can be seen if we recompute β for this case; we find $\beta = 1.3 \times 10^{-6} g^2 T$ MeV^3, an improvement of 10^8 over the previous scenario. We still get a suppression however, because $kR \simeq \frac{1}{20}$ even for $k \simeq 1.35$ MeV. Thus β is smaller than it was for the case of rectilinear motion. Indeed, if we take $T = 100$ MeV^{-1}, and if we demand $\beta \simeq 10^{-5}$ as before, we find that $g \simeq 0.3$ MeV^{-1}, i.e., about a factor of 10^3 bigger than for the "Coulomb" case. This magnitude for g would be more consistent with a pure QED origin for the ϕ (since the mass scale is then the electron mass) than with anything pertaining to the weak-interaction mass scale or even higher mass scales.

In this paper we have employed a crude model in which the ions are treated as classical external sources traveling on trajectories specified by a vector $\mathbf{r}(t)$. We have examined two possible choices for $\mathbf{r}$, and we have assumed a particular form for the coupling of the ϕ particle to the ions, namely, through the pseudoscalar density $j_{\mathrm{ext}} = g\mathbf{E}\cdot\mathbf{B}$. Clearly many variations of the model are possible in which different forms for $\mathbf{r}$ and different types of j_{ext} are chosen. The advantage of this type of model is that everything is completely calculable, and, despite its crudity, a lot of physics can be built in through the choice of $\mathbf{r}$ and j_{ext}.

In summary, then, our model gives the following results: (i) For both resonant and nonresonant production, the required value of the coupling constant g is much larger than would be expected if it had its origins in weak-interaction physics; (ii) the nonresonant production completely fails to reproduce the sharp peak; and (iii) there are two scenarios for resonant production—(a) ϕ is produced nearly at rest in the c.m. frame with a mass of 1.7 MeV or (b) ϕ is produced with momentum $k = 1.35$ MeV in the c.m. frame and m_ϕ just above the $2m_e$ threshold. Case (a) gives rise to back-to-back e^+e^- pairs but is suppressed because $k \sim 0$; case (b) gives rise to nearly collinear e^+e^- pairs (which may be in conflict with recent data[5]) but has somewhat enhanced production as a result of the larger value of k.

If the explanation (b) above withstands subsequent experimental investigations it naturally raises the question of why the ϕ mass should turn out to be so close to $2m_e$. One possibility is that it is simply an accident. Another is that the ϕ, far from being a new particle, is really a state of positronium that is somehow ionized by the strong electric fields present in the neighborhood of the two ions.

The case of $E^2 - B^2$ production will be treated in a future publication[6]; also, $\mathbf{E}\cdot\mathbf{B}$ production will be redone with charge distributions that are more realistic than the point charges considered in the present paper. We shall find that while the results do change somewhat (in particular, $E^2 - B^2$ gives enhanced ϕ production predominantly in the scattering plane), the overall orders of magnitude show that our results are stable under reasonable changes of input, thereby bolstering the credibility of our conclusions.

F. Gürsey pointed out to us the possible relevance of the work of Wheeler,[7] which discusses the binding of e^+e^-, $e^+e^-e^+$, and $e^+e^-e^+e^-$. The kinematics of the decay $X = e^+e^-e^+e^-$ to e^+e^- indicate that the kinetic energy of e^+ in the c.m. frame of X is 500 keV. Recently Wong[8] has considered the decay $Y = e^+e^-e^+$ to $\gamma + e^+$. Kinematics indicate that the e^+ kinetic energy is 340 keV, consistent with the observed value in the experiment. If this scenario is correct an e^- will not be observed in coincidence with the e^+.

We thank J. S. Greenberg for his patience in explaining the details of his experiment and for numerous and valuable conversations, F. Gürsey for pointing out the possible relevance of the work of Wheeler and for illuminating discussions, and T. Appelquist, M. Bowick, and L. Krauss for useful conversations. This work is supported in part by funds provided by the U.S. Department of Energy under Contract No. DE-AC-02-ER0 3075.

[1]J. Scheweppe *et al.*, Phys. Rev. Lett. **51**, 2261 (1983); M. Clemente *et al.*, Phys. Lett. **137B**, 41 (1984).

[2]T. Cowan *et al.*, Phys. Rev. Lett. **54**, 1761 (1985).

[3]A. B. Balantekin, C. Bottcher, M. R. Strayer, and S. J. Lee, Phys. Rev. Lett. **55**, 461 (1985).

[4]A. Schäfer, J. Reinhardt, B. Müller, W. Greiner, and G. Soff, J. Phys. **11**, 169 (1985).

[5]T. Cowan *et al.*, to be published.

[6]D. Carrier, Alan Chodos, and L. C. R. Wijewardhana, Yale University Report No. 33, 1985 (to be published).

[7]J. A. Wheeler, Ann. N.Y. Acad. Sci. **48**, 219 (1946).

[8]C. Y. Wong, to be published.