Search for Long-Lived Neutral Resonances in Bhabha Scattering around 1.8 MeV/c^2

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(Received 5 February 1990)

A search has been carried out for long-lived neutral particles which could be created in resonant e^+e^- scattering, with an invariant mass around 1.8 MeV/c^2. A monoenergetic positron beam was scattered from a thin Be foil, and an active-shadow technique was used to suppress elastic e^+e^- scattering. No evidence was found for neutral particles decaying dominantly into e^+e^- pairs, in the lifetime region between 4.5×10^{-13} and 7.5×10^{-12} s (95% C.L.). This result, together with our previous work, eliminates recent theoretical models that have introduced new neutral particles in this mass region.

PACS numbers: 13.10.+q, 12.20.Fv, 14.80.Pb

The appearance of narrow e^+ lines and correlated e^+e^- sum lines, emitted in heavy-ion collisions,[1] is a well-established experimental fact, and has been verified by two independent groups at GSI. A possible interpretation of this phenomenon is the existence of a new particle, which was initially thought to be an axionlike neutral boson.[2] This conjecture has prompted a series of independent searches for the particle, all with negative outcome.[2] However, the hypothetical particle might have a rather complex internal structure with a finite size, as indicated by the occurrence of multiple e^+ lines[3] and e^+e^- sum lines.[1] It has been pointed out that this requirement may invalidate the constraints which were calculated assuming a pointlike elementary particle.[2] Consequently, the possible existence of an extended neutral system, with a mass between 1.5 and 2.0 MeV/c^2, has been discussed by a large number of authors.[4] Recently, a "composite-particle" scenario, which involves a completely new branch of particle physics, has been put forward by Graf *et al.*[5] Alternatively, Arbuzov *et al.*[6] have predicted a series of bound states for e^+e^- and e^-e^- systems based on an approach within conventional QED.

The study of e^+e^- scattering (Bhabha scattering) provides a model-independent method to search for any neutral particle that has an e^+e^- decay branch.[4] By measuring the excitation function, the particle would reveal itself as a resonancelike enhancement of the elastic cross section, on the top of the Bhabha-scattering continuum, when the c.m. energy becomes equal to its invariant mass. From investigations of elastic e^+e^- scattering at the high-flux reactor of the Institut Laue-Langevin (ILL), the lower limit of 3.5×10^{-13} s has been established for the particle lifetime,[7,8] which is still away from the upper bound of 10^{-10} s set by the heavy-ion experiments.[3] It is therefore of general interest to continue the search for the hypothetical particle, especially as none of the recent experiments covered the lifetime region from 3.5×10^{-13} to 10^{-10} s. However, such lifetimes cannot be studied by measuring conventional Bhabha scattering as utilized in our previous setup.[7] In this paper we present the first results of a follow-up experiment which improved the sensitivity for long-lived particles by employing an active-shadow technique.

As in the previous experiments,[7,8] a beam of monoenergetic positrons was produced using the ILL β spectrometer (BILL). The positron production target consisted of a $3.3\times50\times130$-mm^3 titanium plate covered by two platinum foils (each $0.25\times50\times50$ mm^3). A positron-beam intensity of 3×10^6 s^{-1} was measured at the focal plane of the spectrometer, which covers a range of $\sim$30 keV at a beam energy of 2.0 MeV; this is double the intensity achieved previously. The positron current was stable to within a few parts in a thousand. The beam of positrons was focused onto a 4.6-mg/cm^2-thick Be foil (20×100 mm^2), which was suspended along the focal plane of the spectrometer at an angle of 30° relative to the positron beam (Fig. 1). Two arrays of four high-resolution (<7 keV) Si(Li) detectors were positioned to detect electron-positron pairs from the decay of the hypothetical particle. As the particle would be produced with a velocity of $\sim0.8c$, it would leave the Be foil within 5×10^{-14} s, and so, for the lifetimes of interest, the particle would decay outside of the foil. The high background due to e^+e^- pairs from Bhabha scattering within the Be foil could therefore be eliminated by interposing a plastic scintillator between the foil and one of the detector arrays. In this way, only e^+e^- pairs which originated outside of the foil could reach both detector rows. Care was taken to ensure that the Be foil, the edge of the plastic scintillator, and the inner side of the detector aperture lay on the same line. It was estimated that the foil could be positioned to within 0.1 mm of the ideal position. The effect of multiple scattering in the foil is rather small ($\bar{\theta}\leq3°$), and does not play any role searching for a deviation in the excitation function. The single spectra obtained from the shielded detector row show a smooth background (see below), whereas those from the opposite row are dominated by the Mott-scattering peak

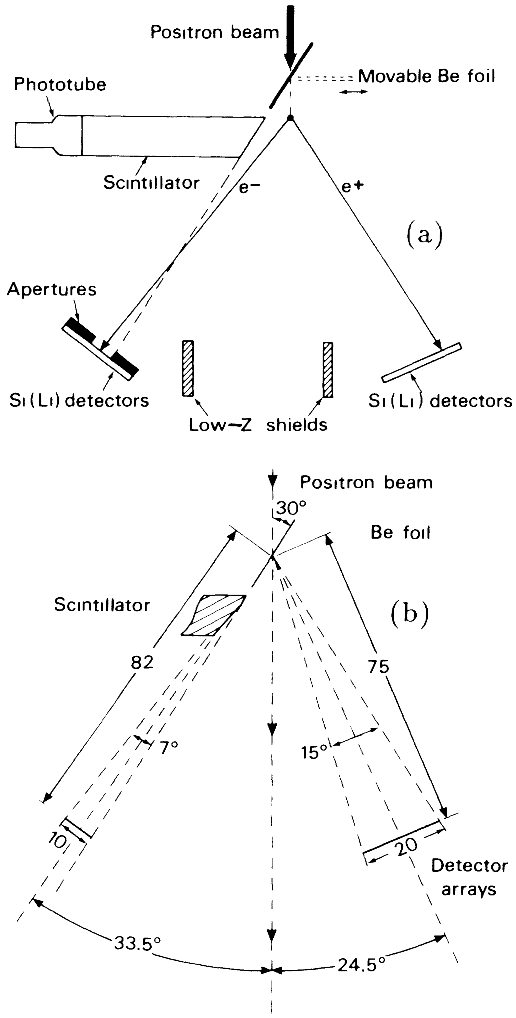

FIG. 1. Schematic diagram of the detection system for electron-positron pairs emitted in the decay of long-lived neutral particles. The monoenergetic positron beam was scattered from a 4.6-mg/cm^2-thick Be foil, mounted at an angle of 30° relative to the beam direction. Coincident e^+e^- pairs, emitted outside of the foil, were detected by two arrays of four 2-mm-thick Si(Li) detectors. Bhabha-scattering events from within the foil itself were excluded by shielding one detector array, by means of a plastic scintillator [(a)]. The dimensions of the system are shown in (b).

(see Ref. 7).

The excitation function was obtained from four independent runs during one reactor cycle. For each run, the spectrometer field was scanned automatically from 2.08 to 2.4 MeV in constant steps of 5 keV, with a measuring time of about 45 min per step. At the beginning and end of each run, the energy calibration of the Si(Li) detectors was checked by measuring Bhabha and Mott scattering from a second Be foil, which could be moved in to a position perpendicular to the positron beam to a position behind the inclined scattering foil.

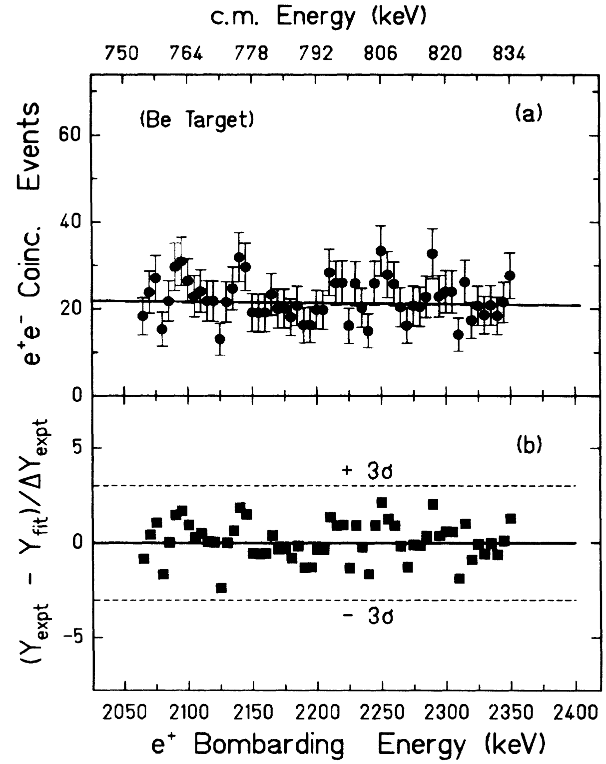

FIG. 2. Number of coincident events observed in the total count time of 10800 s as a function of the incident energy (lower scale) and the c.m. excitation energy (upper scale). The solid line is the result of a least-squares fit of a straight line to the data [(a)]. The standard deviations from the fitted curve are displayed in (b).

The data were analyzed in a similar manner to that described in Ref. 7. At each setting of the spectrometer field, a sum spectrum was formed of the events detected in coincidence that were also in anticoincidence with a signal of the scintillator. The number of counts in a narrow window in which e^+e^- resonance decays should occur was then calculated for each energy step. The position and width of the window was chosen from the calibration runs with the movable Be foil. The result is displayed in Fig. 2(a) as a function of the energy of the incident positrons. The continuum observed is mainly due to Bhabha-scattering events in the foil, or in the scintillator itself, which deposited less than 60 keV (lower threshold) in the scintillator and hence were hidden in the electronic noise. The e^+e^- decay of a long-lived particle would appear as a peak superimposed on this continuum, with a FWHM of ~28 keV which is governed by the momentum distribution of the electrons in the solid target.[7] (Note that the intrinsic width of the hypothetical resonance is much narrower.) However, no peak was observed and the data can be fitted by a straight line [Fig. 2(a), solid line], yielding a χ^2/(degrees of freedom) of 58/56. Figure 2(b) shows the standard deviations from the fitted curve, lying within $\pm 3\sigma$.

Using the procedure described in Ref. 7, the maximum peak height for a possible resonant contribution was determined to be $\leq 25\%$ (95% C.L.) relative to the fitted curve; i.e., ~ 5 counts at 810-keV c.m. energy. From this, a limit can be estimated for the energy-integrated total cross section for the formation of the particle (assuming isotropic decay) as follows:[7]

$$(\sigma \Delta E^*)_{\text{expt}} \leq 4\pi \left(\frac{d\sigma_B}{d\Omega^*} \right)_{\text{eff}} \Delta E^*_{\text{expt}} \delta \,, \quad (1)$$

where $(d\sigma_B/d\Omega^*)_{\text{eff}} \simeq 18.5$ mb/sr is the effective Bhabha cross section at 810-keV c.m. energy,[7] $\Delta E^*_{\text{expt}} = 7.8$ keV is the experimental FWHM in the c.m. system, and $\delta = (N_p/N_B)/\epsilon(\tau^*)$. (An asterisk refers in this work to quantities in the c.m. system.) Here $N_p \simeq 5$ counts is the limit on the number of particle decays, N_B is the number of Bhabha events that could be detected with the shield (scintillator) removed, and $\epsilon(\tau^*)$ denotes the lifetime-dependent detection efficiency for e^+e^- pairs from the particle decay relative to the detection efficiency for Bhabha-scattering events with the shield removed.

Hence, an estimate of δ can be obtained from the observed rate in the Mott peaks detected in the unshielded detector row, and the Bhabha-to-Mott ratio determined previously.[7] At 810-keV c.m. energy, 3.3×10^5 Mott events were detected in the total count time of 10800 s; this corresponds to a total of $N_B \simeq 5.4 \times 10^4$ Bhabha events (after a correction has been applied for the different mean scattering angles and aperture sizes compared to the previous experiment). The relative detection efficiency ϵ was calculated by means of a numerical model, taking into account the effects of possible misalignments of the foil and the detectors, and also relativistic time dilation. The calculation assumes that, if the decay occurs near to the foil, the detection efficiency is given by the solid angle subtended by the shielded detector from the position of the decay. The results of the calculation are shown in Fig. 3. For decays further from the foil, kinematic effects become important and the efficiency decreases, as indicated by the dotted line.

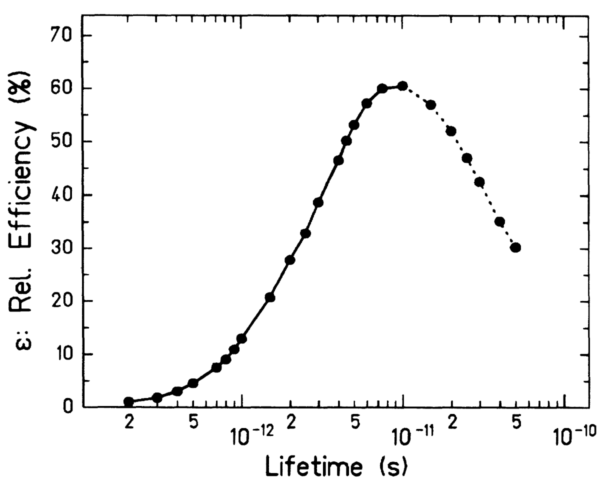

FIG. 3. The calculated relative detection efficiency for the decay of a long-lived particle as a function of its lifetime. The lines through the calculated points are to guide the eye. Typical uncertainties of the calculation lie between 20% and 30% for $\tau^* \leq 10^{-12}$ s and about 10% for $\tau^* > 10^{-12}$ s.

Figure 4 shows the result (circles) of the calculated limit (95% C.L.) for the energy-integrated total cross section [Eq. (1)] of the hypothetical particle as a function of its lifetime. Also shown is the result (triangles) from a less sensitive measurement of van Klinken *et al.*[9] For a resonance having a Breit-Wigner distribution, the energy-integrated cross section is related to the intrinsic resonance with Γ_R^* ($\simeq \hbar/\tau^*$) by the expression[7,10]

$$(\sigma \Delta E^*)_{\text{expt}} = \frac{2\pi^2 (2J+1)\hbar^2}{M_R^2 - 4m_0^2} \left(\frac{\Gamma^*_{e^+e^-}}{\Gamma^*_R} \right)^2 \Gamma^*_R \,, \quad (2)$$

where $\Gamma^*_{e^+e^-}$ denotes the partial e^+e^- decay width. The solid line in Fig. 4 shows the expected total cross section of a spinless ($J=0$) resonance with an invariant mass of $M_R = 1.832$ MeV/c^2 in the unitarity limit, assuming that no competing decay channel exists (i.e., $\Gamma^*_{e^+e^-} = \Gamma^*_R$). This limit gives the minimum sensitivity which must be achieved experimentally in order to be able to exclude a hypothetical resonance at a given lifetime.[10] As can be seen, the limit on the cross section for the formation of the particle lies below the unitarity limit for a lifetime between 4.5×10^{-13} and 7.5×10^{-12} s. Comparable limits can also be set within the whole mass range investi-

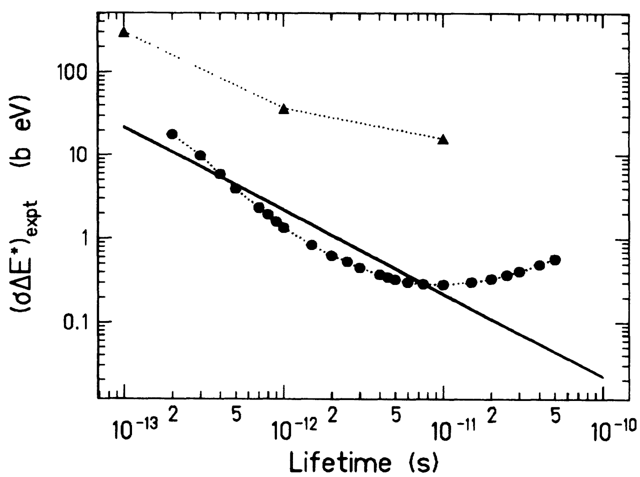

FIG. 4. The upper limits (95% C.L.) for the energy-integrated total cross section for the formation of a neutral particle with an invariant mass of 1.832 MeV/c^2, as a function of the lifetime of the particle (circles). The solid line shows the model-independent total cross section of a spinless ($J=0$) resonance at 1.832 MeV/c^2 in the unitarity limit. Also shown is the result (triangles) from a less sensitive measurement of van Klinken *et al.* (Ref. 9). The dotted lines through the data points are to guide the eye.

gated (1.776–1.856 MeV/c^2).

We emphasize that these limits might be too stringent for two reasons. If the particle could decay by another channel, for example, by the emission of two photons (with a partial width of $\Gamma^*_{2\gamma}$), the limit would be less sensitive to the square of the branching ratio $\Gamma^*_{e^+e^-}/(\Gamma^*_{e^+e^-}+\Gamma^*_{2\gamma})$ [Eq. (2)]. However, no evidence has yet been found for other decay modes; the $2\gamma/e^+e^-$ branching ratio has been determined to be $\leq 3\times 10^{-3}$ from recent investigations in heavy-ion collisions.[11] Second, if the hypothetical particle is rather large (a radius of $\sim$1000 fm has been suggested[5,6]), it could be destroyed before leaving the target because of electromagnetic polarization effects. Assuming no pronounced dependence on the particle velocity, the cross section of this process is expected to be proportional to dZ^2/A, where d is the mass per unit area of the target and Z and A are its atomic number and atomic weight, respectively. The magnitude of this effect in the Be target used in this experiment is therefore comparable to that in the $\sim$0.4-$\mathrm{mg/cm^2}$-thick uranium targets, as employed in heavy-ion experiments. Nevertheless, polarization effects could be more important for experiments that use significantly thicker targets.[9,12]

To summarize, this experiment achieved for the first time the sensitivity to detect possible long-lived ($\tau^* > 3.5\times 10^{-13}$ s) resonances formed in e^+e^- scattering around the invariant mass of 1.8 MeV/c^2. For lifetimes shorter than 7.5×10^{-12} s (95% C.L.), our results rule out the existence of a neutral particle ($J=0$), as recently proposed,[5,6] leaving open only a small lifetime window from 7.5×10^{-12} to 10^{-10} s for such a hypothesis. The new limit of $\tau^* > 7.5\times 10^{-12}$ s ($\Gamma^*_{e^+e^-} < 8.8\times 10^{-5}$ eV) is an improvement on that derived from the $g-2$ factor of the electron[10] by approximately 2 orders of magnitude, and can be considered to be a new experimental constraint for the validity of perturbative QED in this mass region.

It is a pleasure to thank F. Dropmann, T. Manning, J. Oddon, and D. Robinson for their technical help as well as P. Ledebt for assistance with the data-acquisition system. For fruitful discussions we are indebted to P. Armbruster, F. Bosch, W. Koenig, C. Kozhuharov, and G. Soff as well as to our colleagues from the Frankfurt theory group (W. Greiner).

[1]The most recent results, obtained by both the EPOS and the Orange Collaboration, are summarized in *Tests of Fundamental Laws in Physics,* edited by O. Fackler and J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1989); P. Kienle, *ibid.*, p. 63; H. Bokemeyer *et al.*, *ibid.*, p. 77; see also W. Koenig *et al.*, Phys. Lett. B **218**, 12 (1989); and references listed in H. Tsertos, C. Kozhuharov, P. Armbruster, P. Kienle, B. Krusche, and K. Schreckenbach, Phys. Rev. D **40**, 1397 (1989).

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