Search for Resonances in the $e^+e^- \rightarrow \gamma\gamma$ Process in the Mass Region around 1.062 MeV/c^2

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We have searched for narrow resonance peaks in the process $e^+e^- \rightarrow \gamma\gamma$, utilizing a ^{22}Na β^+ source and a pair of Ge detectors to detect the final two γ's. No statistically significant peak is observed at the center-of-mass energy of 1062 keV, where the heavy-ion-collision experiment at LBL has seen a peak. The upper limit to the quantity $\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma$ is 1.1×10^{-4} eV at the 95% confidence level for a scalar or pseudoscalar resonance at 1062 keV/c^2. Similar upper limits are obtained in the mass region between 1045 and 1085 keV/c^2.

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Recent experiments[1] at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany, have detected a series of narrow correlated peaks in the spectrum of electron and positron emitted from heavy-ion collisions near the Coulomb barrier. Among many theoretical explanations,[2] one of the possibilities is that these peaks are due to the production and subsequent decay of neutral particles with masses of 1498, 1646, 1782, and 1837 keV/c^2. For this reason, there have been searches for the peaks in Bhabha scattering in the mass region between 1300 and 2000 keV/c^2.[3]

Recently a narrow peak at 1062 keV was observed in the correlated two-photon spectrum from U+Th collisions.[4] In this paper, we report on the search for narrow structure in the process $e^+e^- \rightarrow \gamma\gamma$ in the mass region between 1045 and 1085 keV/c^2.

The experimental setup is schematically shown in Fig. 1(a). Positrons, emitted from a ^{22}Na source of 10 mCi, impinged on a polyethylene target of thickness 3 mm. A fraction of the positrons annihilate in flight with atomic electrons before stopping. The two photons emerging from such an annihilation come out as an acollinear pair, and are detected by two Ge detectors. The positron energy (E_+) and direction at the instance of the collision are not fixed due to the continuous spectrum of the β^+ decay and energy loss, as well as multiple scattering in the target. However, the sum of the energies of the two photons (k_1+k_2) is uniquely related to E_+ and to the total center-of-mass energy (W). Therefore, a narrow resonance in the process $e^+e^- \rightarrow \gamma\gamma$, if it exists, can be detected as a sharp peak in the k_1+k_2 spectrum. To cover a broad energy region, data are taken at three setups. Opening angles of the detectors and distances from the target to the detector surfaces are 150° and 15 cm, 153° and 17 cm, and 160° and 25 cm for setups 1, 2, and 3, respectively.

The two pure-Ge detectors have dimensions 60 mm in diameter and 70 mm in length (ORTEC GEM-38195). Preamplifiers of the Ge detectors are furnished with transistor reset circuits to cope with the high-singles-rate environment for this experiment. Typical singles rate of the Ge detectors are between 20 and 50 kHz depending on the setup. One of the two outputs from each preamplifier is amplified by a shaping amplifier. The gated integrator output of the shaping amplifier is sent to a CAMAC peak-sensitive analog-to-digital converter. The unipolar outputs from the two shaping amplifiers are linearly summed and then are discriminated to provide a fast total-energy trigger. The other preamplifier output is utilized for the coincidence and timing measurement. For this purpose, the output is first amplified by a timing-filter amplifier with integration time of 10 nsec and differentiation time of 50 nsec. The signal is then discriminated by a constant fraction discriminator with slow-rise-time rejection. An event trigger is issued if the discriminator outputs from the two Ge detectors are coincident within 150 nsec and the energy sum of the two Ge detectors exceeds 950 keV. The latter requirement is switched off for 1% of the time to obtain a sample of data below the energy sum threshold for checking purposes. The timing information (t_1,t_2) and the analog-to-digital converter values of the two Ge detectors are then recorded event by event on magnetic tape.

The energy calibrations are performed periodically by placing additional weak ^{137}Cs and ^{22}Na sources behind the target. The γ-ray lines at 511, 662, and 1274 keV from these sources give an energy calibration of the detectors in the actual environment of data taking. The positions of the peaks were stable within 1 keV throughout the experiment. The energy resolutions of the Ge detectors were 2.9 and 3.2 keV FWHM at the energies of 662 and 1274 keV, respectively.

Figure 1(b) shows a typical scatter plot, k_2 vs k_1, for the data taken with setup 2. A clear band structure coming from the annihilation in flight $e^+e^- \rightarrow \gamma\gamma$ is visible in this figure. Events from this process would fall on a unique curve $1/k_1+1/k_2=(1-\cos\theta_\gamma)/m_e$ in the scatter plot if the opening angle θ_γ between the two photons were fixed. The finite width of the band seen in Fig. 1(b) reflects the finite angular acceptance of the experi-

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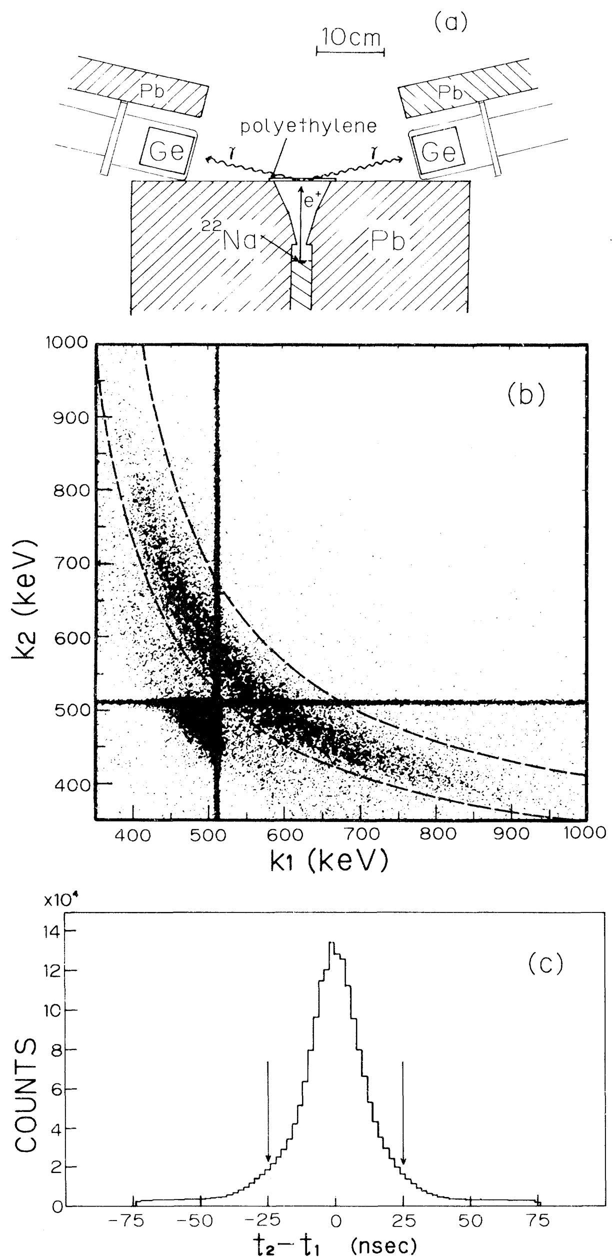

FIG. 1. (a) Experimental setup. Polyethylene target is irradiated by positrons from a ^{22}Na source. An acollinear pair of photons, originating from annihilation in flight, are detected by two Ge detectors. (b) Typical scatter plot of two photon energies, k_1 vs k_2, taken at setup 2. Events between the two dashed lines, except for the ones along the lines k_1 or $k_2=511$ keV, are used for further analysis. (c) Typical (setup 2) timing spectrum t_2-t_1 of the two photons. Events between the two arrows are accepted.

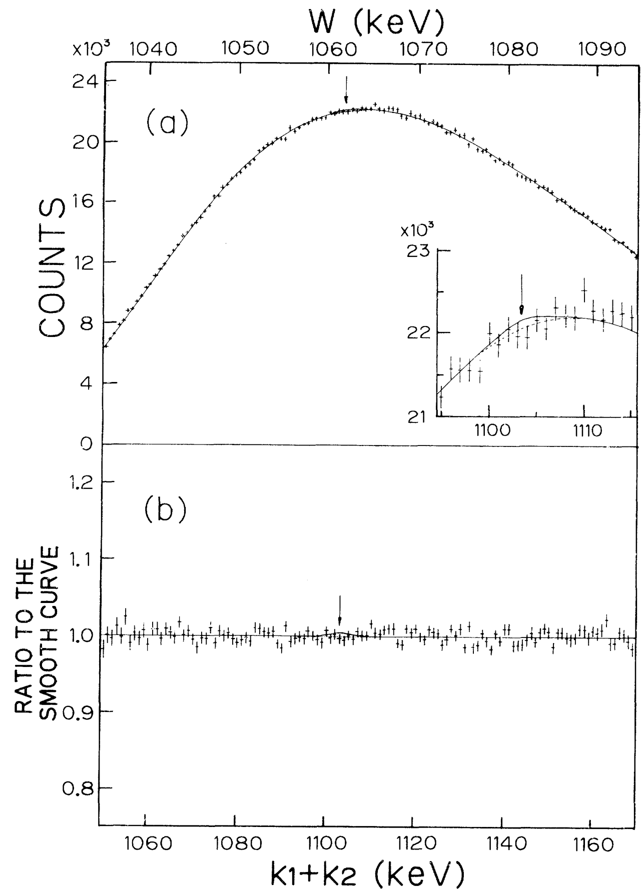

FIG. 2. (a) Summed photon energy spectrum k_1+k_2. Events from the three setups are added. The corresponding center-of-mass energy W is also shown as the top scale. The smooth curve shows the polynomial fitting to the data. Inset: A magnified view around $W=1062$ keV. The arrows indicate the position of the 1062-keV peak observed by LBL experiment. (b) Ratio of the data to the smooth curve. Resonance curve at $W=1062$ keV corresponds to the upper limit at the 95% confidence level.

ment. Narrow vertical and horizontal lines at k_1 or $k_2=511$ keV are due to the random coincidences of the overwhelming number of γ rays from the annihilation at rest. It should be noted that the lower edge of the band is clearly separated from the peak at $k_1=k_2=511$ keV which is due to random coincidences. To minimize backgrounds, we accept only the events between the two dashed lines shown in Fig. 1(b). Also, the events along the lines k_1 or $k_2=511$ keV are not used.

Figure 1(c) shows a typical timing curve (t_2-t_1) of the accepted events. A clear peak at $t_2-t_1=0$ demonstrates a small randomly coincident background in the sample. Events within $|t_2-t_1|<25$ nsec are accepted for further analysis. The number of events accepted from setups 1, 2, and 3 are 9.4×10^5, 3.0×10^5, and 1.6×10^6, respectively, from the total running time of 1673 h.

The events from the three setups are simply added.[5] The resulting k_1+k_2 spectrum is shown in Fig. 2(a). Backgrounds in this spectrum originate from (1) the randomly coincident 511- or 1274-keV γ rays, or (2) the Compton tails of $e^+e^- \rightarrow \gamma\gamma$ itself. We estimate that these backgrounds contribute at most 10%, based on the timing spectra and on the density profile in the (k_1,k_2) scatter plot. Therefore the spectrum is dominated by the ordinary QED process $e^+e^- \rightarrow \gamma\gamma$.

We search for narrow peak structures in the k_1+k_2 spectrum by checking if the data are consistent with an overall smooth curve plus a sharp peak. The smooth curve should reflect the acceptance of the experiment, and can be simulated in principle by a Monte Carlo method by taking into account the energy losses and the multiple scatterings of the β^+, the geometry, and the responses of the Ge detectors. However, an accurate reproduction of the exact acceptance is rather difficult. In this Letter, we follow a phenomenological procedure by fitting the data with a polynomial function. A polynomial of the fifth order turns out to be sufficient since the inclusion of higher orders up to 8 does not significantly change the final result. The data between $k_1+k_2=1050$ and 1170 keV were used in the fitting except for the region $\pm\Delta k$ of the assumed peak, where Δk is the expected FWHM energy spread. Then a resonance at the assumed position was added. By varying the strength of the resonance, the best fit to the data was searched for. We scanned the region between $k_1+k_2=1068$ and 1152 keV by moving the resonance position in steps of 2 keV.

The resonance shape was assumed to be Gaussian with a FWHM of Δk. The expected energy spread Δk of the peak is mainly determined by two factors, i.e., the motion of the target electrons and the resolutions of the Ge detectors. In the polyethylene used in this experiment, 75% of the target electrons are in C—H or C—C bonds. The momentum distribution of these bond electrons has been measured by the Compton profiles[6] and by the study of the 511-keV annihilation γ rays.[7] This contributes to the expected energy spread in the k_1+k_2 spectrum between 2.2 and 3.8 keV (FWHM) in the energy region of this experiment. The remaining 25% of the target electrons are core electrons, strongly bound to C. These core electrons result in too large an energy spread. In this search, we rely only on the bond electrons and correct for the inefficiency at a later stage. This energy spread due to the motion of the target electrons must be further folded with the energy resolution of the Ge detectors, resulting in a total energy spread Δk between 4.6 and 5.6 keV in the energy region of this experiment.

No statistically significant peaks were found in the region between $k_1+k_2=1068$ and 1152 keV. A typical fitting curve is shown in Fig. 2(a) for a specific resonance position at $W=1062$ keV. The small resonance in this figure, barely visible on top of the smooth curve, corresponds to the 95%-confidence-level upper limit obtained at this position. As seen in Fig. 2(b), the upper limits to the strength of the resonance were calculated as ratios to the smooth curve, which is dominated by the QED process. One can then obtain the upper limits of the resonance cross section relative to the QED process. This procedure is especially simple for the scalar or pseudoscalar resonances, since the angular distribution of the photons from the QED process at this low energy is almost isotropic in the center-of-mass system, and is very similar to that from the scalar or pseudoscalar resonances.[8] The QED cross section was calculated with the formulas (6) and (10) of Ref. 9.

This upper limit of the resonance cross section can be converted to a limit of the resonance parameter $A=\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma$ by using the Breit-Wigner formula of the integrated resonance cross section,

$$\int \sigma_{\text{res}}(W)dW = \frac{2\pi^2 A}{M_\phi^2\{1-(2m_e/M_\phi)^2\}},$$

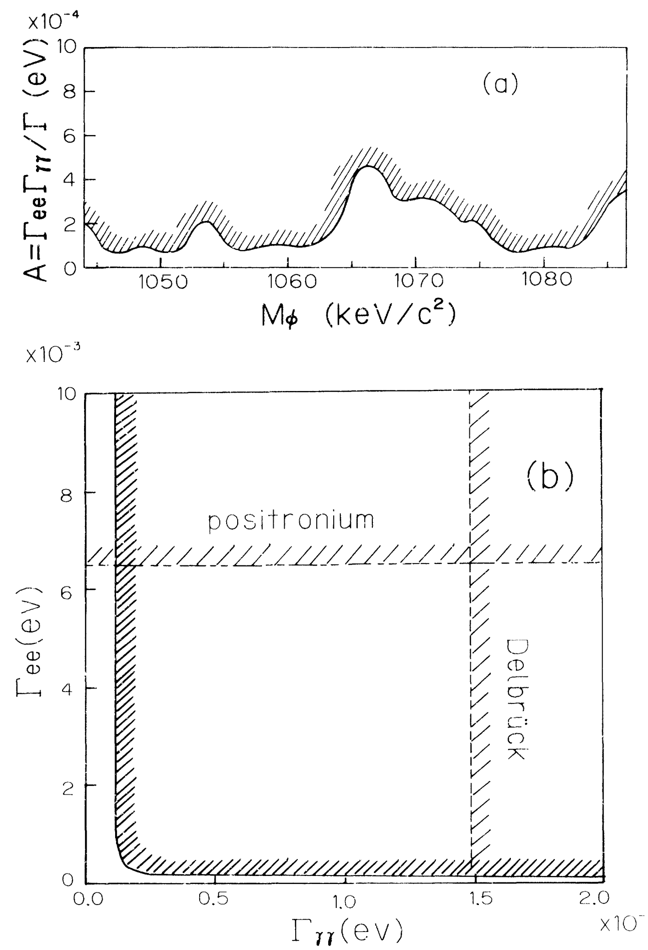

FIG. 3. (a) The upper limits at 95% confidence level to the resonance parameter $A=\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma$ as a function of the resonance mass. These limits apply to the scalar or pseudoscalar resonance. (b) The region excluded by this experiment in the plane of Γ_{ee} vs $\Gamma_{\gamma\gamma}$ for a pseudoscalar resonance at 1062 keV/c^2. Regions excluded by Delbrück-scattering and positronium-hyperfine-splitting measurements are also shown.

where M_ϕ, Γ, Γ_{ee}, and $\Gamma_{\gamma\gamma}$ are mass, total decay width, partial decay width into e^+e^-, and partial width into $\gamma\gamma$ of the resonance, respectively. To obtain the final upper limit of A, the value thus obtained was multiplied by the factor 1.1 to account for the background in the k_1+k_2 spectrum, and then divided by 0.75 to correct for the inefficiency due to the core target electrons. Figure 3(a) shows the 95%-confidence-level upper limits of A for scalar or pseudoscalar resonance as a function of the mass.

In Fig. 3(b), we compare the present limits with those of existing experiments for a specific case of pseudoscalar resonance at 1062 keV/c^2. Shown in this figure is the region in the Γ_{ee} vs $\Gamma_{\gamma\gamma}$ plane excluded by the present experiment, assuming that the resonance decays only into e^+e^- and $\gamma\gamma$ ($\Gamma=\Gamma_{ee}+\Gamma_{\gamma\gamma}$), together with the existing limits obtained from the measurements of positronium hyperfine splitting and Delbrück scattering.[10]

It should be noted that our experiment is sensitive in principle to the resonances of any spin, while the limit from the positronium hyperfine splitting applies only to the case of the pseudoscalar resonance. Electron $g-2$ measurements provide a stringent limit to $\Gamma_{ee}\Gamma_{\gamma\gamma}$,[11] which is, however, obtained under the assumption that there exists no cancellation[10] among the contributions of several resonances of different spin and parity.

In summary, we have found no statistically significant peak in the process $e^+e^- \rightarrow \gamma\gamma$ at the center-of-mass energy of 1062 keV, where the heavy-ion-collision experiment at LBL has seen a peak. The upper limit to the quantity $A=\Gamma_{ee}\Gamma_{\gamma\gamma}/\Gamma$ is 1.1×10^{-4} eV at the 95% confidence level for the scalar or pseudoscalar resonance at 1062 keV/c^2. Similar upper limits are obtained in the mass region between 1045 and 1085 keV/c^2 [see Fig. 3(a)]. We are presently continuing our experiment to explore the higher mass region.[12]

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