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Reexamination of an Anomaly in near-threshold pair production

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We investigated a reported anomaly in near-threshold pair production, using radioactive sources to measure the $\gamma+\mathrm{Ge} \rightarrow e^{+}+e^{-}+\mathrm{Ge}$ cross-section at E_γ=1063, 1086, 1112, 1173, 1213, 1299, 1332, and 1408 keV. Although the data agree with the theory (numerical calculations based on an exact partial-wave formulation for a screened central potential) at the higher energies, the data lie above the theory at 1063, 1082, and 1112 keV. The discrepancy is reduced by including the final-state Coulomb interaction between the e^+ and e^-.

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A near-threshold discrepancy between the measured cross section for pair production by photons

$$\gamma+Z \rightarrow e^{+}+e^{-}+Z \tag{1}$$

and theoretical expectations [1–5] has been observed in several experiments [6–13]. The existing experimental results and the standard theory are summarized in Fig. 1. (Throughout this paper all cross sections are given in units of the plane-wave Bethe-Heitler cross section σ_{BH}.) There are at least three possible explanations for this discrepancy:

(1) The experiments could suffer from a common systematic error.

(2) The theoretical prediction could neglect some important effect.

(3) The resonancelike discrepancy could possibly indicate new physics, perhaps related to the unexplained e^+-e^- peaks observed in heavy-ion collisions [14, 15].

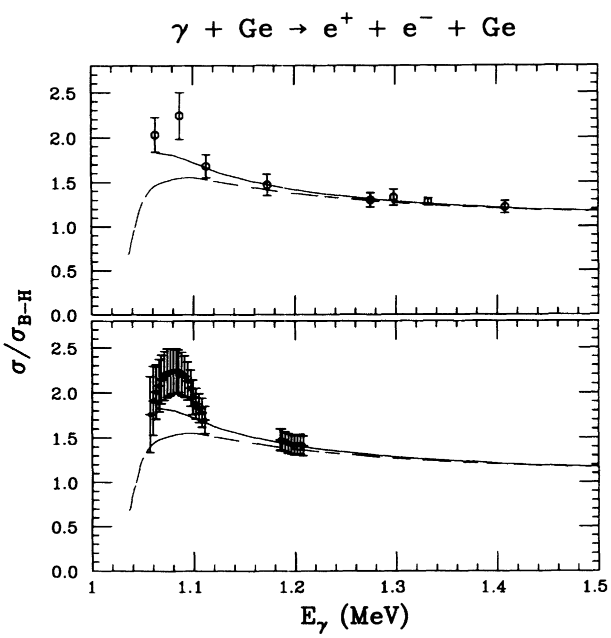

FIG. 1. Previous results for the near-threshold pair production in units of the Bethe-Heitler cross section. Top panel: points show results from line γ sources [7, 8]; bottom panel: points show results using continuous γ spectra obtained by Compton scattering [9, 10]. The curves are theoretical expectations: the solid line is the standard theory for a screened point nucleus; the dash-dotted line is for a bare point nucleus.

In this Rapid Communication we report an experimental and theoretical reexamination of this anomaly.

We investigated the γ + Ge $\rightarrow$ e^+ + e^- + Ge cross section with a classical pair spectrometer. Pair creation occurred in a Ge counter (either a 40-cm^3 coaxial or a 10-cm^3 planar device) surrounded by two 12.7 × 15.2-cm NaI counters that detected the 511-keV quanta from e^+ annihilation. Monoenergetic γ rays were provided by radioactive sources of ^{152}Eu (E_γ =1408, 1299, 1213, 1112, and 1086 keV), ^{60}Co (E_γ=1330 and 1170 keV), ^{88}Y (E_γ=1836 keV), and ^{207}Bi (E_γ =1770 and 1063 keV). Five-parameter (three energy and two timing signals) triple-coincidence events were recorded in an on-line computer for subsequent analysis. Sample Ge detector spectra gated on 511-keV photopeaks in both NaI detectors are shown in Fig. 2.

Due to phase-space considerations, the pair-production cross section falls very rapidly with decreasing photon energies. At E_γ =1086 keV our counting rate is only approximately equal to ten events per day so that a 5–10 % statistical error bar required a few weeks of acquisition time. Long-term drifts in the NaI detector gains could have constituted a serious problem. This difficulty was avoided by adopting the following procedures. The ratio of the pair-production cross sections at 1408 and 1836 keV was measured using a combined source of ^{152}Eu and ^{88}Y. (This was actually done by measuring the ratio of the double-escape to the full-energy peaks in a single spectrum, and using the relative full-energy peak efficiency deduced from the known [16] intensities of the ^{152}Eu lines.) Similarly, the ratio of the pair-production cross section at 1332 and 1836 keV was measured using combined sources of ^{60}Co and ^{88}Y. Finally, the pair-production cross section at 1173 keV was measured relative to that at 1332 keV with a ^{60}Co source and the cross sections at 1299, 1213, 1112, and 1086 keV were measured relative to that at 1408 keV with the Eu source. A simi-

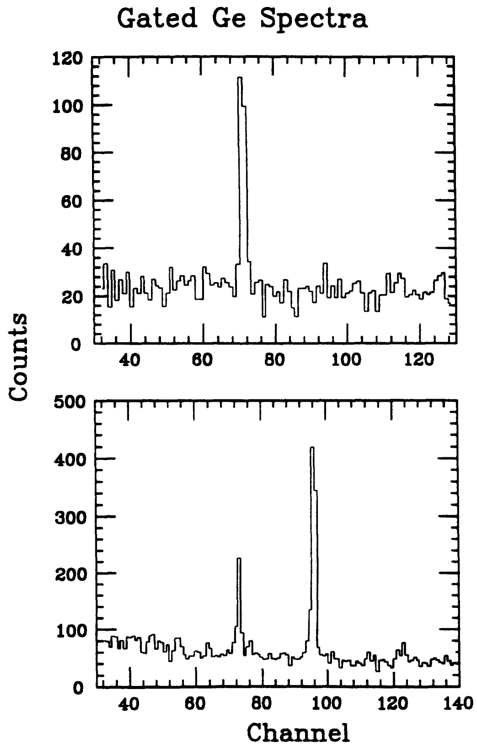

FIG. 2. Gated Ge detector spectra showing the double-escape peaks in the planar detector. Top panel: 1063-keV photons; bottom panel: 1086- and 1112-keV photons. The double-escape yields were obtained by integrating peak areas above the continuous background, which also effectively subtracted random coincidences. These spectra show the lowest energies investigated and therefore the worst signal-to-background ratio involved in this measurement.

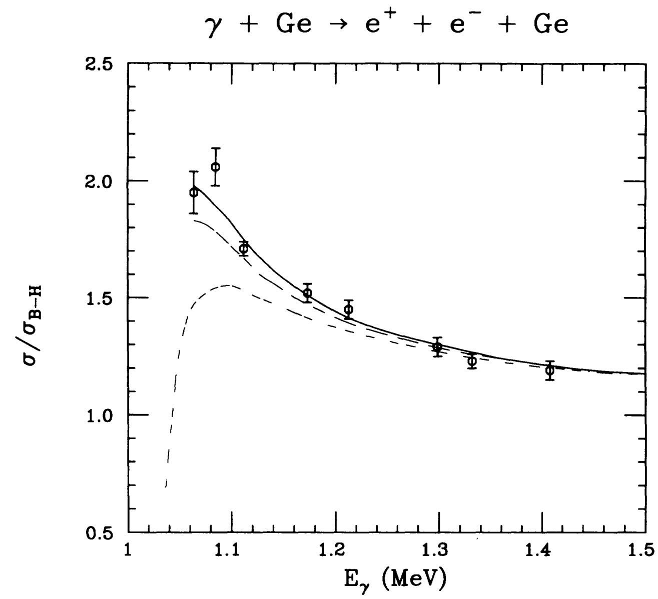

FIG. 3. Our results for the pair-production cross section in Ge in units of the Bethe-Heitler cross section. The error bars are relative, absolute cross sections were normalized to the prediction [4, 5] at 1836 keV. The solid curve shows our calculation including the e^+-e^- final-state interaction; the dashed and dash-dotted curves show the standard theory, which neglects this interaction, for a screened and bare point nucleus, respectively.

lar procedure was used for the 1063- and 1770-keV lines emitted by the ^{207}Bi source. Thus, any shifts in the gain of the NaI counters cancelled in the ratio measurements.

Our data were corrected for the following effects: (1) attenuation of the photon flux inside the counter, (2) multiple photon interactions inside the counter, and (3) escape of the leptons from the active volume of the detector.

The procedures for making the three corrections were similar to those described in Ref. [6]. The largest correction due to photon flux attenuation is only 2% because the attenuation is a rather small effect for the counters used and the total cross section does not vary drastically over the energy range we investigated. The probability that a photon interacts via Compton scattering and then produces a pair increases with both its energy and the counter thickness; we estimate that probability to be 3–4% for the highest energy (1836 keV) investigated with the coaxial counter. Finally, the escape of leptons from the active volume of the detector increases with photon energy and decreases with counter thickness. Since we measure only low-energy pair production cross sections, this effect is totally negligible for the coaxial detector and less than a percent for the planar counter, an upper limit which is easily verified by looking at the low-energy side of a double-escape peak.

Our results, which are displayed in Fig. 3, have error bars that are between two and four times smaller than those reported in previous works. We are consistent with the measurements of Coquette [7, 8], Avignone and Khalil [12], and En'yo, Numao, and Yamasaki [11], and would also agree with the work of Yamzaki and Hollander [6] if their results were renormalized downward by 18% to bring their measurement of the cross section at 1836 keV in agreement with the theoretical expectation [4, 5] for that energy. In fact, we checked that the absolute cross section at 1836 keV agrees with the theory [4, 5], e.g., $\sigma_{\rm expt}(1836\ {\rm keV})/\sigma_{\rm theor}(1836\ {\rm keV}) = 0.89 \pm 0.12$. Although our data do agree with the theory at the higher energies, they fall above the theory at 1063, 1112, and particularly at 1082 keV.

Because the discrepancy occurs near threshold, where the lepton kinetic energies are quite small (roughly 30 keV), it may be important to consider the e^+-e^- final-state Coulomb interaction. We estimate the effect of this final-state interaction using an expression derived by Sakharov [17] for pairs produced in a different kinematic regime (high photon energy but low relative velocity of the pair). This leads to a multiplicative correction factor

$$F = \frac{2\pi\alpha/v}{1 - \exp(-2\pi\alpha/v)} \tag{2}$$

(where v is the relative velocity of the leptons), which we integrate over the lepton kinematics at each photon energy, assuming the Bethe-Heitler [1] angular and energy distribution. The standard theory with this correction, shown as the solid line in Fig. 3, gives a reasonable account of our results. It should be pointed out that expression (2) could overestimate the final-state interaction because it ignores the perturbation of the lepton wave functions caused by their interaction with the nuclear charge. A more realistic description of this effect would be welcome and could possibly open the door for additional experimental investigation of both the total and differential cross sections.

In conclusion, we have confirmed a near-threshold enhancement of the pair-production cross section relative to the most sophisticated previous calculations. However, this discrepancy cannot be interpreted as an anomaly because none of the previous calculations included the Coulomb final-state interaction of the leptons. Indeed, a crude estimate of this final-state interaction shows that the effect is not negligible near threshold and brings the prediction into qualitative agreement with the data. Thus near-threshold pair production does not provide evidence for any unusual resonancelike behavior that could possibly be related to the unexplained e^+-e^- lines seen in heavy-ion collisions[14, 15].

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[1] C.M. Davidson, in *$\alpha \cdot \beta \cdot \gamma$-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1968), Vol. 1, p. 37.
[2] I. Øverbø, K.J. Mork, and H.A. Olsen, Phys. Rev. **175**, 1978 (1968).
[3] I. Øverbø, K.J. Mork, and H.A. Olsen, Phys. Rev. A **8**, 668 (1973).
[4] H.K. Tseng and R.H. Pratt, Phys. Rev. A **21**, 454 (1980).
[5] H.K. Tseng and R.H. Pratt, Phys. Rev. A **24**, 1127 (1981).
[6] T. Yamazaki and J.M. Hollander, Phys. Rev. **140**, B630 (1965).
[7] A. Coquette, Nucl Instrum. Methods **144**, 571 (1977).
[8] A. Coquette, J. Phys. (Paris) **39**, 1055 (1978).
[9] A. Coquette, Nucl. Instrum. Methods **164**, 337 (1979).
[10] A. Coquette, J. Phys. (Paris) **41**, 97 (1980).
[11] H. En'yo, T. Numao, and T. Yamasaki, Phys. Rev. A **21**, 1439 (1980).
[12] F. T. Avignone III and A.E. Khalil, Phys. Rev. A **24**, 2920 (1981).
[13] F. T. Avignone III *et al.*, Phys. Rev. A **32**, 2622 (1985).
[14] T. Cowan *et al.*, Phys. Rev. Lett. **54**, 444 (1986).
[15] W. Koenig *et al.*, Phys. Lett. **218B**, 12 (1989).
[16] R.J. Gehrke *et al.*, Nucl. Instrum. Methods **147**, 405 (1977).
[17] A.D. Sakharov, Zh. Eksp. Teor. Fiz. **18**, 631 (1948); Usp. Fiz. Nauk **161** (5), 29 (1991) [Sov. Phys. Usp. **34**, 375 (1991)].