Cross section of pair production near threshold

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The cross section of the pair production in germanium at 1064 keV, only 42 keV above threshold, has been measured with the use of a Ge(Li) detector. The obtained cross section is 0.182 mb/atom and has a large deviation from the theoretical value by Øverbø, Mork, and Olsen. The present result suggests that the screening effect of atomic electrons has a large contribution to the pair-production cross section near threshold.

I. INTRODUCTION

It has been well known that the Bethe-Heitler formula, hereafter abbreviated as (BH),[1] for the electron-positron pair-production cross section based on the first-order Born approximation is not applicable to low photon energies near the threshold $2m_e c^2$ where the interaction cannot be treated as a perturbation. Jaeger and Hulme[2] (JH) calculated the correction to the BH formula about several photon energies near threshold for $Z=56$, 65, and 82. An "exact" calculation was performed by Øverbø, Mork, and Olsen[3] (ØMO) in essentially the same way as the JH calculation, and they were consistent with each other. Although in these calculations the screening of atomic electrons was neglected and the reaction field was assumed to be caused by a point nucleus, their results were in good agreement with old experimental data.

The cross sections near threshold were measured in Ge ($Z=32$) by Yamazaki and Hollander[4] (YH). Their results indicated that the cross sections are larger than the ØMO values and the deviation becomes larger towards the threshold.[5]

In 1971, Tesung and Pratt[5] (TP) calculated the cross section by the partial-wave analysis for various atomic numbers, taking account of the screening effect of the nuclear charge by atomic electrons. The results seemed to be able to explain the discrepancy between the experimental data of YH and the theoretical values of ØMO to some extent; a small discrepancy is within experimental error at 1077 keV, which is the lowest energy examined by Yamazaki and Hollander, but TP reported that there is approximately a 30% discrepancy between the experimental data of Rao *et al.*[6] and the TP calculations.

In the energy region below 1077 keV, there have been no experimental data which would provide a crucial test for the theories. In this paper we reexamine the tendency of these discrepancies, investigating a still-lower energy region.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The present experiment was performed by the method of pair spectrometer, whose principles are well described in Ref. 4. A ^{207}Bi source of about 20 μCi was used for the incident photon beam. ^{207}Bi has a long life, and the decay scheme is well known. It has a 1064-keV γ ray with a strong branch, about 40% of total intensity. Furthermore, it has a weak γ-ray decay of 1770 keV ($I_\gamma=3.6\%$), and the energy of 1770 keV is quite close to the 1772-keV value which we could obtain from the γ ray from ^{56}Co decay. Hence, we also used ^{56}Co as an incident beam source, and we normalized the relative cross sections of γ rays of ^{207}Bi and ^{56}Co at these energies, 1770 and 1772 keV. We obtained absolute cross sections when they were normalized to the BH value at 3254 keV, another γ-ray energy of the ^{56}Co decay, assuming that in the energy region above 3 MeV the BH formula is correct to within 1%.

The experimental setup was similar to that employed by YH. The cross section near the threshold was reported to be a small value of about 0.34 mb/atom at 1077 keV, and it was expected to be less at 1064 keV; therefore, in order to increase the efficiency, we used two sets of 7.6-cm-depth, 7.6-cm-diameter NaI(Tl) pairs and placed them 5 mm from the surface of the 40-cm^3 Ge(Li) detector which was used as a target for the γ-ray beam, and obtained a large solid angle against the Ge target.

Conventional fast-slow coincidence logic was employed. The time resolution of the fast coincidences of NaI-Ge-NaI was about 50 nsec. The energy signal of the Ge(Li) detector was gated by the fast coincidence signal and slow coincidence signals which indicated that both annihilation γ rays (511 keV), emitted from the Ge(Li) detector, lost their full energy in an NaI pair. Although the slow coincidence decreased the efficiency, it increased the signal-to-noise ratio.

After all, this type of pair spectrometer turned out to have the best signal-to-noise ratio from various tests. The total efficiency of the present system was found to be about 10%.

Figure 1 shows a "double-escape" spectrum of γ rays from the ^{207}Bi decay which was accumulated for 28.5 days. The area of the 42-keV double-escape peak (the original γ-ray energy is 1064 keV) was obtained to be 118 ± 21 counts. Table I summarizes the results after corrections for the ^{207}Bi source as well as ^{56}Co. Details of corrections are reported in the following section.

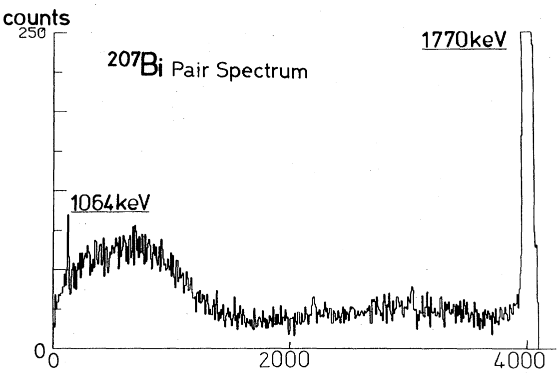

FIG. 1. ^{207}Bi pair spectrum. Shown are the original photon beam energies; detected energies are 42 and 748 keV.

III. CORRECTIONS TO THE EXPERIMENTAL DATA

In order to deduce the total pair-production cross section from the relative pair-peak areas in the spectrum obtained, the following corrections must be considered.

(1) High-energy photons, which lose a part of their energy by Compton scattering, can still contribute to the pair-production yield. We cannot distinguish this contribution from a pure pair production. The ratio

$$\alpha = \frac{(\text{pair production by scattered } \gamma \text{ rays})}{(\text{pair production by incident } \gamma \text{ rays})}$$

is given roughly as

$$\frac{\int_2^k \mu_{\text{pair}}(k')dk'}{\mu_{\text{pair}}(k)} \frac{\partial \mu_{\text{Compton}}(k)}{\partial k} \left(\frac{1}{l\mu_{\text{tot}}} - \frac{1}{e^{l\mu_{\text{tot}}} - 1} \right) l ,$$

where, $\mu_{\text{pair}}(k)$ and $\mu_{\text{Compton}}(k)$ are the absorption coefficient of each effect at energy kmc^2, μ_{tot} is the total absorption coefficient that is almost constant in this experimental energy region, and l is the thickness of the Ge(Li) detector. The value $\mu_{\text{Compton}}(k)$ turned out to be constant in this energy region from the Klein-Nishina formula. The α values are shown in Table II.

(2) Incomplete absorption of positron and electron energies in the Ge crystal. This factor was reported in Ref. 4 in detail. The incomplete absorption occurs near the cylindrical surface and the far end of the Ge(Li) crystal in the present energy region. However, both corrections turn out to be small as shown by the following considerations. Since the radial momentum of a produced electron is small because of the kinematic condition, the effective length corresponding to the radial momentum of electrons is about 1 mm for the 1770-keV γ rays. The volume of the "surface escape" region was estimated to be less than 2% of the total volume of the detector in the present energy region. Since the "far-end escape" region is about 3% of the total volume and the solid angle of seeing the NaI pairs is smaller than that of the middle part of the Ge detector, the far-end region contributes less to the total events. From a rough estimation the correction factor is less than 1% and is able to be corrected.

(3) The attenuation of γ rays in the Ge crystal ($e^{-\mu x}$) is energy dependent: This effect is de-

TABLE I. Data and results.

Isotopes	Photon energy (keV)	Energy above threshold (units of mc^2)	Area (error)	Intensity of photon (error)[a]	Corrected σ_{pair}[b]	$\sigma/\sigma_{\text{BH}}$	Total error (%)
^{56}Co	3254	4.37	381.2(20.7)	7.4 (0.5)	1.016	1.00	8.8
	2035	1.98	150.1(13.3)	7.78(0.12)	0.302	1.216	12.6
	1772	1.47	192.3(16.9)	15.52(0.14)	0.255	1.35	12.2
^{207}Bi	1770	1.46	11 356.3(112.3)	7.0 (0.2)	0.254[c]	1.34	
	1064	0.082	118.0(21.0)	76.6 (1.0)	3.066(−4[d])	2.34	26.0

[a] Data from Nucl. Data Sheet (1977).
[b] Normalized at 3254 keV to the BH formula, and represented in units of $Z^2 r_0^2/137 = 0.5933$ b/atom for $Z = 32$.
[c] Normalized at 1772 and 1770 keV.
[d] An absolute value is 0.182 mb/atom.

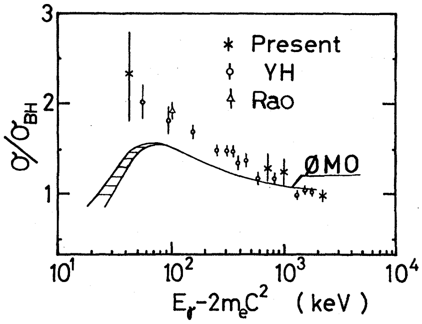

FIG. 2. The ratio of $\sigma_{pair}(\mathrm{expt})/\sigma_{pair}(\mathrm{BH})$. The crosses show the present results, circles, the experimental data by Yamazaki and Hollander, and a triangle, the interpolated value which is obtained from Rao's data between $Z=29$ and 40. The smooth curve shows the theoretical values by ØMO which is reproduced by interpolation about mass numbers from their original paper (Ref. 3). The striped pattern is an error in reproduction.

scribed as

$$\int_0^l \Omega(z)e^{-\mu z}dz\,,$$

where $\Omega(z)$ is the geometrical efficiency, which is maximum at $z=l/2$ and minimum at $z=0, l$. After all, this factor is negligible because the coefficient μ_{tot} is almost constant in the present energy region.

(4) Positrons are captured in flight, and the annihilation γ rays are not 511 keV: This term depends on incident photon energy. Assuming the cross section of the annihilation in flight,[7] this term was estimated to be less than 2%.

(5) In order to decrease the time jitter, a constant fraction discriminator (CFD) for the fast timing signals from the Ge(Li) detector was operated in a slow-rise-time rejection mode, so that the system sometimes failed to count low-energy events. Therefore, the discrimination of the CFD was not like a step function, and the shape of the discrimination was able to be expected from the form of the background around the 1064-keV double-escape peak in Fig. 1; this hilly background was caused by the Compton scattering of 1770-keV photons. We estimated this correction using the ^{22}Na β^+ decay to the 1274-keV level. With a setup similar to the cross-section measurement except for the detector position, we measured a "singles" spectrum of the 1274-keV γ rays in the triple coincidence of 511-511-1274 keV. This spectrum should have a flat part caused by the Compton

TABLE II. Correction for multiple-scattered events, which is most dominant among several corrections considered.

Isotope	Photon energy (keV)	$\mu(\mathrm{cm}^{-1})$	α
Co	3254	0.117	0.08
	2599	0.115	0.07
	2035	0.117	0.06
Bi	1770	0.118	0.05
	1064	0.130	0.01

scattering if it were not distorted by the discrimination. Therefore, we determined the correction factor to be 0.75 ± 0.13 for the 1064-keV γ rays. The factor was unity for the other energies. This correction caused a large part of the total error.

IV. DISCUSSION

Figure 2 shows the present results together with those of YH, as well as an interpolated value from the data of Rao *et al.* It is clear that the results of these experiments are consistent and deviate from the BH prediction in the low-energy region near threshold. The present data at 1064 keV further deviate from the theoretical value of ØMO, which was reproduced through the interpolation about the atomic number. According to Tseng and Pratt, the deviation was ascribed to the screening effect of atomic electrons—the cloud of atomic electrons suppresses the Coulomb field of the nucleus and decreases the repulsion of positrons, so that this factor suppresses asymmetric kinematics of the pair production. This effect increases the cross section for low-energy photons and is more effective than the other contribution that decreases the cross section because of a weakened Coulomb field; however, the two contributions are caused from the same origin. The TP calculation explained the deviation between the YH and the ØMO values at 1077 keV for $Z=32$, and it produced a 30% larger value than the result by Rao *et al.* at 1119 keV for $Z=29$; however, the interpolated value for $Z=32$ is consistent with the YH and the present results. Hence it can be said that the TP calculation is not satisfactory, especially in its Z dependence, and there remains room for reconsideration as to the method of taking a screening effect into account in the energy region near threshold.

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