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Cross section for the production of electron-positron pairs by 1.064-MeV photons on germanium

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The relative pair-production rates by 1.064- and 1.770-MeV photons on Ge were measured in a double-escape-peak pair spectrometer consisting of a 2.44-cm diameter by 1-cm-thick intrinsic, planar Ge detector inside of a split NaI(Tl) annulus. Guided by previous experiments, the theoretical cross section $\sigma(1.770)$ was assumed to be correct and the value $\sigma(1.064) = 0.131 \pm 0.012$ mb/atom was deduced from the data. This is in excellent agreement with recent direct numerical screened calculations of Tseng and Pratt.

I. INTRODUCTION

The importance of screening corrections in the calculation of pair-production cross sections has been recognized for some time.[1–6] Until very recently, however, experimental results have been compared to predictions based on point-Coulomb wave functions which include approximate treatments of the screening effects. Previous measurements of these cross sections involving high-Z targets indicate that these approximate treatments may not be adequate.[7–10] More recently, Tseng and Pratt[11] have reported the results of direct screened, full numerical calculations based on an exact partial-wave formulation. It is highly important to determine whether the discrepancy between theory and experiment observed earlier for low-energy photons on high-Z targets extends to lower-Z targets ($Z \cong 32$) as well. There have been three recent measurements for γ rays near threshold on Ge detectors.[12–14] The central values differ significantly but all indicate a departure from theory in which $\sigma_{\text{expt}}/\sigma_{\text{theor}} > 1$ for γ rays near threshold. The recently reported cross section of Coquette[12] for 1.0628 ± 0.0014-MeV γ rays was 0.143 ± 0.023 mb/atom, which has a central value 10% above the calculated value of 0.130 mb/atom given by Tseng and Pratt.[6] In the measurements of Ref. 12 a variable energy source was used in which the uncertainty in energy can lead to an approximate cross-section shift of 0.015 mb/atom.[15] Coquette had earlier reported a cross section of 0.150 ± 0.014 mb/atom using the 1.064-MeV γ ray in the decay of ^{207}Bi. Recently, En'yo, Numao, and Yamasaki[14] reported a value, measured with the same γ ray, of 0.182 ± 0.047 mb/atom. This central value is 41% above the theoretical value; however, the error is 26% and a strong conclusion cannot be drawn. In the measurements reported in in Ref. 14, the energy was also that of the well-known 1.064-MeV γ ray in the decay of ^{207}Bi, but the results suffered from poor statistics (118 counts) and large corrections which led to the total error of 26%. None of these measurements alone, nor considered together, can serve as a stringent test of the new calculations. These considerations stimulated the present experiment which was also designed to use the well-known γ rays in the decay of ^{207}Bi, but in an improved spectrometer with an increased efficiency for detecting coincident annihilation radiation pairs and a more collimated γ-ray beam. The basic concept of this spectrometer is otherwise similar to that described by Yamazaki and Hollander.[16]

Earlier theoretical investigations of Tseng and Pratt[2–4] and of Øverbø[5,6] have shown that the screened atomic wave functions in the vicinity of the nucleus are very similar to point-Coulomb wave functions of shifted positron and electron energies. The screening-corrected pair-production cross section can then be approximately calculated using the energy shifted, point-Coulomb wave functions. The proper energy shifts are selected by comparison of exact screened wave functions to energy shifted wave functions. It is important to point out, however, that in the present analysis the data are compared directly to the recent exact numerical calculations of Tseng and Pratt,[11] which employed a Hartree-Fock-Slater potential with the exchange term omitted. A more extensive comparison of these new calculations to existing experimental results of $Z=32$ are made in a recent paper by Tseng and Pratt.[17] One very important point can be made by reference to Fig. 1 of Ref. 12 which shows excellent agreement with the theory of cross sections in targets of $Z=32$ for γ rays with energies above 1.3 MeV. Excellent agreement with theory was also reported for the mixture of the 1.17 and 1.33 γ rays in the decay of ^{60}Co in a target of $Z=29$ (Ref. 18) using a technique for making absolute cross-section measurements.[19] This point is crucial in the present investigation because the measured relative cross section $\sigma(1.064)/\sigma(1.770)$ can easily be converted into an absolute cross section but only if the cross section $\sigma(1.770)$ is reliably known. In our analysis we therefore assume that the theoretical value $\sigma(1.770)=124.4$ mb is exactly known.

II. EXPERIMENTAL PROCEDURE

In the previous experimental investigations[12,14] Ge(Li) detectors were used; however, a planar, intrinsic Ge detector was used in the present investigation. This removes some of the uncertainties concerning the exact geometry of the active region. The detector was 2.44 cm in diameter by 1-cm thick and was placed in a split NaI(Tl) annulus formed by cutting hemispherical channels across the faces of two 15.24 cm by 15.24-cm NaI(Tl) scintillators (see Fig. 1). A 100-μ Ci source of ^{207}Bi was placed in front of a 15-cm-long lead collimator which was 8 cm from the detector face. The signals from the NaI(Tl) detectors were used as start and stop signals in a time-to-amplitude converter (TAC) followed by a differential discriminator and gate and delay generator. A slow linear gate was triggered by the coincidence pulse from the TAC discriminator (see Fig. 2). Thus, the spectral pulses from the Ge detector were gated by 0.511−0.511-MeV coincidences from the split NaI(Tl) annulus. We found that this simple procedure resulted in a neglegible change rate while the use of more elaborate timing procedures, like those used in Ref. 14, led to distortions in the low-energy portion of the gated spectrum. Unlike the spectrometer described in Ref. 15, which was used for both measurements reported by Coquette,[12,13] the present annulus was split with the two halves completely optically isolated. The requirement for 0.511−0.511-MeV coincidences severly reduces the interferences from background γ rays, hence no lead shielding was required. Background effects were measured by removing the ^{207}Bi source and collecting a spectrum. They were found to be very small. The cross-section data were collected for about 37 days and resulted in almost 700 counts under the double-escape peak at 42 keV compared to 118 counts reported in Ref. 14. In addition, our spectrum did not show any cutoff in the vicinity of the 42-keV peak (see Fig. 3). The corresponding net rate under the 1.064-MeV γ-ray's double-escape peak at 42 keV was 18.7 ± 0.8 coincidences per day. The corresponding rate under the 1.770-MeV γ-ray's double-escape peak at 0.748 MeV was 1659 ± 23 coincidences per day. The ratio of the rates under these peaks is then $R(1.064)/R(1.770)=1.127\times10^{-2}$ as compared to the corresponding ratio of these rates given in Ref. 14 as 1.039×10^{-2}. At first glance it appears as though the present data should yield a much larger cross section. The fact that the double-escape peak of Ref. 14 was located on the edge of a cutoff resulted in a significant loss of coincidence efficiency which required a correction factor of 0.75 ± 0.013. This low-energy cutoff was caused by operating the system with constant fraction discriminators in a way which caused the system to fail to count some of the low-energy pulses.

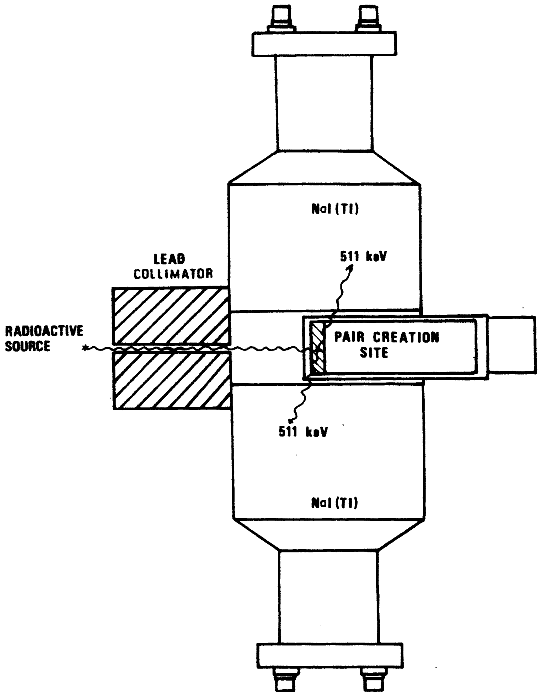

FIG. 1. Experimental geometry showing the source, detector, and wrap-around, two piece NaI(Tl) annulus.

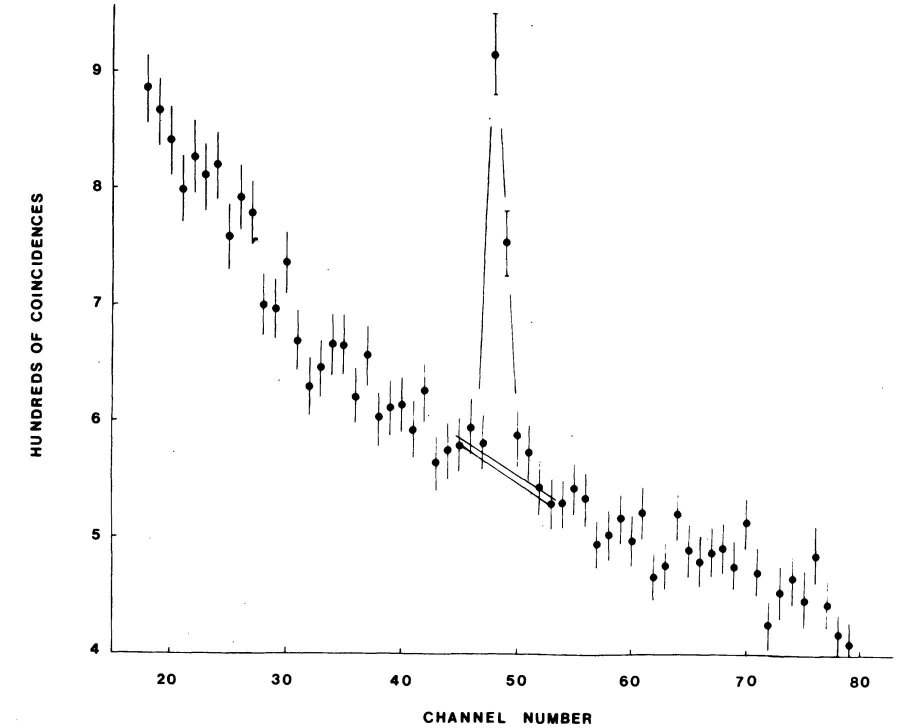

FIG. 2. Block diagram of the electronic instrumentation.

This difficulty was avoided in the present experiment by using fast coincidences between the NaI(Tl) annulus halves as a slow gate for the pulses from the Ge detector. The energy independence of this system was partially tested by placing the source of ^{133}Ba between the annuli and observing the 365γ-81γ-Kx coincidence spectrum in the very low-energy region. We did not find it necessary to use a fast coincidence between the annulus and the Ge detector when the source is well collimated and shielded from the annulus. In fact, chance coincidences did not present any problem at all.

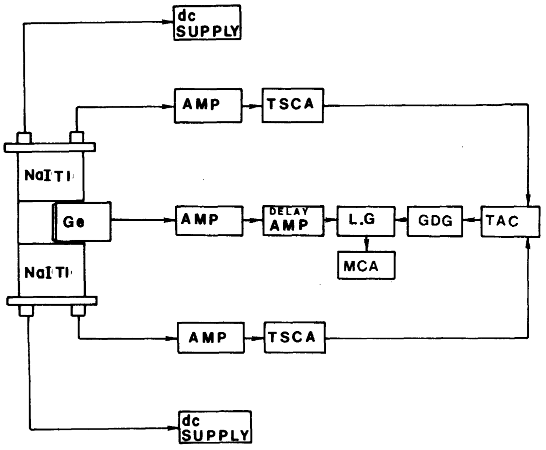

FIG. 3. Raw coincidence spectrum showing the double-escape peak from the pair production of the 1.064-MeV γ ray and the continuum. (MCA, multichannel analyzer; TAC, time-to-amplitude converter; TSCA, timing single-channel analyzer; GDG, gate and delay generator; LG, linear gate.)

III. RESULTS AND CONCLUSIONS

The main source of error in the present experiment were statistical in nature. The corrections applied to the present data were in fact very small and only shifted the result by less than 3%. The correction required to acount for the fact that some electrons and positrons do not deposit all of their energy in the crystal but scatter out was found to be extremely γ-ray energy independent when a well collimated γ-ray beam is used with the detector dimensions quoted above. This correction was calculated using a simple Monte Carlo technique and was found to be small. This correction is much easier to calculate in an intrinsic planar detector than in a coaxial Ge(Li) detector because the active region is far better known. The most important correction arises from the fact that a γ

ray with energy well above $2m_ec^2$ can Compton scatter one or more times and then produce an electron-positron pair. The energies of the Compton electrons are summed with those of the pairs which simulates the events of interest, namely, the production of electron-positron pairs in the first interaction. This correction was carefully calculated using the complex Monte Carlo code described in an earlier article.[20] The calculation of the average energy of the Compton scattered γ rays after one scatter is straightforward. These are 1.042 and 1.376 MeV for initial γ-ray energies of 1.064 and 1.770 MeV, respectively. The relative probability that the 1.064-MeV γ ray will produce a pair on the second interaction, compared by that for the 1.77-MeV γ ray, can be expressed as $\sigma_p(1.044)/\sigma_p(1.376)$, where σ_p is the pair-production cross section. The numerator is obviously not known; however, limits can be placed on this quantity by extrapolating the results of Ref. 12. It can be seen that $\sigma(1.044) << 10^{-2}$ mb/atom. An approximate value for the cross section $\sigma(1.376)$ was obtained by extending the best-fit polynomials given earlier[21] to lower energies using the results of Coquette.[12] The resulting cross section is 28.3 mb/atom. The ratio is then $\sigma(1.044)/\sigma(1.376) < 0.0004$. These extrapolated cross sections were also used in a full Monte Carlo calculation where the result was somewhat larger because some of the γ rays suffer only small-angle scattering; however, this average value was reproduced. The probability that the 1.064-MeV γ ray will produce a pair after Compton scattering one or more times is then negligible.

The total number of 1.770-MeV γ rays which produce pairs can be expressed as

$$N = N_0 + N_1 + N_2 + \cdots ,$$

where the subscript indicates the number of Compton scattering events the photon suffered prior to producing a pair. This leads to a non-neglible correction in the case of the 1.770-MeV γ ray, which was calculated with the Monte Carlo code. In a typical computer run, 10^6 γ-ray histories were followed until they were either absorbed or escaped. On the average, of the 10^6 cases, 560 γ rays scattered once and then produced a pair while 28 scattered twice prior to producing a pair. The number of cases in which a γ ray scattered three times and then produced a pair was zero, within statical uncertainty. The ratio of the total number of pairs produced to the number produced on the first interaction was calculated to be 1.0235. This would correspond to the quantity $(1+\alpha)$ defined in Ref. 14. The estimated values of α given in Ref. 14 are 0.05 and 0.01 for the 1.770- and 1.064-MeV γ rays, respectively, whereas our corresponding calculated values are 0.0235 and $< 10^{-5}$. Since the correction factor is $(1+\alpha)$, the difference in the final result due to the differences between the estimated[14] and the calculated values of α is only $\sim 2\frac{1}{2}\%$.

The number of events under the double-escape peak at 44 keV, shown in Fig. 2, was found by fitting a series of second-order polynomials to the continuum excluding the peak. A measure of the error introduced by this procedure was obtained by comparing the best-fit curves obtained by including points further and further from the peak. The total uncertainty in the number of events in the continuum under the peak was 29. The net number of counts under the peak was found to be 692 ± 26 where this error is purely statistical. When the uncertainty in the continuum is added the net number of events becomes 692 ± 55, which corresponds to 18.69 ± 1.49 events per day. There was almost no continuum under the double-escape peak of the 1.770-MeV γ ray which has a rate of 1659 ± 23 events per day. These event rates can be used with the theoretical value of $\sigma(1.770) = 124.4$ mb, and the relative γ-ray intensities $I(1.064)$ and $I(1.770)$, to obtain $\sigma(1.064)$ as follows:

$$\sigma(1.064) = \left[\frac{R(1.064)}{R(1.770)}\,\frac{I(1.770)}{I(1.064)}\right] \times [1+\alpha(1.770)]^{-1}\sigma_{\text{theor}}(1.770)$$

$$= 0.131 \pm 0.012 \text{ mb/atom} ,$$

where the error quoted is the most probable error. The relative intensities $I(1.064) = 76.6 \pm 1.0$ and $I(1.770) = 7.0 \pm 0.2$ were obtained from a recent compilation.[22]

This result is in excellent agreement with the recent exact calculation of Tseng and Pratt[11] which was $\sigma(1.063) = 0.130$ mb/atom. It should be noted, however, that the energy of the calculation is 1 keV lower than the energy of the present measurement. This energy difference can result in a change in the cross section of approximately 0.011 mb. This result is to be compared to the value $\sigma(1.064) = 0.182 \pm 0.047$ mb given by En'yo *et al.*[14] and to $\sigma(1.063) = 0.143 \pm 0.021$ and $\sigma(1.064) = 0.150 \pm 0.014$ mb/atom given by Coquette in

Refs. 12 and 13, respectively. The discrepancy between the cross section reported here and that reported in Ref. 14 is partly due to their measured cross section $\sigma(1.770)=150.6$ mb which is significantly larger than the theoretical value of $\sigma_{\text{theor}}(1.770)=124.4$ mb. Such a deviation (21%) from theory at this energy is not consistent with the current literature (see Fig. 1 of Ref. 12).

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