Low-energy absolute pair-production cross-section measurements in targets of $Z = 13, 26, 29, 50$, and 82

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Absolute cross sections for pair production by photons incident on targets of aluminum, iron, copper, tin, and lead were measured using the internal-source method. The measurements were made for the 1.119- and 2.6145-MeV γ rays in the decays of ^{46}Sc and ^{228}Th, respectively, and also a composite cross section was measured for the mixture of the 1.1732- and 1.3325-MeV γ rays in the decay of ^{60}Co. The results are in general agreement with the theoretical predictions of Øverbø and those of Tseng and Pratt, and clearly demonstrate the importance of accounting for electron screening of the nuclear Coulomb potential in the calculations.

I. INTRODUCTION

The production of electron-positron pairs by photons in the nuclear Coulomb field is a well-known phenomenon which has been extensively studied for many years. A comprehensive review of the theoretical and experimental investigations of the subject through 1968 was given by Motz, Olsen, and Koch.[1] Since this review, however, renewed interest in the process has been generated by the publication of several theoretical papers concerned primarily with the use of exact Coulomb wave functions to describe the produced lepton pair.[2,3] Deviations of experimentally measured pair-production cross sections from those predicted by the Born approximation are now generally understood in terms of these exact calculations when they are corrected for the screening of the nuclear Coulomb potential by the atomic electrons. The effect of screening for the low-energy photons considered here is to increase the pair-production cross section, in contrast to the opposite effect which occurs at high photon energies. In either case, the screening effect is largest for target nuclei with large atomic number Z. This can be qualitatively understood by considering the time reversed process because the amplitude of the incoming positron will be enhanced in the vicinity of the nucleus by the screening electrons which effectively reduce the repulsion by reducing the effective nuclear charge. The treatments of screening given in Refs. 2 and 3 are both somewhat parameter dependent and a good test of these would seem to lie in cross-section measurements in high-Z targets and at low photon energy, both of which enhance the sensitivity of the cross section to screening.

Although extensive experimental investigation of the variation of low-energy pair-production cross sections with Z and incident photon energy can be found in the literature, almost all of these papers report relative rather than absolute cross sections. In addition the body of data lack both accuracy and consistency to enable one to draw strong conclusions, possibly favoring one of the theoretical treatments. One of the few sets of absolute measurements were reported by Rao *et al.*[4] for $E_\gamma = 1.119$ MeV and are all 20%–30% larger than the screening corrected calculations of Tseng and Pratt reported in Ref. 2. A close examination of the experimental technique and the error analysis presented in Ref. 4 leads us to believe that the errors quoted therein are almost all associated only with the statistics and are far too small. The apparent disagreement between the experimental results of Ref. 4, for $E_\gamma = 1.119$ MeV and $Z = 29$, and the theoretical results of Ref. 2 are probably due to systematic errors associated with energy resolution and target effects which were only estimated. In the present investigation all known sources of error in the experiment and in the corrections for scattering within the source, etc., have been carefully accounted for and the cross section for the above values of E_γ and Z are in far better agreement with the screening corrected calculations of both Refs. 2 and 3.

In two previous papers[5,6] we reported the use of a recently developed internal source technique for measuring absolute pair-production cross sections in a target of $Z = 50$ and for photons of several energies between 1.119 and 2.6145 MeV. The results of these measurements were in general agreement with both the screened and unscreened calculations and were not accurate enough to observe screening effects with photon energies above 1.33 MeV, while below this energy a significant departure of the measured cross sections from both screened and unscreened calculations was observed.

The purpose of this paper is to report the results of a continuation of absolute pair-production cross-section measurements utilizing the internal-source method. The data reported here includes measurements in targets of aluminum, copper, tin, and lead at 1.119 and 2.6145 MeV and also with the mixture of the 1.1732- and 1.3325-MeV γ rays in the decay of ^{60}Co. The main purpose for including the measurements with $E_\gamma = 2.6145$ MeV, over a range of values of Z is that the sign of the screening correction in both theoretical treatments changes in this energy region. In addition, the high accuracy with which the cross sections can be measured at this energy allows us to accurately renormalize the earlier relative cross-section results so that we can compare them to the absolute cross sections reported here.

II. EXPERIMENTAL PROCEDURE

The details of the internal-source technique for measurement of absolute pair-production cross sections, including a description of the Monte Carlo computer codes used to correct the data for scattering and absorption of annihilation radiations in the source, are given in Refs. 5 and 6 and will not be repeated here. In this technique, a radioactive source bead of approximately 2 mm diam is located at the center of a solid sphere of chemically pure metal. This target-source assembly is mounted at the intersection of the axes of the two detectors of a standard directional correlation apparatus. One detector is a 33-cm^3 Ge(Li) detector and the other is a 7.62×7.62 cm, NaI(Tl) scintillation detector. Standard two-detector coincidence techniques were used which consisted of two preamplifiers, two linear amplifiers, two single-channel pulse height analyzers, a coincidence circuit with a resolving time of 100 ns and a multichannel, pulse height analyzer. The energy window associated with the Ge(Li) detector was set to accept pulses corresponding to an energy range of 400–600 keV while that associated with the scintillation detector was set to accept only a narrow region about the full energy peak of the 511-keV annihilation radiations. The coincidence output pulse is used to gate the multichannel analyzer so that it collects the coincidence-gated spectrum of the Ge(Li) detector. The data were collected with the detector axes at 180° and also at 90°. The 90° position data is found to have a continuum of almost exactly the same shape and magnitude as the continuum of the 180° data and can be used to correct the coincidence spectrum for chance coincidences under full energy peak and for the continuum due to scattering between the detectors. The efficiency ϵ of the detectors for measuring back-to-back annihilation radiation pairs was measured using an absolute intensity calibrated source of ^{22}Na. The coincidence-gated annihilation radiation peaks observed with the Ge(Li) detector are shown in Fig. 1.

The sources of ^{46}Sc and ^{60}Co used in these measurements were distributed homogeneously throughout small spherical epoxy beads, while the source of ^{228}Th was plated on a fine wire and encapsulated in a brass bead, so that a correction for the pair production in the brass and solder in the source assembly must be made. The targets of Al, Fe, Cu, Sn, and Pb were each approximately spherical in shape with outside diameters of 1.9 cm. The Sn and Pb targets were molded in hemispheres with a small hemisphere milled at the center for the source. The Al, Fe, and Cu targets were machined into spheres with access to the center provided by a threaded hole and a threaded plug to seal the source inside.

The absolute cross sections are computed from the data using the following equation given in Refs. 5 and 6:

$$\kappa_n = \mu C / N A \epsilon \langle X \rangle \;, \qquad (1)$$

where μ is the mean experimental total γ-ray absorption coefficient in cm^{-1} (see Ref. 5 of Ref. 6), C is the annihilation radiation coincidence rate in number of γ-ray pairs per second, N is the number of target atoms per unit volume, A is the source activity in γ-rays per second, ϵ is the annihilation pair detection efficiency, and X is a factor which, for a perfectly spherical target, is given by

$$\langle X \rangle = 1 - \exp[-\mu(R - r_0)] \;, \qquad (2)$$

where R and r_0 are the outer and inner radii, respectively. While it is a simple matter to machine a target with axial symmetry it is difficult to machine one which is almost perfectly spherical. We find that our spherical targets all have a small nonsphericity which can be accurately described to first order as a quadrupole deformation which is written as follows:

$$R = R_0[1 + a_2 Y_2^0(\theta\phi)] \;, \qquad (3)$$

where R_0 and a_2 are determined by directly measuring the equatorial and polar diameters. The mean value $\langle X \rangle$ used in Eq. (1) was obtained for each target by using Eq. (3) to calculate the probability of absorption of a γ-ray emitted at the center of a deformed target. When the quad-

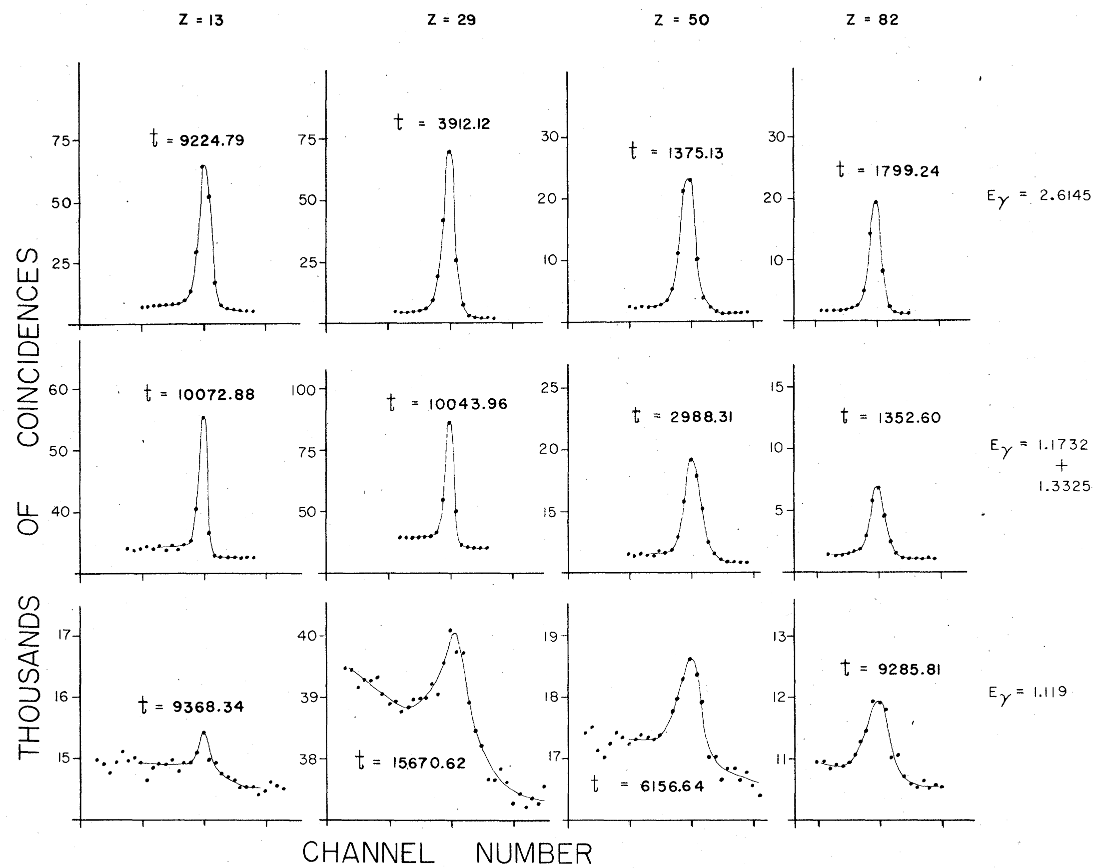

FIG. 1. Coincidence-gated Ge(Li) spectrum showing the 0.511-MeV annihilation radiation peaks. These are typical data and the data collection time t in minutes is given for each peak.

rupole deformation is accounted for in this manner, the expression for $\langle X\rangle$ given in Eq. (4) is used in Eq. (1):

$$\langle X\rangle = 1 - \exp\{-\mu(R_0[1-a_2(5/16\pi)^{1/2}-r_0])\} \times[1-\mu R_0 a_2(5/16\pi)^{1/2}] \ . \qquad (4)$$

The cross sections determined from the data, using Eq. (1), were corrected by application of the Monte-Carlo calculations described in Refs. 5 and 6 for Compton scattering of the incident photon, the escape of positrons formed near the surface, and the scattering and absorption of the annihilation radiations in the target. As reported in Ref. 6, the largest of these corrections is about 5% for the absorption of the annihilation radiations in the target while all of the other corrections are on the order of 1% or less and decrease with decreasing incident photon energy.

III. RESULTS AND CONCLUSIONS

The results of the present measurements are given in Table I, together with the corresponding theoretical cross sections calculated by Øverbø,[7] by Tseng and Pratt,[8] and those calculated with the Born approximation.[9] A comparison of the present results with other experimental values is given in Table II. The departure of the experimental cross sections from those of Born approximation is clear as seen earlier.[10] It is also evident that in the low-energy, high-Z case, where screening is important, the unscreened, point Coulomb approximation fails as anticipated. Moreover, in this region the measured cross sections slightly favor the screening-corrected calculations of Øverbø, although strong conclusions concerning this distinction cannot be drawn based on the present results.

The disagreement between theory and experiment reported earlier[6] for the mixed (1.1732 + 1.3325) MeV γ rays in the decay of ^{60}Co and for $Z = 50$ is not in evidence in the present results; however, the two sets of results are within the quoted experimental errors. The disagreement between theory and experiment at $E = 1.119$ MeV is still observed as reported in Ref. 6 but to a

TABLE I. Experimental and theoretical pair-creation cross sections. σ_{Born}: Born approximation, unscreened; $\sigma^{\text{PC}}_{\text{Ø}}$: Øverbø, point Coulomb; $\sigma^{\text{SC}}_{\text{Ø}}$: Øverbø, screened; $\sigma^{\text{SC}}_{\text{TP}}$: Tseng and Pratt, screened.

E_γ	Z	σ_{exp} (mb)	σ_{Born} (mb)	$\sigma^{\text{PC}}_{\text{Ø}}$ (mb)	$\sigma^{\text{SC}}_{\text{Ø}}$ (mb)	$\sigma^{\text{SC}}_{\text{TP}}$ (mb)
1.119	13	0.23(0.03)	0.1427	0.1617	0.164	0.164
	29	1.11(0.07)	0.7099	1.039	1.11	1.11
	50	4.66(0.21)	2.110	3.541	4.32	4.11
	82	14.5(0.8)	5.676	7.352	13.3	11.2
1.1732	13	2.05(0.11)	1.625	1.69	1.72	1.72
+	26	7.84(0.33)	6.50	7.73	7.82	7.81
1.3325	29	10.5(0.5)	8.08	9.95	10.10	10.0
	50	40.5(2.0)	24.03	38.2	39.9	39.5
	82	161.0(6.0)	64.66	137.9	157.2	151.2
2.6145	13	65.2(2.9)	63.63	64.22	64.21	64.2
	26	265.0(11.0)	254.5	263.8	263.7	265.0
	29	328.0(14.0)	316.6	331.0	330.8	332.0
	50	1046.0(36.0	941.0	1063.0	1061.0	1063.0
	82	3357.0(107.0)	2532.0	3309.0	3306.0	3340.0

lesser degree and when compared to the recent screening corrected calculation of Øverbø, this disagreement disappears. While the experimental uncertainties at the higher photon energies have been reduced in the present investigation compared to those given in Ref. 6, the most significant source of error in the low-energy photon data continues to lie in stripping the annihilation radiation peaks from the large continuum which is due to the poor energy resolution of one of the detectors. This resolution problem is somewhat compensated for by virtue of the fact that NaI(Tl) detectors are more efficient; hence the statistical fluctuations in the coincidence rates are far smaller.

However, a disagreement between theory and experiment in the case of aluminum below energies of 1.33 MeV is in evidence, ranging from 13% with the mixed ^{60}Co γ rays to 40% in the case of $E_\gamma = 1.119$ MeV. The only previous measurements of the pair production cross sections in aluminum at these energies were made by Dayton, and also by Shkolnik and Standil, both using the mixed ^{60}Co γ rays. If we normalize their results to our absolute cross sections at $Z=82$, their cross sections for $Z=13$ are 1.98 ± 0.10 and 2.09 ± 0.08 mb, respectively, both of which are in excellent agreement with the present results. The only other cross section measured in aluminum at these energies is that of 59 ± 10 mb at 2.62 MeV reported by Titus and Levy,[11] which is also consistent with the present result. The results of the present investigation for $E_\gamma = 1.119$ and $Z=13$ are still not

TABLE II. Experimental comparisons. σ_B, Born approximation; σ_0, present investigation; σ_1, Ref. 6; σ_2, Ref. 4; σ_3, Ref. 9; σ_4, Ref. 10; σ_5, Ref. 11; σ_6, Ref. 12; σ_7, Ref. 13; σ_8, Ref. 14; σ_9, Ref. 15.

E_γ^{inc}		σ_0/σ_B	σ_1/σ_B	σ_2/σ_B	σ_3/σ_B	σ_4/σ_B	σ_5/σ_B	σ_6/σ_B	σ_7/σ_B	σ_8/σ_B	σ_9/σ_B
1.119	29	1.56	...	2.10	...	...	...	...	...	...	...
	50	2.21	2.56	2.37	...	...	...	...	...	...	...
	82	2.59	...	2.61	1.59	...	...	1.96	...	...	2.36
1.1732	13	1.26	...	...	...	0.997	...	...	...	...	1.04
+	26	1.21	...	...	...	...	...	...	...	...	1.10
1.3325	29	1.27	...	...	1.20	1.111	...	...	1.18	...	1.16
	50	1.69	1.75	...		1.494	...	...	1.38	...	1.36
	82	2.49	...	...	2.20	2.04	...	...	2.02	2.12	2.02
2.6145	13	1.02	...	...	...	1.006	0.93	...	...	...	...
	26	1.04	...	...	...	...		...	...	...	...
	29	1.04	...	...	...	1.03	...	...	...	...	...
	50	1.11	1.16	...	...	1.081	1.04	...	...	...	...
	82	1.33	...	...	...	1.229	...	...	...	...	...

accurate enough for a conclusive comparison with theory. The difficulty still lies in the poor energy resolution of the NaI(Tl) which results in a significant continuum under the annihilation peak and becomes particularly noticeable for low photon energies incident on low-Z targets. The development of a method involving two Ge(Li) detectors is presently underway; however, this technique significantly reduces the counting efficiency which also results in poor quality data.

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