PHYSICAL REVIEW A VOLUME 10, NUMBER 3 SEPTEMBER 1974

Low-energy pair-production cross-section measurements for $Z = 50$

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(Received 8 November 1973; revised manuscript received 5 June 1974)

Absolute cross sections for the production of positron-electron pairs by photons incident on a pure tin target have been measured at photon energies of 1.1205, 1.3325, 1.8362, and 2.6145 MeV and also with the mixed 1.1732- and 1.3325-MeV γ rays in the decay of ^{60}Co. The resulting cross-sections are $\sigma(1.1205) = 5.4 \pm 0.5$, $\sigma(1.1732 + 1.3325) = 42 \pm 4$, $\sigma(1.3325) = 65 \pm 3$, $\sigma(1.8362) = 419 \pm 20$, and $\sigma(2.6145) = 1090 \pm 50$ mb. The comparison of these results with recent calculations shows that the importance of the screening correction appears rather sharply as the energy decreases. For $Z = 50$, we observe a sharp and sudden disagreement between the present measurements and the unscreened theoretical values below about 1.3 MeV. While screening corrections result in cross sections in much better agreement with the present experimental values, there is still a small discrepancy. The measurements were performed using a new technique in which a small spherical radioactive source is placed at the center of a spherical target. It was shown earlier that the corrections necessary to account for internal scattering of the γ rays in the target can be accurately made using Monte Carlo methods. The corrections were very small in all cases studied.

I. INTRODUCTION

The pair-production process of interest here is the fundamental process by which electron-positron pairs are created by γ rays in the electron-screened, nuclear Coulomb field. The first theoretical treatment of pair production was presented in 1933 by Nîshina and Tomonaga. There has since been a long series of theoretical developments on the subject which have been extensively reviewed by Motz *et al.*[1] Since that review, however, there have been several important theoretical papers which are mainly concerned with electron screening corrections and the use of exact Coulomb wave functions to describe the produced lepton pair. In particular we refer to the recent work of Tseng and Pratt[2] in which exact numerical screening corrections were made and also to the work of Øverbø *et al.*,[3] in which unscreened cross sections were calculated using exact, relativistic Coulomb wave functions. The results presented in Ref. 3 represent the first part of a program which will also result in screening corrected cross sections.

The screening corrections discussed in Ref. 2 are rather sophisticated calculations which result in an increase in the total pair-production cross section, at low photon energies, rather than in a decrease which might be argued from a somewhat naive picture involving a simple replacement of the nuclear charge Z by a smaller effective charge. The increase can be qualitatively understood by requiring that the lepton wave functions be normalized such that the probability currents for both leptons are the same at large distances from the nucleus as observed. If one now pictures the time-reversed process in which the leptons approach the nucleus from infinity, it can be seen that the probability density of the positron in the vicinity of the nucleus behaves very differently than that of the electron. This is because of its repulsion and screening tends to allow the positron to approach the nucleus with higher probability which results in the fact that electron screening might significantly increase the pair-production matrix elements, especially near threshold.

Even on the basis of such oversimplified considerations, one would conclude that the screening corrections might be very sensitive to the particular assumptions made as well as other details of the calculations. This would indicate that careful comparison of the theoretical and experimental cross sections, at several energies approaching threshold, would constitute a very important test of the screening corrections. An extensive comparison of theory and experiment was made in Ref. 2; however, many of the experimental results were not consistent nor accurate enough in order to draw strong conclusions. In addition, there have been very few actual absolute cross-section measurements made at low energies.

The purpose of the present investigation was to apply a recently developed, internal-source technique,[4] to measure the absolute pair-production cross sections for photons of several energies ranging from well above threshold (~2.6 MeV) to an energy much nearer threshold (~1.12 MeV) at which screening effects are expected to be important. In Sec. III, a direct comparison of the present experimental cross sections is made with the screening corrected cross sections of Ref. 2, the unscreened cross sections of Ref. 3, and with the results obtained using the Born approximation.

II. EXPERIMENTAL PROCEDURE

In this section we shall discuss the general features of the present experimental method, while a more detailed description is given in Ref. 4. The experimental setup used in the present investigation is easily understood by reference to Fig. 1. A radioactive source, in the form of an epoxy bead approximately 2 mm in diameter, was placed at the center of a solid sphere of chemically pure tin. The spherical target was cast in hemispheres with hemispherical holes milled at the center of each, which formed the source volume when the hemispheres are placed together. The target-source assembly was then placed on the mutual axis of the two detectors as shown in Fig. 1. The electronics consisted of a standard coincidence system with a resolving time of 100 nsec. The window of the single channel analyzer, corresponding to the 7.62×7.62 cm, NaI(Tl) detector, was adjusted to accept pulses corresponding to the 0.511-MeV annihilation radiations, while that corresponding to the 33 cm^3, Ge(Li) detector was set to accept pulses corresponding to the energy range of 400–600 keV. The coincidence pulse was used to gate a multichannel pulse-height analyzer, which observed the spectrum from the Ge(Li) detector. The efficiency calibration is discussed in Ref. 4.

Gamma rays of 1.205, (1.1732, 1.3325), 1.8362, and 2.6145 MeV were used from the radioactive decays of ^{46}Sc, ^{60}Co, ^{88}Y, and ^{228}Th, respectively. The sources ranged from 10 to 20 μCi in activity.

The cross section for the 1.3325-MeV γ ray in the decay of ^{60}Co was measured directly while the effective cross section for the 1.3325- and 1.1732-MeV γ rays together was also measured. The justification for the comparison of this cross section with theory stems from the excellent agreement with theory which was obtained with the 1.3325-MeV γ ray. The cross section for the 1.3325-MeV γ ray was measured in a rather tedious, three-counter coincidence experiment which would have been much more difficult in the case of the 1.1732-MeV γ ray, because of the smaller cross section. The cross section for the mixed 1.1732- and 1.3325-MeV γ rays was assigned an effective energy for the purpose of including this measurement in Fig. 2. This effective energy was chosen to be that which theoretically corresponds to the average theoretical cross section simply calculated by assuming equal intensities for the two γ rays. This average is then simply,

$$\langle \sigma_{\text{theor}} \rangle = \tfrac{1}{2}[\sigma_{\text{theor}}(1.1732) + \sigma_{\text{theor}}(1.3325)].$$

These γ rays are well known to be equal in intensity to a very excellent approximation. In addition, the decay of ^{88}Y contains a weak positron branch which gives rise to annihilation radiations which interfere with those following pair creation. This branch is weak enough so that an accurate correction could be made as discussed in Ref. 4.

The spherical symmetry of the target and source configuration results in the following simple relationship between the observed annihilation radiation coincidence rate C and the absolute pair-production cross section σ:

$$\sigma = \frac{\mu C}{NA\epsilon(1 - e^{-\mu(R-r)})},$$

where A is the source activity in γ rays per second, μ is the total γ-ray absorption coefficient in cm^{-1}, N is the number of target atoms per unit volume, ϵ is the annihilation-pair detection ef-

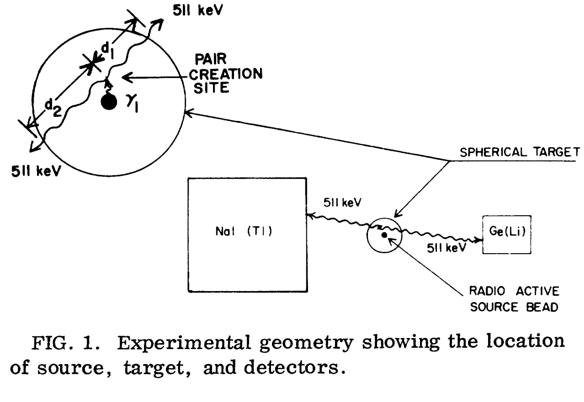

FIG. 1. Experimental geometry showing the location of source, target, and detectors.

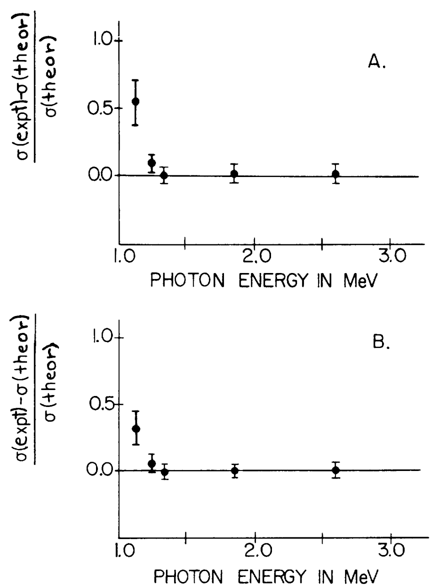

FIG. 2. Comparison of the experimental and theoretical absolute pair-production cross sections. In (A), σ(expt) is compared to the unscreened cross sections of Øverbø *et al.* In (B), σ(expt) is compared to the screened cross sections of Tseng and Pratt.

ficiency, and r and R are the source hole and target radii, respectively. The values for μ adopted were the best fits to the experimental data prepared by the National Bureau of Standards.[5,6] The total absorption coefficients enter into the data analysis only in the calculation of the γ-ray flux distribution throughout the target and the small experimental uncertainties in the values of μ have an insignificant effect on σ.

In addition to the obvious corrections to the data mentioned above, one must carefully evaluate the corrections necessary to account for the absorption or scattering of the annihilation radiations leaving the target, the Compton scattering of the incident γ ray and subsequent pair production at lower energy, the finite escape probability of positrons produced near the outer surface of the target as well as the small angle scattering of the annihilation radiations into and out of the detector solid angles. These corrections were mainly made using Monte Carlo techniques and are described in detail in Ref. 4. The largest correction made to the cross sections was that necessary to account for the absorption of the annihilation pairs in the target material, which was approximately 5%. All other corrections were on the order of 1% or less and, in any case, decreased with decreasing photon energy so as to be almost negligible in the energy region of greatest interest here.

III. RESULTS AND CONCLUSIONS

The pair-production cross sections were analyzed as discussed in Ref. 4 and are presented along with the screened, unscreened, and Born-approximation cross sections, in Table I. The quantity $[\sigma(\text{expt}) - \sigma(\text{theor})]/\sigma(\text{theor})$ is plotted for convenience in Fig. 2. For photon energies greater than about 1.3 MeV we see excellent agreement with both screened and unscreened theoretical values, which one might have expected from a direct comparison of the results presented in Refs. 2 and 3. The much larger deviation of the experimental values from the unscreened theoretical values than from the screened theoretical values, clearly supports the theoretical conclusions drawn in both Refs. 2 and 3 concerning the importance of screening at low photon energies. The fact that the present experimental results at the two lowest energies still appear to be somewhat above the screened theoretical cross sections was at first perplexing and the experiments and analyses were repeated with the same results. The corrections made were shown to be smaller in this energy region than at higher energies, since the volume of the target which contributes most strongly to the coincidence rate is closer to the center, making the primary active volume appear more like a point source than it does at higher incident photon energies. In addition, while the hole in the target does introduce minor complications in the analysis of the data, these complications are accurately accounted for in the Monte Carlo calculations of the corrections. In any case these effects are not nearly large enough to account for the remaining discrepancy.

We have repeated several of the measurements with excellent consistency and conclude that the only major improvement to be made in the present experimental technique would result from the use of two large Ge(Li) detectors. The choice of tin as a target was partly motivated by the desire to use the lowest-Z target for which the data near threshold were still of comparable quality to the data well above threshold. Higher-Z materials result in larger corrections. We have estimated that the use of two large Ge(Li) detectors might allow absolute measurements with accuracies of 3 or 4% even at 1.12 MeV. We are convinced, however, that while the experimental errors on the two cross sections of lowest energy presented here can be reduced by the use of two high-resolution detectors, the small systematic disagreement with

TABLE I. Experimental pair-production cross sections compared to the theoretical cross sections.

E (MeV)	σ(expt) (mb)	σ(TP)[a] (mb)	σ(ØMO)[b] (mb)	σ(Born) (mb)
1.120	5.4 ± 0.5	4.11	3.54	2.11
(1.173 + 1.333)	42 ± 4	39.5	38.2	24.03
1.333	65 ± 3	66.1	64.6	41.33
1.836	419 ± 20	418	402	317.1
2.615	1090 ± 50	1063	1061	941.3

[a] From the calculations of Tseng and Pratt.
[b] From the calculations of Øverbø, Mork, and Olsen.

the screened calculations of Ref. 2 will most probably remain. We conclude then that while the screening corrections appear to strongly improve the agreement between theory and experiment at low energies, the present data indicates that these corrections may still be somewhat inadequate.

ACKNOWLEDGMENTS

The authors are grateful to Professor H. K. Tseng and Professor I. Øverbø for supplying some of the specially calculated cross sections which appear in Table I.

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