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Pair production cross section in lead

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Abstract. The total cross section for the scattering of 40 MeV to 120 MeV photons in lead has been measured. The small difference between the measurements and the calculated values is interpreted as a shortcoming in the calculation of the pair production cross section.

1. Introduction

The cross section for electron pair production by photons in nuclear fields should be given to high accuracy by present quantum electrodynamics. The detailed calculations are not simple, and small errors are to be expected in published results, due to the approximations required to obtain an analytic result. The most suitable calculation to use depends on the energy range under consideration (Motz *et al* 1969). For energies above 20 MeV, the best calculation is that of Davies *et al* (1954). This calculation should show greatest error for nuclei of high atomic number and for decreasing energy. Existing measurements in lead near 90 MeV show discrepancies of about 1 %. We have made further measurements in lead over the range 40 MeV to 120 MeV.

2. Experimental

The total absorption cross section was found in the usual way by measuring the attenuation in a thickness of lead placed in a photon beam. The experimental layout is shown in figure 1.

The 380 MeV internal proton beam of the Liverpool synchrocyclotron produced π^0 mesons in an internal target. Doppler broadened backward-moving decay photons ($\pi^0 \rightarrow 2\gamma$), giving a continuous spectrum with a useful energy range from 30 to about 140 MeV, were used as the source. This beam was collimated by a 1·0 cm diameter aperture at 7·5 m from the target, resulting in a peak intensity at 90 MeV of about 0·5 photon $\mathrm{MeV}^{-1}\,\mathrm{s}^{-1}$.

A monitor, placed immediately after this collimator, used two thin (0·8 mm) plastic scintillators in fast coincidence. These counters will detect mainly the electrons and positrons formed by photons striking the collimator walls, and will therefore give a good measure of the photon flux. The cross section σ for a given energy is then related to

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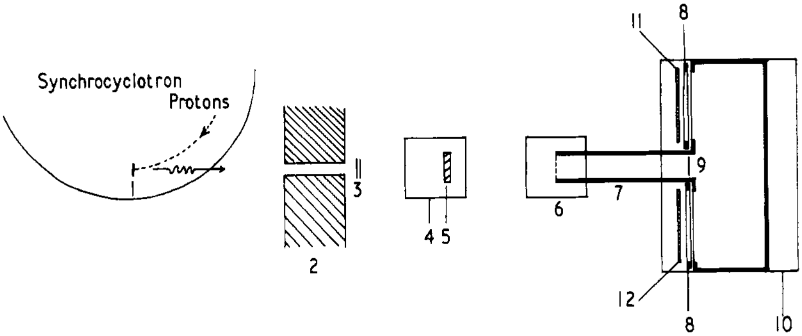

Figure 1. General layout of experiment (not to scale). Key to diagram: 1, Be target; 2, collimators; 3, monitor scintillators; 4, sweeping magnet; 5, absorbers; 6, sweeping magnet; 7, vacuum tank; 8, sonic spark chambers; 9, converter; 10, poles of pair spectrometer magnet; 11 and 12, scintillation counters. Distances: 1–2 7·5 m; 2–5 2·6 m; 5–9 10 m. Sizes: collimator 1 cm diameter; absorbers 7·5 cm × 7·5 cm; converter 2·5 cm × 2·5 cm or 5·0 cm × 5·0 cm × 0·05 cm.

background corrected counts in the spectrometer channel N_{in} and N_{out}, and in the monitor M_{in} and M_{out}, with the absorber in and out respectively. This is given by

$$\frac{N_{\mathrm{in}}/M_{\mathrm{in}}}{N_{\mathrm{out}}/M_{\mathrm{out}}} = \exp(-\sigma x)$$

where x is the absorber thickness in atoms per square centimetre.

A magnet to sweep any charged particles out of the beam was placed before the lead absorbers, which were 7·5 cm square and about 6 mm thick. Two, three or four of these were used. An evacuated pipe extended for 8 m in front of the photon detector. A second sweeping magnet covered the beginning of this pipe.

The photons were detected in a 180° pair spectrometer. Two sonic spark chambers were used to locate the electron–positron pairs (Butler *et al* 1968), which were triggered by a fast coincidence of two scintillation counters (11, 12 in figure 1) detecting the electron pair. The whole detection system and electron-coordinates data handling system had a dead time of 1 s; the event rate was usually of order one every few seconds. A total number of about 3×10^4 events (both absorber in and out) were recorded over an experimental run of 5 d. Background rates, measured by removing the lead converter, were of order less than 1 % of the event rate. Measurements were taken with different sizes of converter in the spectrometer to obtain a check on the effects of secondary processes in the absorber (see below). The energy resolution was estimated to be less than 1 MeV. The results were grouped into bands about 10 MeV wide. The calculation of the mean energies quoted in table 2 took into account the energy dependent efficiency of the detector.

3. Results

The results for the measured total cross sections are shown in column 2 of table 1. Quoted errors are entirely from counting statistics. Errors in measurements of absorber thickness were about 0·2 %. Since good geometry was used—the converters subtended 6×10^{-6} sr at the absorber—the effects of secondary radiations from the absorber were

Table 1. Cross sections in barns

Photon energy (MeV)	Experimental	Theoretical					
		Nuclear pairs	Electron pairs	Compton	Photo-electric	Photo-nuclear	Total
34·7	24·13±0·96	22·1	0·18	1·60	0·09	0·17	24·15
45·7	27·64±0·68	24·56	0·22	1·29	0·07	0·15	26·29
56·2	29·11±0·54	26·32	0·25	1·06	0·05	0·12	27·80
66·7	29·42±0·49	27·70	0·28	0·94	0·04	0·10	29·06
77·7	30·43±0·51	28·84	0·30	0·83	0·04	0·07	30·08
88·9	31·59±0·54	29·82	0·31	0·74	0·03	0·05	30·95
102·0	33·12±0·56	30·77	0·33	0·66	0·03	0·02	31·81
119·4	33·50±0·79	31·77	0·35	0·58	0·03	0·00	32·73

negligible. This was confirmed experimentally by verifying that the measured absorption cross section did not vary with either absorber thickness or converter area. For example the average cross sections $\bar{\sigma}_1$ and $\bar{\sigma}_2$, measured over an energy range 30–90 MeV, with converters of area 6 25 cm^2, and 25 cm^2 respectively, were in the ratio

$$\frac{\bar{\sigma}_1}{\bar{\sigma}_2} = 1{\cdot}022 \pm 0{\cdot}025.$$

For the range 90–130 MeV, this ratio was 1·021 ± 0·032.

4. Theoretical cross sections

The total cross section, as measured above, has contributions from: (*a*) pair creation in the nuclear field; (*b*) pair creation in the electron field; (*c*) Comption scattering; (*d*) photoelectric effect and (*e*) photonuclear absorption.

In the present experiment, (*a*) gives the major contribution, (*b*) about 1 %, (*c*) 2 % to 5 % and (*d*) and (*e*) together less than 1 %.

The results for (*a*) are calculated from the results of Davies *et al* (1954). These were corrected for the energies not being strictly 'extreme relativistic'. The correction was based on the results of Jost *et al* (1950), and gave 0·31 b and 0·04 b at 34·7 MeV and 119·4 MeV respectively. The triplet production cross section is given well enough here by the result of Votruba (1948). The Compton scattering was calculated from the Klein–Nishina formula.

5. Discussion

The measured values are consistently greater than the theoretical ones. In view of the magnitudes of the processes involved, this discrepancy is regarded as being due to an underestimate of the nuclear field contribution to the pair creation. That this should be expected was pointed out by Davies *et al* (1954).

The discrepancy in our results and in data at 88 MeV (Lawson 1949) and 94 MeV (Moffat *et al* 1958) was fitted to a curve of the form $k^{-1}\ln(k/E_0)$, where k is the photon energy and E_0 is the electron rest energy. Another term of the form k^{-1} is to be expected to appear, but the quality of the measurements does not justify its inclusion. The use of the k^{-1} term by itself gives a curve that rises too rapidly below our measurements. The result for the observed pair production cross section σ_{expt} is

$$\sigma_{\mathrm{expt}} = \sigma_{\mathrm{DBM}} + (8{\cdot}4 \pm 1{\cdot}8)k^{-1}\ln(k/E_0)$$

where σ_{DBM} is the result of the calculations of Davies *et al* (1954). The measurements and the fitted curve are shown in figure 2.

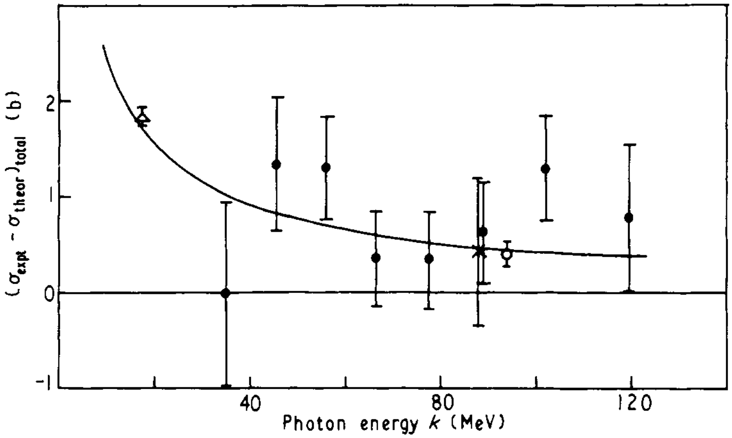

Figure 2. Differences between measured and calculated values of total cross sections. ● present experiment; △ combined result of Walker (1949) and Rosenblum *et al* (1952); × Lawson (1949); ○ Moffat *et al* (1958). The full curves are fits of all the above data, except △, to $k^{-1}\ln(k/E_0)$.

The point at 17·6 MeV, the mean of measurements by Walker (1949) and by Rosenblum *et al* (1952) was not included in our fit. Various measurements at still lower energies are, not surprisingly in disagreement with our curve. However measurements at 280 MeV (De Wire *et al* 1951) and at 319 MeV (Anderson *et al* 1956) agree very closely with our fit. The fit given above therefore is probably reliable at energies above 20 MeV.

Acknowledgments

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