Absorption of 17.6 Mev Gamma-Rays in C, Al, Cu, Sn, and Pb

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The gamma-ray absorption cross sections of C, Al, Cu, Sn, and Pb have been measured for the 17.6 Mev gamma-rays produced in the $Li^7(p, \gamma)Be^8$ reaction. A gamma-ray pair spectrometer was used as a detector for the 17.6 Mev gamma-rays in order to avoid counting lower energy quanta produced either in the $Li^7(p, \gamma)Be^8$ reaction, or as secondary radiation in the absorber. The measured cross sections are compared to the sum of the theoretical cross sections for Compton scattering, pair production in the field of the nucleus and pair production in the field of the atomic electrons. For the light elements, the agreement is within the experimental errors of about one percent, but for lead the theoretical value is ten percent above the measured cross section. This discrepancy probably results from the use of the Born approximation in the Bethe-Heitler calculation of pair production. The present results are in good agreement with recent measurements of Adams at 11.04, 13.73, and 19.10 Mev, and of Lawson at 88 Mev.

INTRODUCTION

THE importance of accurate measurements of the absorption coefficients of high energy gamma-rays in various elements as a means of checking the theoretical predictions concerning pair production and Compton scattering, has long been recognized.[1] Until very recently, however, no very accurate measurements have been made because of difficulties introduced by the production of degraded secondary radiation accompanying the absorption of the primary radiation. This secondary radiation makes it necessary to use for an absorption measurement an energy selective detector which can discriminate between the primary gamma-rays and the lower energy secondary quanta.

The first measurement performed with such a detector was that of Delsasso, Fowler, and Lauritsen,[2] in 1937. They determined the quantum energy of the gamma-rays produced in the $Li^7(p, \gamma)Be^8$ reaction, by measuring the total energy of electron pairs produced by the gamma-rays in a thin lead plate in a cloud chamber. They then used the same technique of counting pairs in a cloud chamber to measure the absorption coefficient for these gamma-rays in lead. Their result was about ten percent below the theoretical value, but the statistical uncertainty was also ten percent. Later McDaniel, von Dardel, and Walker[3] used a magnetic pair spectrometer to measure the absorption of the 17.6 Mev lithium gamma-rays in lead and aluminum. The results were roughly in agreement with the theory within statistical errors of 5 to 10 percent.

Recently, accurate measurements of the absorption of betatron radiation in various elements have been made by Adams, and by Lawson. Adams[4] used threshold detectors to measure the absorption in Al, Fe, Cu, and Pb of 11.04, 13.73, and 19.10 Mev betatron x-rays. Lawson[5] used a magnetic pair-detecting spectrum analyser to measure the absorption of 88 Mev gamma-rays in Be, Al, Cu, Sn, Pb, and U. The experimental results of Adams and of Lawson, as well as those reported in the present paper, show rather good agreement with the theory for light elements (except for Lawson's Be measurement) but discrepancies of the order of 9 to 13 percent for the heaviest elements. These discrepancies for very heavy elements are believed to result from a failure of the Born approximation used in the Bethe-Heitler calculation of pair production.[6] Unfortunately, no more exact calculations are available at present.

The gamma-rays used in the present experiments were those emitted from the 440-kev proton resonance of the $Li^7(p,\gamma)Be^8$ reaction. The spectrum of these gamma-rays consists of a sharp line at 17.6 Mev, and a broad line near 14.8 Mev with a relative intensity about half that of the 17.6 Mev line.[7] The gamma-ray detector was a magnetic pair spectrometer. By adjusting the spectrometer to be sensitive only to gamma-rays in a narrow energy band near 17.6 Mev, one can avoid counting either the lower energy gamma-rays from the source (near 14.8 Mev), or lower energy secondary radiation produced in the absorber. Thus the gamma-rays investigated have a very sharply defined energy rather than a narrow band from a continuous spectrum, as is the case when betatron radiation is used. This advantage is rather unimportant, however, since the absorption cross sections investigated do not vary rapidly with energy.

II. APPARATUS

The gamma-ray spectrometer used in these experiments has been described previously in some detail.[7] It measures the total energy of electron pairs produced by the gamma-rays in a thin radiator. In the absorption experiments, a comparatively thick radiator of 0.006-inch Pb was used in order to obtain a high counting rate, and thus good statistical accuracy.

[1] For example, see W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1936).
[2] Delsasso, Fowler, and Lauritsen, Phys. Rev. **51**, 391 (1937).
[3] B. D. McDaniel, Guy von Dardel, and R. L. Walker, Phys. Rev. **72**, 985 (1947).
[4] G. D. Adams, Phys. Rev. **74**, 1707 (1948).
[5] J. L. Lawson, Phys. Rev. **75**, 433 (1949).
[6] H. A. Bethe and W. Heitler, Proc. Roy. Soc. **146**, 83 (1934).
[7] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).

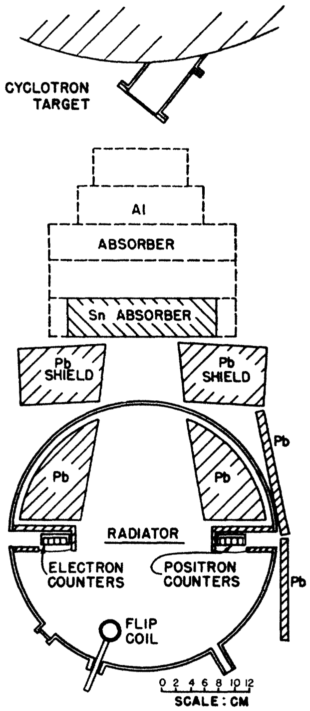

FIG. 1. Geometrical arrangement of the spectrometer, the absorber, and the cyclotron target. The actual positions occupied by the Sn and Al absorbers are shown. The Pb and Cu absorbers occupied a space about like the Sn, whereas the graphite had a configuration similar to that shown for Al.

The geometrical arrangement of the spectrometer, absorber, and cyclotron target is shown in Fig. 1. The transmission of each absorber was measured in the usual way by observing alternately the counting rates with and without the absorber in position. (Because of the wide radiator used in the spectrometer, some of the gamma-rays traverse the absorber at small angles from its normal. Thus the effective thickness of the absorber is slightly greater than its actual thickness, but this effect has been neglected since it amounts to only 0.2 percent.)

In order to monitor the gamma-ray intensity, two small Geiger counters were mounted in lead shields, one 65 cm above and one 21 cm below the cyclotron target. Precautions were taken to insure that the counting rates of the monitors were not affected by the presence of the absorbers, since the graphite and aluminum absorbers extented rather close to the cyclotron target, and might scatter gamma-rays into the monitors. For example, the positions of the monitors were such that radiation reaching them from the absorber must have been scattered through angles $\gtrsim 90°$. Thus most of this scattered radiation had very low energies ($\lesssim 0.5$ Mev) and would be more strongly absorbed in the 4.5 cm lead monitor shield than the primary gamma-rays from the cyclotron target.

A rough calculation indicates that the effect on the monitor counting rates of radiation scattered from the absorber was probably much less than 0.5 percent. This question was also investigated by observing the monitor counting rates relative to the spectrometer counting rate when large blocks of aluminum were placed on both sides of the cyclotron target in such a position that they did not shield the spectrometer radiator, but might be expected to scatter about twice as much radiation into the monitors as the aluminum or graphite absorbers. An effect of 2.2 ± 1.1 percent in the wrong direction was found, which probably has no significance.

III. PROCEDURE

As described in a previous paper[7] the gamma-ray spectrometer records data simultaneously in seven different energy intervals, separated in energy by about 4 percent. In the absorption experiments, the magnetic field of the spectrometer was adjusted so that the center of the 17.6 Mev lithium gamma-ray peak fell midway between the central channel, No. 4, and an adjacent channel, No. 3. The counts in these two channels were then added (after correcting for a difference in statistical weight arising from the fact that channel 4 is fed by coincidences from four counter pairs, whereas channel 3 is fed by only 3 counter pairs). This procedure makes the final "spectrometer counting rate" insensitive to small variations in the magnetic field, since *e.g.* a drop in the counting rate of channel 4, caused by a slight increase in the magnetic field, is closely compensated by an increase in the counting rate of channel 3.

The transmission of each absorber for 17.6 Mev gamma-rays was measured by counting alternately with and without the absorber in position. For each transmission measurement from six to fifteen measurements were made with the absorber, and a like number without. The time required to obtain one percent statistical accuracy in the determination of the cross section for one absorber was usually from eight to fifteen hours, with a proton current of about 100 μa, and a fresh Li target. The proton energy used in these experiments was approximately 460-kev, just above the 440-kev Li resonance. The thick Li targets used were made by evaporation of lithium metal in a vacuum.

A small background of counts obtained with no radiator in the spectrometer was subtracted from the counting rates with and without absorber before calculating the transmission. This background was 0.1 percent of the counting rate without absorber, and about 2.3 percent of the counting rate for the thickest absorber used. The resulting correction to the transmis-

TABLE I. Experimental cross sections.

Absorber element	Thickness (cm)	Thickness (g/cm²)	Transmission T	$1/N \log(1/T)$ (10^{-24} cm²)	Resolution correction (10^{-24} cm²)	Experimental absorption cross section (10^{-24} cm²)
C	29.90	46.15	0.477	0.320	+.003	0.323 ± 0.0045
Al	25.65	69.60	0.2231	0.965	+.007	0.972 ± 0.011
Cu	6.367	56.76	0.1418	3.631	+.016	3.65 ± 0.027
Cu	6.367	56.76	0.1456	3.582	+.016	3.60 ± 0.029
Cu (Av)						3.62 ± 0.020
Sn	4.976	36.27	0.1932	8.93	+.027	8.96 ± 0.09
Pb	1.659	18.78	0.3271	20.46	+.04	20.50 ± 0.26
Pb	2.746	31.10	0.1563	20.53	+.04	20.57 ± 0.17
Pb	4.405	49.88	0.0509	20.54	+.04	20.58 ± 0.21
Pb (Av)						20.56 ± 0.12

TABLE II. Theoretical cross sections.

Element	Compton cross section (10^{-24} cm^2)	Pair production (nucleus unscreened) (10^{-24} cm^2)	Screening correction (percent)	Pair production (nucleus screened) (10^{-24} cm^2)	Pair production (electrons) (10^{-24} cm^2)	σ (theory) (10^{-24} cm^2)
C	0.2004	0.1100	−1.4	0.1085	0.0124	0.3213
Al	0.434	0.516	−2.1	0.505	0.027	0.966
Cu	0.968	2.569	−3.1	2.489	0.060	3.517
Sn	1.67	7.64	−4.0	7.33	0.10	9.10
Pb	2.74	20.54	−5.0	19.51	0.17	22.58*

* The total cross section of lead includes a contribution of 0.16×10^{-24} cm^2 (0.7 percent) for the atomic photoelectric effect.

sion alters the cross section by only 0.8 percent. To obtain confidence that no errors might occur from some unknown and unmeasured background, three quite different thicknesses of lead were used as absorbers. All gave the same result for the absorption cross section, as may be seen in Table I.

Because gamma-rays in a finite energy interval near 17.6 Mev may be recorded by the spectrometer, Compton scattered gamma-rays which have lost only a small fraction of their energy will not appear to have been "absorbed." A "resolution correction" has been made in the absorption cross sections to take account of this effect. This resolution correction has been calculated on the assumption that the Compton scattering is correctly described by the differential Klein-Nishina formula.[1] It is simply the cross section for scattering of a 17.6 Mev gamma-ray in which the scattered quantum has an energy greater than or equal to 16.9 Mev. This correction is 1.6 percent of the total Compton cross section.

IV. EXPERIMENTAL RESULTS

The transmission, T (corrected for background), observed for each of the absorbers is shown in Table I. The column headed $(1/N)\log(1/T)$ then gives the uncorrected absorption cross sections, where N is the thickness of the absorber in atoms per cm^2. After adding the small resolution correction, one obtains the experimental absorption cross section, σ, in the last column of Table I. The errors listed are statistical standard errors obtained either from the total number of counts, or from the root mean square deviations of the individual runs from their average, whichever was larger. (The two measurements of Cu shown in Table I were made with the same Cu absorber, but slightly different geometrical arrangements. In the second measurement the Cu absorber was nearer to the cyclotron target than in the first.)

The purity of the absorbers was checked by obtaining standard, qualitative spectrographic analyses from the New England Spectrochemical Laboratories of Ipswich, Massachusetts. Any impurities reported in amounts which might be significant were then measured quantitatively in our laboratory by Dr. D. R. Miller. No impurities were found in sufficient amounts to warrant making a correction in the data. (The largest correction for impurities would have been only −0.3 percent, for the aluminum absorber.)

V. THEORETICAL CROSS SECTIONS

In Table II are given the theoretical values of the absorption cross sections for 17.6 Mev gamma-rays, assuming that this absorption takes place only by Compton scattering and by pair production in the field of the nucleus or of the atomic electrons. In addition, the cross section of lead includes a small contribution from the atomic photoelectric effect.

The Compton cross section is given directly by the Klein-Nishina formula.[1, 8]

The cross section for pair production in the field of the nucleus has been calculated from the theory of Bethe and Heitler.[6] The unscreened pair cross sections have been obtained from the high energy integral formula given by Hough.[9] The effect of screening is not entirely negligible at 17.6 Mev, since it amounts to 5 percent for lead, for example. Therefore, screening corrections have been calculated from the low energy formula of Bethe and Heitler[6] involving the function $C(\gamma)$. These corrections, and the final screened pair cross sections are shown in Table II.

The cross section for pair production in the field of the atomic electrons is unfortunately not known very certainly at 17.6 Mev, although several calculations have been made for various energy regions.[10] The values given in Table II are obtained from the results of Borsellino, who gives for the ratio of the pair cross section of an electron to that of the proton the (interpolated) value of 0.68 at 17.6 Mev. (Perhaps a ratio nearer 1.0 should be used, according to the calculations of Wheeler and Lamb. However, this change would not make much difference in the total cross sections used.)

The last column of Table II, headed σ(theory), gives the sum of the three cross sections discussed above, except for the lead cross section, which includes a contribution of 0.7 percent for the atomic photoelectric effect.[1] The photoelectric effect is not significant for the other elements. Another process which might contribute

TABLE III. Comparison between theory and experiment.

Element	σ (theory) (10^{-24} cm^2)	σ (experiment) (10^{-24} cm^2)	Difference (%)
C	0.3213	0.323±1.4%	+0.5
Al	0.966	0.972±1.1%	+0.6
Cu	3.517	3.62 ±0.6%	+2.9
Sn	9.10	8.96 ±1.0%	−1.5
Pb	22.58	20.56 ±0.6%	−9.8

[8] O. Klein and Y. Nishina, Zeits. f. Physik **52**, 853 (1929).

[9] P. V. C. Hough, Phys. Rev. **73**, 266 (1948), Eq. (1). The total cross section has been adjusted in the manner described by Hough, by multiplying by the ratio of the exact to the high energy differential cross section at the "midpoint," $E_+=E_-=k/2$.

[10] J. A. Wheeler and W. E. Lamb, Phys. Rev. **55**, 858 (1939); K. M. Watson, Phys. Rev. **72**, 1060 (1947); A. Borsellino, Helv. Phys. Acta **20**, 136 (1947); P. Nemirovsky, J. Phys. U.S.S.R. **11**, 94, (1947) treats energies<3 Mev.; V. Votruba, Phys. Rev. **73**, 1468 (1948).

to the absorption is nuclear photo-disintegration. The possible contribution of this process to the observed absorption cross section for copper will be discussed in the next section.

VI. COMPARISON BETWEEN THEORY AND EXPERIMENT

A comparison is given in Table III between the theoretical absorption cross sections and those observed experimentally. For the light elements, carbon and aluminum, the experimental and theoretical values agree within the statistical errors of 1.4 and 1.1 percent, respectively. This close agreement is secured only by taking into account the production of pairs in the field of the atomic electrons, since this process contributes 3.9 percent of the total cross section for carbon, and 2.8 percent for aluminum.

The experimental cross section for lead, the heaviest element measured, is 9.8 percent below the theoretical value, which far exceeds the statistical error of 0.6 percent. As mentioned above, this discrepancy is believed to result from the use of the Born approximation in the Bethe-Heitler calculation of pair production.[6] (See also references 4 and 5.) Since the condition for validity of the Born approximation is $Ze^2/\hbar v \ll 1$, where v is the velocity of the electron (or positron), it is not surprising to find a ten percent discrepancy for a heavy element. (For high energy electrons, this condition reduces to $Z/137 \ll 1$, which is certainly not very well satisfied for lead.)

The copper absorption cross section for 17.6 Mev gamma-rays is found to exceed the theoretical value by 2.9 percent, which is 5 times the standard statistical error. Although this discrepancy is too small to be very significant, it is not unreasonable to ascribe a part of it to nuclear photo-disintegration, which has a rather large cross section for copper, and which has not been included in the theoretical absorption cross section. If the error in the calculated pair cross section, arising from the use of the Born approximation, is proportional to Z^2,[5] then the absorption in copper by Compton scattering and pair production might be expected to be about 1 percent below the theoretical value of Table II. This means that the observed cross section is roughly 4 percent, or 0.14×10^{-24} cm^2, higher than might be "expected" without considering the nuclear photo-effect. Unfortunately, the cross section for this process has not been measured very accurately. Bothe and Gentner[11] give a value of $\sim 0.05 \times 10^{-24}$ cm^2 for the $Cu^{63}(\gamma, n)Cu^{62}$ cross section at 17.6 Mev. However, recent measurements by Wäffler and Hirzel[12] give a value for the same energy of 0.16×10^{-24} cm^2. Other values which have been reported from betatron measurements are $\sim 0.13 \times 10^{-24}$ cm^2,[13] and $\sim 0.06 \times 10^{-24}$ cm^2.[14] The cross section for the $Cu^{65}(\gamma, n)Cu^{64}$ reaction involving the other copper isotope (abundance 30 percent) is even larger,[12] being about 1.5 times that for Cu^{63}. It thus appears that the photo cross section for copper may be large enough to account for the high absorption observed in the present experiment. (Compare also reference 4.)

It is also of interest to consider the possible contribution of the photo process to the absorption cross sections of the other elements investigated. This contribution is probably unimportant for the light elements, C and Al, since the photo cross section is very small at this energy in light elements.[12] (In fact, the threshold for the (γ, n) reaction in C is above 17.6 Mev.) It might contribute something like 0.3 percent for Al. In Sn and Pb, the photo cross sections may be comparable or even larger than that for Cu, but their effect is masked by the Born approximation error in the pair cross section.

The results of these experiments, in their relation to the theory, are very similar to those of Adams[4] at 11.04, 13.73, and 19.10 Mev, and of Lawson[5] at 88 Mev. One difference is that a 7 or 8 percent discrepancy with theory was found for Be by Lawson, whereas no discrepancy was observed in the present experiments for the light element, C.

An interesting conclusion regarding the "Born approximation discrepancy" for lead as a function of energy may be drawn from a comparison of the three experiments. This discrepancy, in percent, seems to be essentially constant between 11 and 88 Mev. If the entire discrepancy between the experimental and theoretical absorption cross sections is considered to represent an error in the theoretical pair cross section alone, then this error is approximately 12 percent at all the five energies which have been investigated between 11 and 88 Mev.*

Since exact calculations of Hulme and Jaeger[15] at 1.5 and 2.6 Mev give pair cross sections for lead *higher* than the Born approximation values, it would be interesting to measure this pair cross section at energies between 2 and 11 Mev.

VII. ACKNOWLEDGMENTS

I am indebted to Professor B. D. McDaniel for many discussions and continued interest in these measurements. This work was supported in part by the ONR.

[11] W. Bothe and W. Gentner, Zeits. f. Physik **106**, 236 (1937).

[12] H. Wäffler and O. Hirzel, Helv. Phys. Acta **21**, 200 (1948). The value $\sigma = 0.12 \times 10^{-24}$ cm^2 published by Wäffler and Hirzel has been increased by them to 0.16×10^{-24} cm^2 by taking into account the fact that not all the lithium gamma-rays have an energy 17.6 Mev. The 14.8 Mev component is relatively less effective for the (γ, n) process.

[13] Skaggs, Laughlin, Hanson, and Orlin, Phys. Rev. **73**, 420 (1948).

[14] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).

* The energy dependence discussed by Adams for his data arises mainly from inaccuracies of a few percent in the theoretical cross sections used by him. These errors arise from a neglect of screening and from the use of the "usual" high energy integral formula for pair production. (See reference 1, p. 200, Eq. (15).) If Adam's data is compared to more accurate theoretical cross sections, the discrepancy for lead is found to be practically independent of the energy, as discussed above.

[15] H. R. Hulme and J. C. Jaeger, Proc. Roy. Soc. **153**, 443 (1936).