Photon Self-Absorption and Scattering by the 15.1-Mev Level in C^{12}†

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Bremsstrahlung x-rays have been used to excite the 15.1-Mev level in C^{12}. The integral scattering cross section of 19.0±0.27 Mev mb has been determined by measuring the absolute number by 15.1-Mev x-rays scattered. The peak absorption cross section 22.2±2.2 barns has been obtained from a self-absorption experiment. These results combine to give 54.5±9.3 ev for the ground state radiation width and 79±16 ev for the total width of the level.

INTRODUCTION

A NUMBER of particle reactions[1] have been used to excite a 15.1-Mev level in C^{12}. This level has also been excited by irradiating a carbon target with 15.1-Mev x-rays.[2] The angular distribution of the scattered x-rays is consistent with dipole scattering.[3] Although this level is well above the threshold for alpha-particle decay, Kavanagh[4] has found $\Gamma_\alpha/\Gamma_\gamma<0.5$. The inhibited alpha-particle decay and the dipole nature of the ground-state transition establish this level as belonging to the $T=1$, $J=1+$ isobaric spin triad B^{12}, C^{12}, N^{12}.

This paper is an account of an experiment in which bremsstrahlung x-rays have been used to study this level. It contains a description of the methods used to determine the peak absorption cross section in the level and the integral scattering cross section. The peak absorption cross section was determined from a measurement of the attenuation of the 15.1-Mev photons scattered by a carbon target when a carbon absorber was placed in the incident beam. The integral scattering cross section was obtained by measuring the absolute number of 15.1-Mev photons scattered by a target irradiated in a bremsstrahlung beam of known intensity. From these two quantities the branching ratio corresponding to ground-state radiative transitions, Γ_γ/Γ, and the ground-state radiation width, Γ_γ, were obtained.

EXPERIMENTAL ARRANGEMENT

Except for some improvements in the shielding around both the betatron and the detector, the experimental arrangement was the same as the one used in a previous experiment.[5] The arrangement is shown in Fig. 1. The important modifications were: (1) a twenty-channel pulse-height analyzer was used to take the data, (2) the solid angle of the detector was no longer defined by the dimensions of the NaI(Tl) crystal but by a 3-inch diameter hole through a 5-inch lead plug placed in front of it, (3) the Lucite absorber placed between the target and detector to remove electrons and low-energy photons emitted by the target was made as thin as possible (4–8 g/cm^2) to minimize the degradation of the scattered photons.

The pulse-height distribution obtained when a 19-Mev bremsstrahlung beam filtered by 97 g/cm^2 of aluminum irradiates a 1.98 g/cm^2 polystyrene target is given by the histogram in Fig. 2. As will be shown later, the sharp rise in the pulse spectrum below nine millivolts pulse height is not associated with the 15.1-Mev line and probably results from multiple processes in the target. Based on an extrapolation from the 1.13-Mev line from a Zn^{65} source, the peak in this pulse-height distribution corresponds to a photon energy near 15 Mev. The threshold for the production of the carbon line is 15.0±0.2 Mev. This threshold is based on the energy scale for the betatron determined by observing the (γ,n) thresholds in Be^9, B^{10}, Cu^{63}, and Cu^{65}.

The two experiments described below were performed by using graphite and polystyrene targets and absorbers approximately 2 g/cm^2 thick. A bremsstrahlung energy of 19 Mev was chosen in order to maximize the number of 15.1-Mev photons scattered without introducing appreciable neutron background from the $C^{12}(\gamma,n)C^{11}$ process and to eliminate the possibility of feeding the 15-Mev state from higher levels.

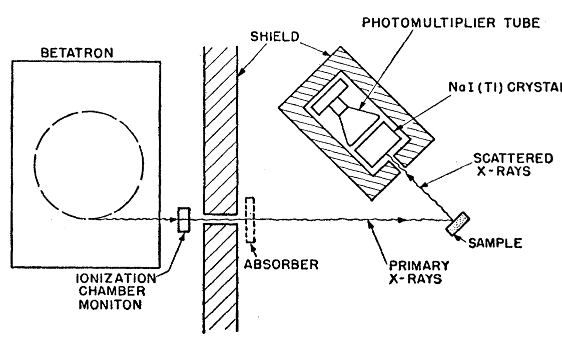

FIG. 1. The experimental arrangement.

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[1] V. R. Johnson, Phys. Rev. **86**, 302 (1952); Cohen, Moyer, Shaw, and Waddell, Phys. Rev. **96**, 714 (1954); Rasmussen, Ree, Sampson, and Wall, Phys. Rev. **96**, 812 (1954); Bigham, Allen, and Almqvist, Phys. Rev. **99**, 631 (1955); C. A. Barns and R. W. Kavanagh, Phys. Rev. **100**, 1796 (1955).

[2] Fuller, Hayward, and Svantesson, Bull. Am. Phys. Soc. Ser. II, **1**, 21 (1956); E. Hayward and E. G. Fuller, Physica, **22**, 1138 (1956).

[3] J. E. Leiss and J. M. Wyckoff, Bull. Am. Phys. Soc. Ser. II, **1**, 197 (1956).

[4] R. W. Kavanagh, Ph.D. dissertation, California Institute of Technology, 1956 (unpublished).

[5] E. G. Fuller and Evans Hayward, Phys. Rev. **101**, 692 (1956).

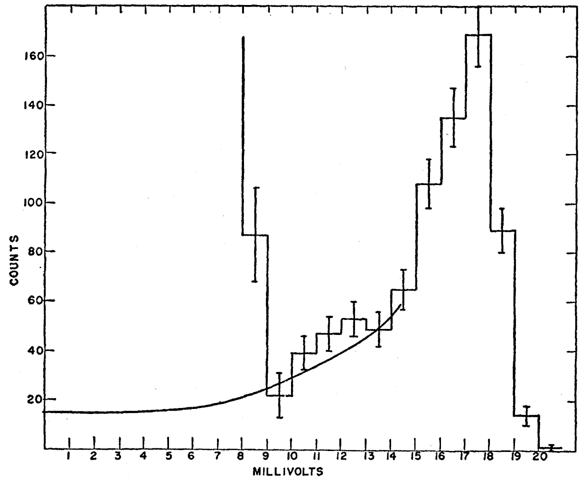

FIG. 2. The pulse-height distribution produced in the NaI(Tl) crystal when a 1.98-g/cm² polystyrene target was irradiated by a 19-Mev bremsstrahlung beam filtered through 97 g/cm² of Al. The solid line represents the extrapolation used to obtain the total number of interactions produced in the crystal by 15.1-Mev photons.

All runs were monitored in terms of the charge produced in the transmission ionization chamber indicated in Fig. 1. This charge was collected on a polystyrene film condenser, the voltage across which was measured with an Applied Physics Corporation Model 30 Vibrating Reed Electrometer.

THE SELF-ABSORPTION EXPERIMENT

The self-absorption experiment from which the peak absorption cross section in the level was obtained was a relative measurement. It consisted of observing the attenuation of the scattered photons when an absorber of the target material was placed in the incident beam. These data were taken in a series of runs made alternately with and without the absorber. Each run lasted approximately 40 minutes. In the "absorber out" runs approximately 150 counts were obtained in each run in the 10 to 20 mv region of the pulse-height distribution shown in Fig. 2. All runs taken under the same conditions were consistent with each other within the statistical uncertainties of the data.

In addition the attenuation produced by an aluminum absorber placed in the incident beam as well as that produced by carbon and aluminum absorbers placed in the scattered beam was measured. The results of the attenuation measurements are given in Table I.

TABLE I. Attenuation measurements.

Thickness g/cm²	Absorber	$Y(\Delta)/Y(0)$	$e^{-\sigma_e\Delta}$
2.07	C in incident beam	0.511±0.025	0.97
1.62	Al in incident beam	1.1 ±0.1	0.97
13.7	Al in scattered beam	0.64 ±0.05	0.74
7.77	C in scattered beam	0.81 ±0.07	0.87

The attenuations are compared with those to be expected from electronic absorption alone. The fact that self-absorption was observed when the carbon absorber was placed in the incident beam and not observed when the absorber was in the scattered beam indicates that the level width is small compared to the energy given to the recoiling carbon nucleus. At 120° this energy is about 30 kev.

Quantitatively it follows from Eq. (5) of reference 5 that the number of photons scattered by a target of thickness T, in which the nuclear scattering cross section is $\sigma_s(E)$ and the nuclear and electronic absorption cross sections are, respectively, $\sigma_n(E)$ and σ_e, is proportional to:

$$Y(0)=\int dE\frac{\sigma_s(E)}{1+\sigma_n(E)/2\sigma_e}\times[1-e^{-(\sigma_n(E)+2\sigma_e)NT/\cos\beta}]. \quad (1)$$

The number of pulses registered in the nine channels around the peak of the distribution of Fig. 2 have been taken as a measure of $Y(0)$. Similarly the number of pulses observed in this peak when an absorber of thickness Δ is placed in the incident beam is proportional to:

TABLE II. Target and absorber properties.

	Graphite	Polystyrene
Target	2.07 g/cm²	1.98 g/cm²
Absorber	2.07 g/cm²	1.98 g/cm²
$2\sigma_e$	0.674 b	0.758 b
$I(\Delta)/I(0)$	0.529±0.026	0.543±0.017

$$Y(\Delta)=e^{-\sigma_e\Delta}\int dE\frac{e^{-\sigma_n\Delta}\sigma_s(E)}{1+\sigma_n(E)/2\sigma_e}\times[1-e^{-(\sigma_n+2\sigma_e)NT/\cos\beta}]. \quad (2)$$

The ratio

$$Y(\Delta)/Y(0)=e^{-\sigma_e\Delta}I(\Delta)/I(0) \quad (3)$$

has been determined experimentally. The ratios $I(\Delta)/I(0)$ calculated from the experimental results are shown in Table II along with the properties of the targets and absorbers.

The ratio $I(\Delta)/I(0)$ may be evaluated by numerical integration for comparison with the experiment. It depends on the shape of $\sigma_n(E)$ as a function of the energy and on its maximum value, σ_n^0. In the absence of thermal Doppler broadening, $\sigma_n(E)$ for a single level is given by a Breit-Wigner expression:

$$\sigma_n(x)=\sigma_n^0/(1+x^2), \quad (4)$$

where $x=(E-E_0)/(\frac{1}{2}\Gamma)$. The curve labelled $t=0$ in Fig. 3 is a plot of $I(\Delta)/I(0)$ as a function of σ_n^0. This curve was calculated numerically for the polystyrene absorber and target used.

In general the absorption cross section is distorted owing to the thermal motions of the target nuclei. The resonance is effectively widened and its peak depressed by an amount proportional to the ratio of the Doppler width, δ, to the level width, Γ. The Doppler-broadened Breit-Wigner cross section obtained by combining the single-resonance formula with a Gaussian of width δ is[6]:

$$\sigma_n(x,t)=\sigma_n{}^0\frac{1}{2(\pi t)^{\frac{1}{2}}}\int\frac{\exp[-(x-y)^2/4t]}{1+y^2}dy, \quad (5)$$

where $t=(\delta|\Gamma)^2$. This function is available in tabular form[7] and has been inserted into the integrals of Eq. (3) to obtain the ratios, $I(\Delta)/I(0)$, plotted in Fig. 3 for three values of the parameter t.

The horizontal lines in Fig. 3 represent the most probable value and the limit of error of the observed ratio $I(\Delta)/I(0)$. For values of t between 0 and 1 the observed attenuation is consistent with a peak absorption cross section of about 24 barns. A similar set of curves calculated for the parameters corresponding to the graphite target and absorber gave similar results. It will be shown later that values of $t>1$ do not give results consistent with both the self-absorption and scattering experiments.

INTEGRAL SCATTERING CROSS SECTION

The scattering cross section for a single level cannot be determined by the method used in the elastic scattering experiment.[5] This is because the spectrum of scattered photons, consisting of a sharp well-defined line, is very different from the incident continuous bremsstrahlung spectrum.

From Eq. (5) of reference 5 it can readily be shown that the number of photons scattered will be given by[8]:

$$C=\frac{\Delta\Omega}{13.3}\frac{n(15)}{2\sigma_e}\int dE\frac{\sigma_s(E)}{1+\sigma_n(E)/2\sigma_e}[1-e^{-(\sigma_n+2\sigma_e)NT/\cos\beta}]$$
$$=\frac{\Delta\Omega}{13.3}\frac{n(15)}{2\sigma_e}I(0). \quad (6)$$

In this expression $\Delta\Omega$ is the solid angle for detecting a photon scattered at 120°; the number 13.3 is the ratio of the total cross section to the differential cross section at 120° for an angular distribution of the scattered radiation varying as $(1+\cos^2\theta)$; $n(15)$ is the number of 15.1-Mev photons per Mev incident on the scattering target. The determination of the scattering integral then required the absolute measurement of C, $n(15)$, and $\Delta\Omega$.

The solid angle, $\Delta\Omega$, was taken to be the geometrical solid angle for a photon scattered by a point at the center of the beam on the front surface of the target. This solid angle was 0.0344 steradian. The use of this figure was justified by two experiments. A small radioactive source scanned across the surface of the target showed that to within the statistical accuracy of the measurements ($\pm 2\%$) the average solid angle over the target area was equal to the solid angle for detecting a photon scattered at its center. It was also shown with a standard Co^{60} source that this solid angle is within 5% the geometrical solid angle.

The number of 15.1-Mev photons scattered into $\Delta\Omega$ is the number of interactions they produce in the crystal divided by the detection efficiency. The efficiency is the product of the fraction of the photons that are not removed by the Lucite absorber of thickness D, $e^{-\mu_L D}$, and the probability that an interaction does take place in the NaI(Tl) crystal of length Z, $1-\exp(-\mu_{\mathrm{NaI}}Z)$. The attenuation of the scattered 15.1-Mev photons was measured as a function of the thickness of Lucite placed in the scattered beam. These data showed that no appreciable error was made by using the narrow beam absorption coefficient in calculating the number of photons that pass through the Lucite absorber.

The number of interactions in the crystal produced by 15.1-Mev photons was determined from the pulse-height distribution shown in Fig. 2. When a carbon absorber was placed in the incident beam the pulses larger than nine mv were attenuated in the same way as those in the peak of the distribution and are therefore associated with the 15.1-Mev line. The large number of smaller pulses were not absorbed in the appropriate way and must result from multiple processes in the target. The solid line in Fig. 2 represents the extrapolation used to

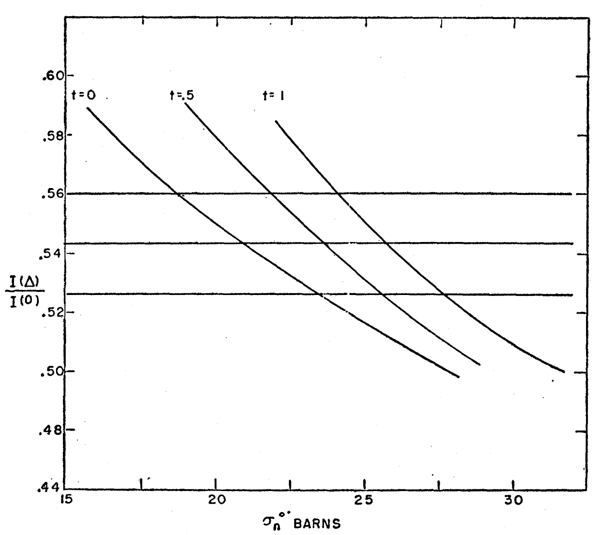

FIG. 3. The smooth curves represent the ratio of the integrals $I(\Delta)/I(0)$ as a function of the peak absorption cross section in the levels for three values of the parameter $t=(\delta/\Gamma)^2$. The horizontal lines represent the most probable value and limits of error obtained for this ratio from the observed transmission.

[6] H. A. Bethe, Revs. Modern Phys. **9**, 71 (1937), Sec. 61.

[7] Rose, Miranker, Leak, Rosenthal, and Hendrickson, Westinghouse Atomic Power Division Report SR-506, 1954 (unpublished), Vols. I and II.

[8] The $\cos\beta$ factor in the denominator of Eq. (5) of reference 5 is in error. The cross sections given there are 13% too high.

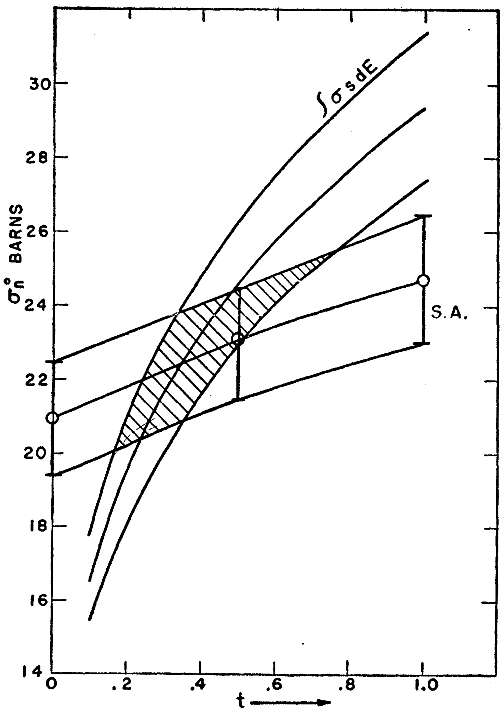

FIG. 4. The peak absorption cross section, σ_n^0, as a function of t as derived from the two experiments. The points at $t=0$, 0.5, and 1 have been read from the curves of Fig. 3. The smooth curves are plots as a function of t of the expression:

$$\sigma_n^0=\left[\frac{2}{\pi}\frac{\sqrt{t}}{\delta}6\pi\lambda\!\!\!^{-2}\int\sigma_s dE\right]^{\frac{1}{2}}.$$

The experimental value of the integral scattering cross section and its limits of error have been used to obtain the three curves. The cross-hatched area is that consistent with both the integral scattering cross section and the self-absorption measurements.

obtain the total number of interactions. The slight rise in the pulse-height distribution near 12 mv represents not more than ten percent of the scattered photons. It probably results from 12.8- and 10.7-Mev photons produced in elastic scattering by the 12.8-Mev level[9] and inelastic transitions from the 15.1- to the 4.43-Mev level in C^{12}. The extrapolation has been made to exclude this contribution and the integral scattering cross section obtained therefore corresponds only to elastic scattering events.

The determination of $n(15)$ was made by calibrating the transmission ionization chamber used to monitor the exposure in terms of the absolute response of a 25-r Victoreen thimble chamber in an $\frac{1}{8}$-in. Pb cap.[10] The number of photons per Mev at 15 Mev was obtained from the 19-Mev Schiff spectrum as tabulated by Penfold and Leiss[11] after normalizing this spectrum to the intensity used in the scattering runs and correcting for the attenuation in the 97 g/cm^2 of aluminum filter used in the incident bremsstrahlung beam.

From Eq. (6), since $\sigma_e \ll \sigma_n$, it can be seen that if $\sigma_n(E)$ is the same function of energy for polystyrene and graphite, then the product $N\sigma_e$ will be constant when one target is substituted for the other. The product $N\sigma_e$ was found experimentally to be the same within $\pm 3\%$. This result implies either that the Doppler width is the same for the two materials or that it is small compared to the level width, Γ.

Combining the measured quantities for polystyrene and graphite gives $(9.5\pm1.3)\times10^{-5}$ Mev-b for the scattering integral, $I(0)$. The quoted error results from counting statistics $\pm3\%$, monitor calibration $\pm8\%$, determination of the solid angle $\pm5\%$, and extrapolation of the pulse-height distribution $\pm10\%$.

The quantity which is of interest theoretically is not the experimentally determined scattering integral $I(0)$, but the actual integral scattering cross section, $\int\sigma_s(E)dE$. The ratio, R, of $\int\sigma_s(E)dE$ to $I(0)$ depends both on the size of the nuclear absorption cross section and on its energy dependence. This ratio has been evaluated for the three values of t used in the analysis of the self-absorption experiment and for the corresponding values of σ_n^0 derived from the observed attenuation. The values obtained center around $R=20$ and vary by only 3% over the range of t considered so that $\int\sigma_s(E)dE=1.90\pm0.27$ Mev-mb.

ANALYSIS OF THE DATA AND DISCUSSION

The value of the peak absorption cross section derived from the experimental data as presented in Fig. 3 depends on the value of the parameter t assumed. The range of values of σ_n^0 and t consistent with both the self-absorption and scattering experiments were found in the following way: Values for the peak absorption cross section, σ_n^0, consistent with the self-absorption experiment have been read from the curves of Fig. 3 for the three values of t given in Fig. 3. Similar values were obtained from the graphite data. For each value of t the value of σ_n^0 obtained from the polystyrene and graphite data agreed well within the experimental errors. The two sets of data were then averaged to obtain a value for the peak absorption cross section at each value of t. These points are shown in Fig. 4.

The integral scattering cross section may also be expressed in terms of σ_n^0 and t:

$$\int\sigma_s(E)dE=\frac{\pi}{2}\Gamma\frac{\Gamma_\gamma}{\Gamma}\sigma_n^0=\frac{\pi}{2}\frac{\delta}{\sqrt{t}}\frac{(\sigma_n^0)^2}{6\pi\lambda\!\!\!^{-2}},\qquad(7)$$

since $\Gamma_\gamma/\Gamma=\sigma_n^0/6\pi\lambda\!\!\!^{-2}$ for a dipole transition. The smooth

[9] Gove, Litherfield, and Almqvist, Bull. Am. Phys. Soc. Ser. II, 2, 51 (1957); C. N. Waddell (private communication).

[10] *National Bureau of Standards Handbook 55* (U. S. Government Printing Office, Washington, D. C. 1954). This calculated response has been checked experimentally to within 5% at 22 Mev calorimetrically [Laughlin, Beattie, Henderson, and Harvey, Am. J. Roentgenol. Radium Therapy, Nuclear Med. **70**, 294 (1953)], and at 19 Mev by E. G. Fuller (unpublished data) using the total spectrum method [Koch, Leiss, and Pruitt, Bull. Am. Phys. Soc. Ser. II, **1**, 199, (1956)].

[11] A. S. Penfold and J. E. Leiss, Phys. Rev. **95**, 637 (1954).

curves in Fig. 4 are a plot of $\sigma_n{}^0$ *versus* t where the experimental value of $\int \sigma_s dE$ and its limits of error have been used to obtain the three curves.[12] The cross-hatched area is that consistent with the two experiments.

The best value of the peak absorption cross section consistent with both experiments is 22.2±2.2 barns. This result was obtained from Fig. 4. The branching ratio is then: $\Gamma_\gamma/\Gamma = \sigma_n{}^0/\sigma\pi\lambda\!\!\!^{-2} = 22.2/32 = 0.69\pm0.07$. The ground state radiation width, Γ_γ, may be obtained from Eq. (7) by combining $\sigma_n{}^0$ with the measured value for the integral scattering cross section. The result, $\Gamma_\gamma = 54.5\pm9.3$ ev, may be compared to the single-particle radiation width of 65 ev given by Moszkowski.[13]

[12] In calculating $\sigma_n{}^0$ from this expression a value for δ of 45 electron volts was assumed. This is the value of the Doppler width given by the mean energy of the carbon nuclei in the diamond lattice. The mean energy was calculated from the frequencies of the diamond lattice given by H. M. J. Smith [Trans. Roy. Soc. (London) **241**, 105, (1948)]. The value of the Doppler width obtained in this way is probably an upper limit. A lower limit would be 31.6 electron volts; the value corresponding to a gas of carbon atoms at room temperature. The upper limit was used since in the targets used the mean energy of the carbon nuclei will be determined chiefly by the presence of the carbon-carbon bond [E. Montroll (private communication)]. Fortunately, the value of $\sigma_n{}^0$ derived from a plot such as given in Fig. 4 is not sensitive to the exact value assumed for δ.

TABLE III. Properties of the 15.1 Mev, $T=1$, $J=1+$level in C^{12}.

Radiation width to the ground state of C^{12}	54.5± 9.3 ev
Total level width	79 ±16 ev
Radiation width to the 4.43-Mev state of C^{12}	≤5.5± 0.9 ev
Alpha particle width to the 2.9-Mev state of Be^8	$(18.6\leq\Gamma_\alpha\leq24.5)\pm8.2$ ev

The 15.1-Mev level in C^{12} also decays by gamma-ray emission to the 4.43-Mev state in C^{12} and by α-particle emission to the $J=2^+$ state in Be^8. (Decay to the 0^+ ground state of Be^8 is forbidden.) From the pulse-height distribution of Fig. 2 an upper limit of ten percent may be placed on the branching ratio to the 4.43-Mev level, $\Gamma_{4.43}/\Gamma_\gamma \leq 0.1$. If one assumes no transitions to the 4.43-Mev state in C^{12}, these data give as an upper limit for alpha-particle decay, $\Gamma_\alpha/\Gamma_\gamma \leq 0.45\pm0.15$. This result is consistent with the upper limit of 0.5 given by Kavanagh.[4] The properties of the 15.1-Mev level in C^{12} obtained from this experiment are summarized in Table III.

[13] S. A. Moszkowski, *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 373.

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Inelastic Proton Scattering and (*p*,*d*) Reactions in Heavy Elements

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A previous study of anomalous inelastic scattering is extended to include heavy elements, higher excitation energies of the final nucleus, and deuterons from (p,d) reactions. The energy distributions of protons inelastically scattered from each of the principle isotopes of lead and from bismuth are very similar; there are seven relatively well-defined groups with the same energy, cross section, and angular distribution. All elements studied with atomic number above 40 have prominent groups with $E_p - E_p' \cong 2.5$ Mev. The deuteron energy distributions from (p,d) reactions in Bi and Pb isotopes are very similar (five prominent groups with the same energy and similar cross sections) in spite of differing Q values. There are also strong similarities in the deteron spectra from Au and Pt, and from Pd and Ag.

INTRODUCTION

IN a previous paper[1] (hereafter referred to as A), one of us presented a survey of the energy distributions obtained from the inelastic scattering of 23-Mev protons from a number of elements between Z-26 and 92. The most unexpected results of this survey were the appearance of a rather sharply defined energy group with negative Q between 2 and 3 Mev in all elements with $Z=40$ to 52, and of a more complicated but still sharply defined energy group structure in the elements with $Z=26-30$ extending up to $-Q=5$ Mev. In A, these features were studied in detail, and the energies, cross sections, and angular distributions of these groups were found to exhibit very striking regularities as a function of mass number. In this paper the study is extended to include both heavier elements and higher negative Q values.

In A, the most striking feature among the heavy elements was the sharp structures in the spectra from Pb and Bi, and the almost perfect similarity of these two elements. This effect was therefore studied in more detail by the use of targets enriched in each of the three major isotopes of Pb. In the course of the extension to higher negative Q values, it was found that, contrary to the assumptions[2] and findings[3] of previous workers,

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[1] B. L. Cohen, Phys. Rev. **105**, 1549 (1957).

[2] P. C. Gugelot, Phys. Rev. **93**, 425 (1954).
[3] R. M. Eisberg and G. Igo, Phys. Rev. **93**, 103 (1954).