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, $\Gamma_{4.43}/\Gamma_\gamma\leq0.1$. 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, $\Gamma_\alpha/\Gamma_\gamma\leq0.45\pm0.15$. 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 $E_p-E_p'\cong2.5$ 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).

there is a relatively high intensity of deuterons from (p,d) reactions. These were therefore separated from the protons, and their energy distributions were studied in some detail.

In the deuteron studies it was found that groups with the same energy, rather than those corresponding to the same reaction Q value, exhibit regularities in energy and cross section as a function of mass number, so that the quantity $E_p - E_d$, the difference in energy between the incident proton and the outgoing deuteron in the center-of-mass system, is used as the energy parameter. In conformity with this notation, the energy parameter in the inelastic proton scattering is taken as $E_p - E_p'$; this is numerically identical with the negative Q value used in A.

EXPERIMENTAL

The experimental method consisted, briefly, of passing a collimated and energy-analyzed 23-Mev proton beam from the ORNL 86-inch cyclotron through thin targets of the elements being studied, and detecting the reaction products with a NaI(Tl) scintillation crystal; a 20-channel pulse-height analyzer was used. Most data was obtained at a detection angle of 60° although a number of checks were made at 45°, 90°, and other angles. The Bi, Pb isotope, and Th targets were about 15 mg/cm² thick, and all other targets were between 5 and 8 mg/cm². The proton spectra were obtained by covering the detector with a 227 mg/cm² aluminum absorber; this degraded the deuteron energy sufficiently to allow measurements up to $E_p - E_p' = 9.3$ Mev for all elements studied. It was necessary to make corrections for the elastic and inelastic groups from carbon and oxygen contamination in the Bi, Pb isotope, and Th targets. This was done by measuring the carbon and oxygen spectra with a Mylar target and by determining the relative amounts of these elements in the target under consideration and in the Mylar by measuring their elastic peaks at angles where these peaks are well separated from others in the spectrum. These latter measurements were made at 90° for carbon and at 75° for oxygen. A typical inelastic proton energy distribution (for Bi) is shown in Fig. 1(a).

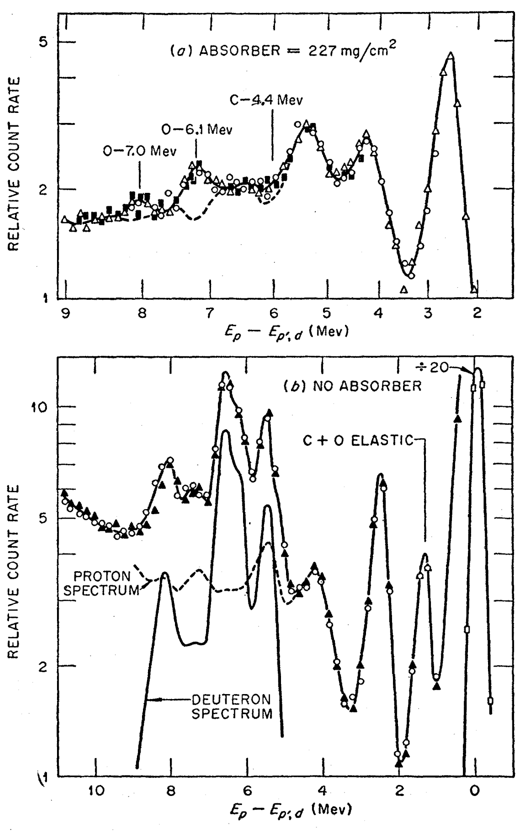

FIG. 1. Pulse-height distribution in a NaI(Tl) crystal of particles emitted at 60° from a bismuth target. Curve *a* was taken with the detector covered by a 227-mg/cm² aluminum absorber. The dashed line shows the curve corrected for the inelastically scattered protons from carbon and oxygen contaminants. Curve *b* was obtained with no absorber. The dashed line is the proton spectrum from curve *a* corrected for the nonlinear energy scale. The solid line, labeled "deuteron spectrum," was obtained by subtraction of the dashed curve from the original curve.

The deuteron spectra were obtained by measuring the pulse-height distributions with no absorber over the detector, and subtracting off the proton spectra. An example of this procedure is shown in Fig. 1(b). In addition, a measurement was made with a 49 mg/cm² absorber to determine the contribution from alpha particles (it was negligible in all cases) and to ascertain that the peaks assigned as due to deuterons were shifted by the proper amount (approximately 1 Mev) relative to the proton spectrum.

Energy scale calibrations were made frequently with the elastic and inelastic proton groups from carbon and oxygen; the corrections to the energy scale calculated by assuming a linear pulse height *vs* energy relationship for NaI(Tl) and using corrected[4] range energy curves[5] was never more than 0.3 Mev. This rather accurate maintenance of an energy scale represents an improvement over the work reported in A. It was achieved by analyzing the energy of the proton beam from the cyclotron with a wedge magnet, and by using moderate

TABLE I. Proton groups from Bi and Pb isotopes.

Bi^{209} $E_p - E_p'$ (Mev)	$d\sigma/d\Omega$ (mb/sterad)	Pb^{208} $E_p - E_p'$ (Mev)	$d\sigma/d\Omega$ (mb/sterad)	Pb^{207} $E_p - E_p'$ (Mev)	$d\sigma/d\Omega$ (mb/sterad)	Pb^{206} $E_p - E_p'$ (Mev)	$d\sigma/d\Omega$ (mb/sterad)
2.6	2.6	2.6	2.5	2.6	2.4	2.6	2.5
∼3.1	∼0.7	3.3	∼0.5	3.6	∼0.5	3.7	∼0.5
4.3	1.45	4.2	1.39	4.2	1.42	4.2	1.39
4.7	∼0.7	4.8	∼0.9	4.9	∼1.2	5.0	∼1.0
5.4	1.68	5.4	1.73	5.4	1.73	5.5	1.51
6.4	1.30	6.4	1.27	6.6	1.47	6.5	1.30
7.4	∼1.1	7.4	∼1.0	7.4	∼1.2	7.6	∼1.0

[4] H. Bichsel and R. F. Mozley, Phys. Rev. **90**, 354 (1953); also private communication via R. W. Peele.

[5] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663 (unpublished).

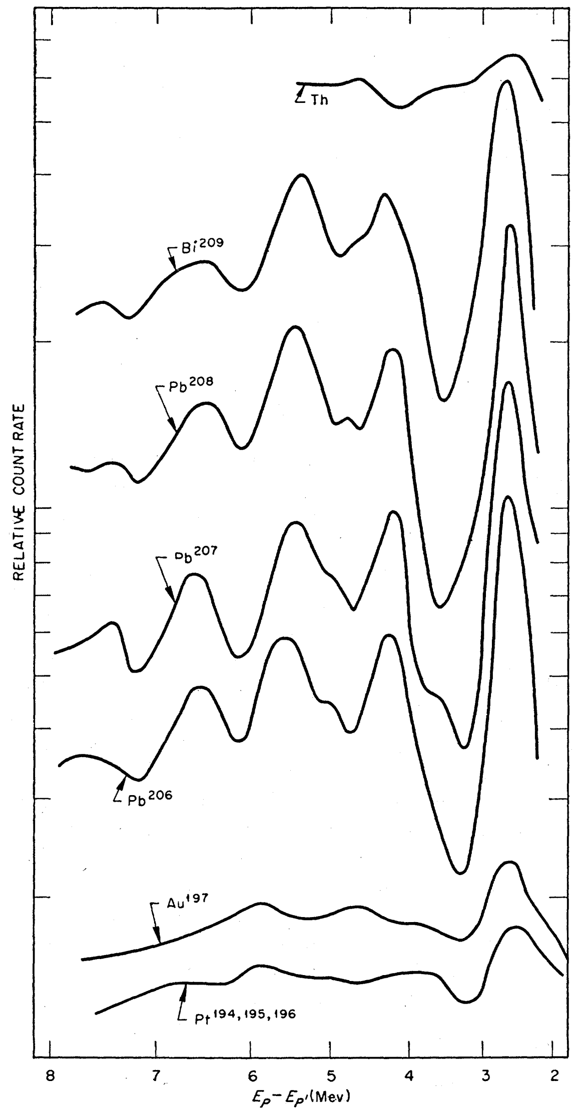

FIG. 2. Energy distribution of protons inelastically scattered from elements $Z-78$–90. Ordinates for each curve are displaced arbitrarily. Data were corrected for contributions from carbon and oxygen contamination. The detection angle is 60°.

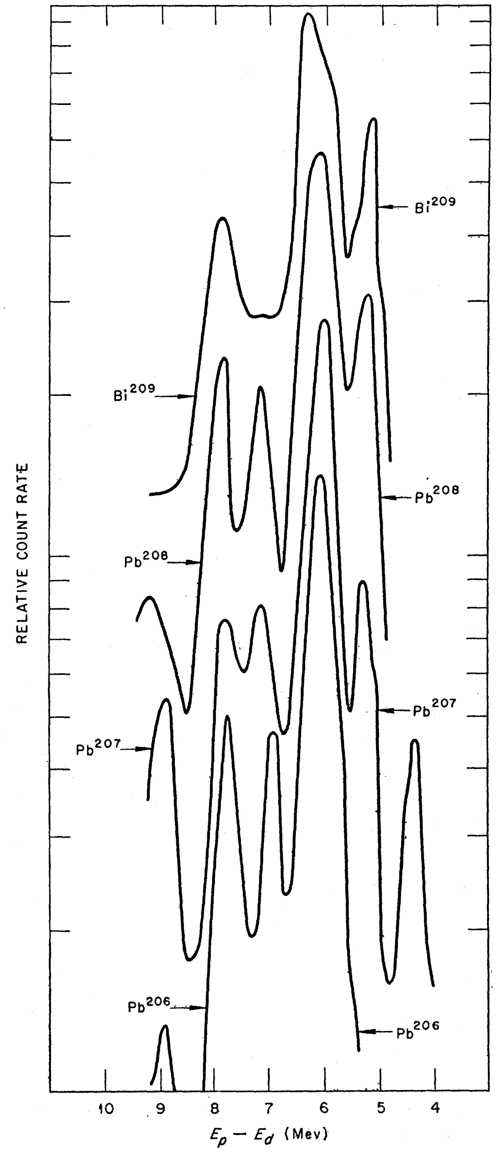

FIG. 3. Energy distribution of deuterons from (p,d) reactions in Bi and in Pb isotopes. The detection angle is 60°.

(1000 total counts per second), and uniform counting rates. The scintillator resolution was somewhat improved relative to that in A; at one time it was as good as 1.5% full width at half-maximum for the elastic protons (about 7.5% for Cs^{135} gamma rays). It was maintained near this level for the work on Bi and the Pb isotopes, but it degenerated to 2.0–2.5% for the rest of the work even though the crystal was remounted several times.

RESULTS

Bismuth and Lead

The proton energy spectra from Bi and the Pb isotopes are shown in Fig. 2. The almost perfect similarity among the four spectra is very strikingly obvious; the only clear differences are in the uniform energy shifting of two minor peaks from 3.7 Mev to 3.3 Mev, and from 5.0 Mev to 4.7 Mev, and a gradual broadening of the 6.5-Mev group as the mass number increases. The relatively large widths indicate that the 5.4-Mev and 6.5-Mev peaks are not due to single monoenergetic groups. On the other hand, the 2.6-Mev and 4.2-Mev peaks do appear to be monoenergetic, within the resolving power of the detection system. For purposes of assigning cross sections, it was assumed that each peak is due to a monoenergetic group with a width equal to that of the 2.6-Mev groups; the values obtained are listed in Table I. Because of the above assumption, the sum of the listed cross sections is only about 75% of

TABLE II. Deuteron groups from Bi and Pb isotopes.

	Bi^{209} E_p-E_d (Mev) Observed	Harvey	$d\sigma/d\Omega$ (mb/sterad)	Pb^{208} E_p-E_d (Mev) Observed	Harvey	$d\sigma/d\Omega$ (mb/sterad)	Pb^{207} E_p-E_d (Mev) Observed	Harvey	$d\sigma/d\Omega$ (mb/sterad)	Pb^{206} E_p-E_d (Mev) Observed	Harvey	$d\sigma/d\Omega$ (mb/sterad)
a							4.3[a]	4.3	0.26			
b	5.1[a]	5.1	1.7	5.1[a]	5.0	1.6	5.2	5.2	0.50			
c	5.8	5.7	4.0	~5.8	5.6	3.7	~5.6	5.7	2.9	~5.7[a]	5.7	3.7
d	6.2	6.1		6.1	6.0		5.9	6.0		6.0	6.0	
e	7.0		0.6	7.1		1.1	7.1		0.83	6.9		0.92
f	7.8		1.4	7.8		1.2	7.7		0.40	7.7		1.2
g	~9.0		~0.4	9.1		0.4	8.9		0.5	8.9		0.3
	Total to 9.3 Mev		8.1			8.0			5.4			6.1

[a] Ground-state group.

the area under the curves; however, Table I serves to illustrate the point that the similarity between the four isotopes extends to the absolute cross sections. With one or two possible exceptions, all deviations are within the experimental error.

In addition to the groups listed in Table I, runs at 90° indicated a group with $(E_p-E_p')=1.0$, 1.2, 1.4, and 1.6 Mev in Bi^{209}, Pb^{208}, Pb^{207}, and Pb^{206}, respectively. The ratio of the cross sections for these groups to those for the 2.6-Mev groups is approximately 0.33, 0.11, 0.15, and 0.13, respectively. The appearance of this group in Pb^{208} is especially surprising since the 2.6-Mev level is widely believed to be its true first excited state. Such a group could conceivably arise as an elastic group from an impurity such as silicon, but a spectrographic analysis indicated that the amount of silicon present was far too small. In addition, the regularity of the energy shift with mass number strongly suggests that these are true proton groups. This matter will be investigated further.

The deuteron spectra from Bi and the Pb isotopes are shown in Fig. 3. All groups appear to be monoenergetic except the group at $E_p-E_d\simeq 6$ Mev, which is obviously double in Bi and appears to be double in the Pb isotopes. The energies and cross sections for the various groups are listed in Table II. The cross sections were corrected for isotopic abundances in the various targets. Groups *a* to *d* were observed by Harvey[6] in (d,t) reactions, and he was able to resolve groups *c* and *d*. He also observed a few addition al higher energy groups with very small cross sections, but these do not appear to correspond to groups *e*, *f*, and *g* of Table II. His energy values are listed in Table II; the agreement with the present work is within experimental error.

While the similarity between the four isotopes is not as perfect as in the (p,p') case, it is nevertheless overwhelmingly obvious. The fact that the Q values vary by 1.4 Mev seems to be evidenced only by the fact that groups which are energetically forbidden are missing. The principle other dissimilarity is that the cross sections for some of the Pb^{207} groups, especially *b* and *f*, are lower than for the other isotopes. Also, group *e* is appreciably weaker in Bi^{209} than in the others. It is quite clear the the similarities between the four isotopes would be essentially destroyed if the Q of the reactions were used as the abscissa in Fig. 3.

While angular distribution measurements were considered to be beyond the scope of this paper, some indication of the behavior of the angular distributions may be seen in Fig. 4. This is a plot of the pulse-height spectrum from Bi at various angles with no absorber. At each of five peaks, two due to protons and three due principally to deuterons, the height of that peak for each of the Pb isotopes is indicated, It is immediately clear from Fig. 4 that the angular distributions of all parts of the spectrum are strongly peaked in the forward direction. It is perhaps surprising to note that the forward peaking is even stronger for the protons (including the low-energy continuum which is predominantly protons) than for the deuterons. This is notably true for the 3.1-Mev group which increases by a factor of 20 from 60° to 30° whereas the general increase is only by a factor of 5. While a large number of minor exceptions may be noted, it seems to fair state that the very striking similarity among the four isotopes considered here extends also to the angular distributions.

Platinum, Gold, and Thorium

The energy distribution of the inelastic protons from Au, Pt, and Th are shown in Fig. 2. The Th spectrum could not be reliably extended to higher energies because of the large corrections for C and O contami-

TABLE III. (p,p') cross sections.

Atomic No.	Element	$d\sigma/d\Omega$ at 60° (mb/sterad) "2.5-Mev" group	Total to 9.3 Mev
26	Fe		11.3
27	Co		10.0
28	Ni		12.4
29	Cu		10.4
30	Zn		10.0
46	Pd	2.4	9.7
47	Ag	2.5	10.4
78	Pt	1.7	8.2
79	Au	1.9	9.2
82	Pb	2.6	13
83	Bi	2.6	13
90	Th	~1.4	8.8

[6] J. A. Harvey, Can. J. Phys. 31, 278 (1953).

nation, and in fact, the peak at 2.5 Mev is not obvious until a correction for C is applied. However, data at 45°, where the C peak does not interfere, corroborate the existence of this peak.

The only major feature in the proton energy spectra from Au, Pt, and Th is the peak at 2.5 Mev. In all cases it seems somewhat too broad to be due to a monoenergetic group. The cross section for this peak is listed in Table III, along with the cross sections for the strong groups at about this energy in other elements. The total cross section for inelastic scattering with an energy loss less than 9.3 Mev is also given. It is seen that, while the cross section for this group is somewhat less than in Pb

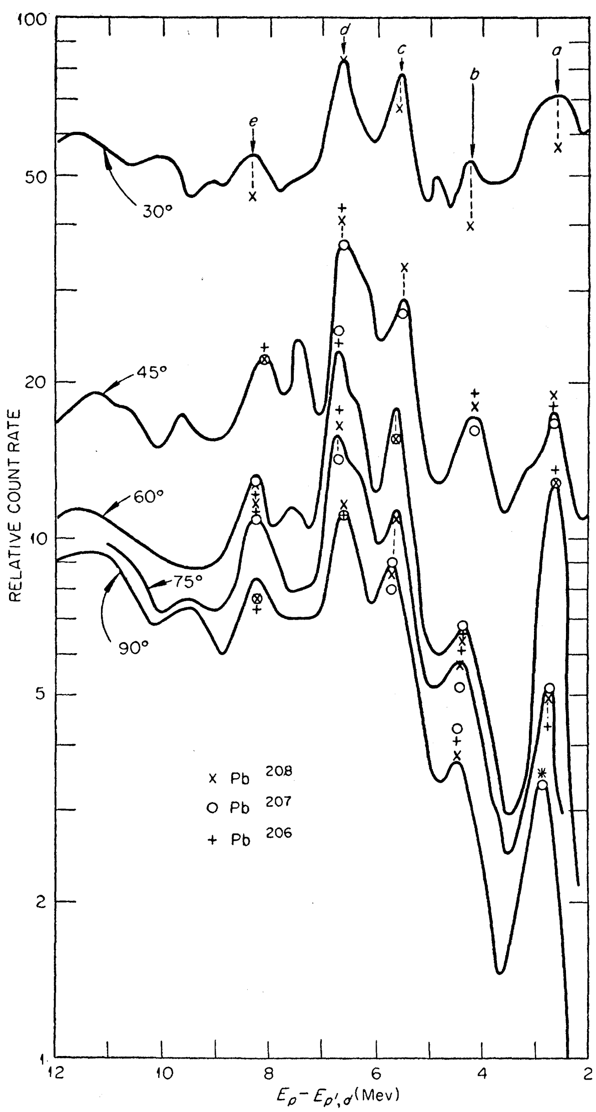

FIG. 4. Pulse-height distribution from a bismuth target at various angles of detection. Ordinate scale is same for all curves. Pointers indicate position of corresponding peaks in spectra from the Pb isotopes. Peaks a and b are due to protons and peaks c, d, and e are due principally to deuterons.

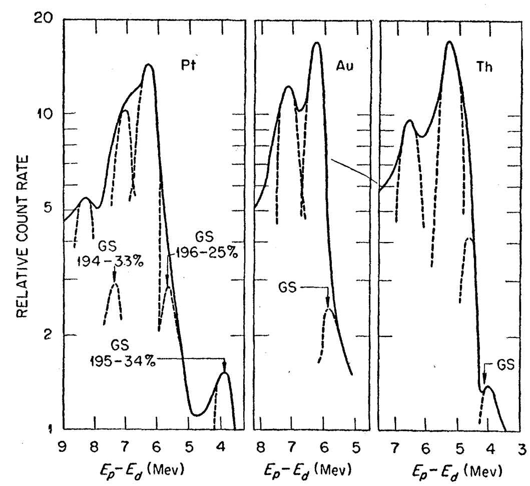

FIG. 5. Energy distributions of deuterons from (p,d) reactions in Pt, Au, and Th. GS represents the ground-state group from the indicated isotope. The detection angle is 60°.

and Bi, it is still about the same fraction, about 20%, of the total (p,p') cross section up to 9.3 Mev.

The high-energy portion of these spectra seems to be quite smooth, at least relative to Bi and Pb. Some non-uniformities do seem, however, to be greater than would be expected from experimental error.

The deuteron spectra from Pt, Au, and Th are shown in Fig. 5. In each case, the spectrum seems to be characterized by two very strong groups with approximately the same cross sections for each element. The similarity is especially striking for Pt and Au, where the peaks also occur at the same energy. The other groups shown resolved are the ground-state groups whose location is known from other data,[7] principally from (γ,n) thresholds.

As in the case of Pb and Bi, the strong similarity between the neighboring elements Pt and Au would disappear if the abscissa were taken as the Q value of the reaction. There is at least some similarity between the Pt and Au spectra and the Pb and Bi spectra shown in Fig. 3. The strong groups at 6.3 Mev, and the weaker ones at 7.1 and 8.3 Mev might be related to the strong Pb-Bi groups at 6.1 Mev, and the weaker ones at 7.1 and 7.8 Mev. There are, however, large differences in the cross section, both absolute and relative. The peaks in the spectrum from Th are shifted by about 1 Mev from those in Pt and Au. This is not unexpected since Th differs by 11 atomic numbers from these.

Palladium, Silver, and Lighter Elements

The proton spectra from Pd, Ag, Co, Cu, Fe, Ni, and Zn show little structure other than that already described in A, where the resolution was somewhat better. The cross sections are listed in Table III; it is seen that the "2.5-Mev groups" represent a somewhat

[7] J. P. Elliott and A. M. Lane, in *Handbuch der Physik* (Springer-Verlag, Berlin, to be published).

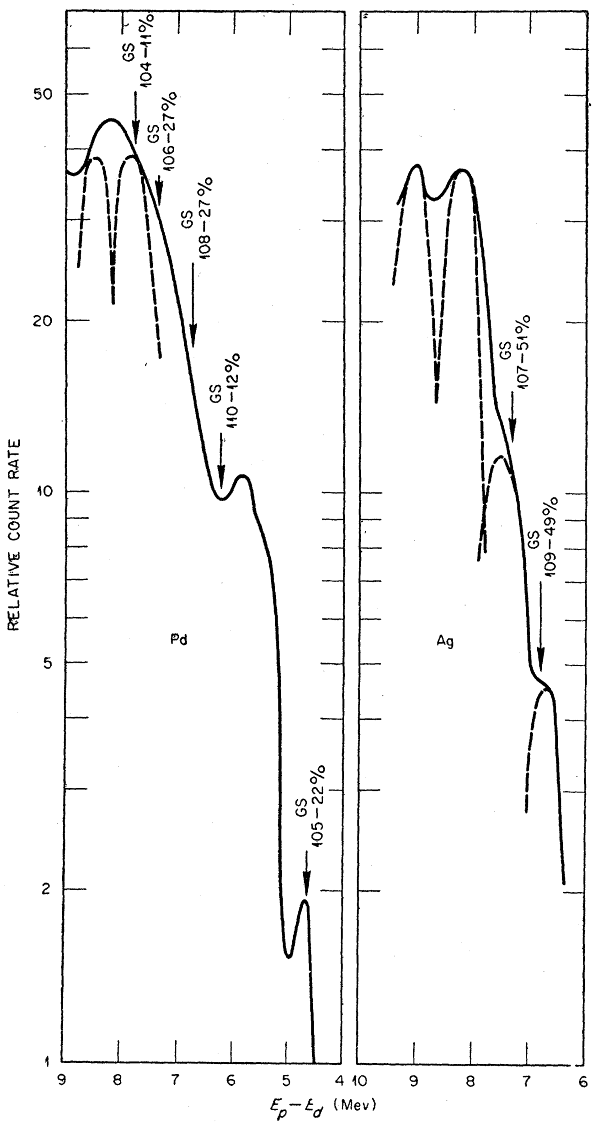

FIG. 6. Energy distribution of deuterons from (p,d) reactions in Ag and Pd. See caption for Fig. 5.

larger fraction of the total cross section in Pd and Ag than in the heavier elements.

The deuteron spectra from Pd and Ag are shown in Fig. 6. Here again they are featured by strong, obviously double, peaks at about the same value of (E_p-E_d)—but not at the same Q value—and with about the same cross sections. The cross sections under these peaks are about 0.65 mb/sterad in each case, which is considerably less than in the heavy elements.

No study was made of (p,d) reactions in the lighter elements because their relatively high thresholds would necessitate different techniques.

DISCUSSION

The most interesting result of this work is the great similarity between both the proton and deuteron spectra from Bi and the isotopes of Pb. Harvey[6] explained the similarity between the (d,t) triton spectra from these nuclei by using the shell model and neglecting interactions between the various subshells of the major shell which closes at 126 neutrons. This assumption is highly dubious in the light of recent shell-model calculations which require taking into account all interactions of this type[7] to obtain even an approximate agreement with experiment. Furthermore, Harvey's explanation would not cover the inelastic proton situation, where the similarity between these nuclei is even more complete.

It begins to appear that the general characteristics of anomalous inelastic proton scattering may be due to some generalized property of nuclei, such as the nuclear potential,[8] rather than to the specialized level structures of the particular nuclei. This is suggested by the very choice of E_p-E_p' and E_p-E_d as energy parameters, by the occurence of the "2.5-Mev group" for all heavy elements studied, and by the similarities in both proton and deuteron spectra for neighboring elements. This explanation is also supported by the fact that the 2.5-Mev group is sharp in some elements (Pb,Bi), apparently double in others ($Z=40$–52), and quite diffuse in still others (Pt, Au, and Th). There is certainly nothing in shell-model level structures that can explain these regularities. Conventional collective-motion explanations also have several serious difficulties.[1]

One difficulty with explaining these data as due to the nuclear potential is in the virtual disappearance of structure at high energies in going from Pb to Au. This could be an effect of nonsphericity in nuclei away from closed shells.

This paper concludes the survey study of anomalous inelastic scattering and (p,d) reactions which has been performed with scintillation detectors. A magnetic analyzing system is now being constructed; its use will improve the energy resolutions by an order of magnitude, and should thus clarify matters very considerably.

The authors would like to acknowledge the assistance of E. L. Olson and M. B. Marshall in various phases of equipment maintenance, and the cooperation and encouragement of R. S. Livingston and A. M. Weinberg.

[8] Lane, Thomas, and Wigner, Phys. Rev. **98**, 693 (1955).