Cross Section for Excitation of Pb^{207m} by Inelastic Scattering of Neutrons

P. H. STELSON AND E. C. CAMPBELL
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received November 26, 1954)

The cross section for the excitation of the 0.8-sec metastable state of Pb^{207} by inelastic neutron scattering has been measured for neutron energies up to 3.1 Mev. Neutrons were produced by the $Li(p,n)$ reaction. The lowest neutron energy for which excitation is observed is 1.6 Mev. This is in agreement with the level scheme for Pb^{207} based on other information. For the first 800 kev above threshold, the cross section rises approximately linearly, attaining a value of 75 millibarns at 2.4 Mev. After leveling off, it abruptly increases at 2.75 Mev and has a value of 190 millibarns at 3.1 Mev. It is judged that the absolute values of the cross section are accurate to ± 40 percent. The absolute cross section for excitation of the metastable state as a function of neutron energy is calculated by the use of the strong interaction theory of nuclear reactions. The theoretical predictions agree well with the measured curve.

I. INTRODUCTION

SEVERAL investigations of the excitation of metastable nuclear states by the inelastic scattering of an incident beam of monoenergetic neutrons have now been reported.[1–3] In contrast to states with prompt decay, the study of metastable states obviates the problem of observing the inelastic scattering event with detectors in which there are high background counting rates associated with proximity to the fast neutron source. Consequently, the inelastic neutron scattering process may be studied with a considerable increase in sensitivity for those few cases in which the residual state is metastable. One such case is the 0.8-sec metastable state of Pb^{207}.[4,5] We wish to report the absolute cross section for the excitation of this state as a function of neutron energy.

Hauser and Feshbach,[6] have discussed the application of the strong interaction theory of nuclear reactions to the case of inelastic neutron scattering. They point out that just above threshold, the cross section for the production of an excited state is sensitive to energy, angular momentum, and parity differences which exist between the ground state and the excited states of the target nucleus. Margolis[7] has investigated the prediction of this theory for the experimental cases cited above.[1–3] He finds agreement of experiment with theory is good and remarks that this is notable because of the rather simple assumptions of the strong interaction theory and because recent calculations by Feshbach, Porter, and Weisskopf[8,9] have shown that for total neutron cross sections better agreement with experiment is obtained if one does not assume immediate compound nucleus formation.

The positions, spins, and parities of the low-lying excited states of Pb^{207} are rather well established. According to shell theory, the level scheme is one of the simplest to interpret since the nucleus differs from Pb^{208} by one neutron. The low-lying excited states are expected to be single particle states of the type that are available in the 82 to 126 neutron shell. Experimental information is in agreement with this conclusion.[10] Therefore, the energies, spins, and parities of the isomeric state and the levels below it may be taken as known and one has sufficient information to carry out an effective comparison of the strong interaction theory with the experimentally determined cross section. Using the information on the levels in the lead isotopes, Oleksa[11] has applied the strong interaction theory to predict the inelastic neutron scattering properties of lead.

II. EXPERIMENTAL METHOD

A schematic diagram of the experimental setup is given in Fig. 1. Monoenergetic neutrons were produced by bombarding thin lithium targets by protons from the 5.5-Mev ORNL electrostatic generator. The lead cylinder was irradiated by neutrons emerging from the target in the forward direction. After a suitable bombardment period, the proton beam was deflected off the target and the γ-ray activity induced

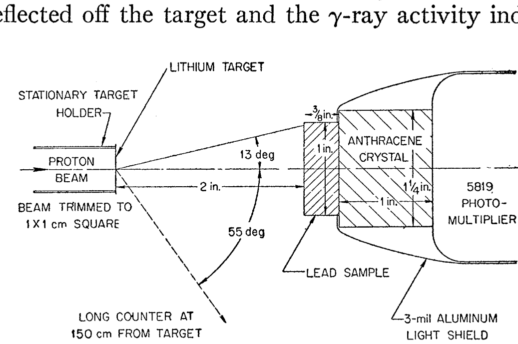

FIG. 1. Schematic diagram of the experimental set-up.

[1] Francis, McCue, and Goodman, Phys. Rev. **89**, 1232 (1953).
[2] A. A. Ebel and C. Goodman, Phys. Rev. **93**, 197 (1954).
[3] Martin, Diven, and Taschek, Phys. Rev. **93**, 199 (1954).
[4] E. C. Campbell and M. Goodrich, Phys. Rev. **78**, 640(A) (1950).
[5] G. Vendryes, Ann. phys. **7**, 655 (1952).
[6] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[7] B. Margolis, Phys. Rev. **93**, 204 (1953).
[8] Feshbach, Porter, and Weisskopf, Phys. Rev. **90**, 166 (1953).
[9] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).
[10] See M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952).
[11] Sophie Oleksa, Brookhaven National Laboratory Report BNL-273 (T-45), December, 1953 (unpublished).

in the lead sample was detected by an anthracene scintillation counter.

The energy homogeneity of the neutrons passing through the lead sample was limited mainly by the target thickness which varied from 70 to 80 kev. The spread in neutron energy caused by the finite solid angle subtended by the sample varied from 15 to 30 kev. Measured cross sections are plotted at mean neutron energies.

An electrostatic deflector, located in the beam tube on the exit side of the analyzing magnet at a distance of 5 meters from the target, was used to remove the proton beam from the target. The deflected protons were caught in a lead plug placed about 1 meter from the deflector. With this arrangement, the neutron flux could be turned off or on in less than 1/100 of a second.

The timing sequence was carried out automatically by the use of a electronic timing device. The proton beam was held on the target for 2.1 second (about $2\frac{1}{2}$ half-lives) to build up the induced activity. The anthracene counter was turned on 0.2 second after the proton beam was cut off the target and held on for 1.3 sec (about $1\frac{1}{2}$ half-lives). A delay of 10 seconds followed and the sequence was then repeated. Fifty to 100 repetitions of the sequence were carried out at each neutron energy. The time interval between the cutoff of the proton beam at the start of the counting interval was variable so that the decay curve of the induced activity could be studied.

To determine the absolute cross section it was necessary to know both the neutron flux incident on the lead sample and the efficiency with which the decay of the metastable state was detected. During the experiment, the neutron flux was monitored by a long counter placed 55° to the forward direction and 1.5 meters from the target. An auxiliary experiment was performed to determine the ratio of the neutron yields at 55° and 0° from the $Li(p,n)$ reaction as a function of the proton energy. The counts recorded by the long counter were converted to absolute neutron flux by calibrating the long counter with a standard Po-Be source. A small percentage of the neutrons from the $Li^7(p,n)$ reaction leave the residual nucleus Be^7 in the first excited state. No correction has been made for the effect of this second group of neutrons because of the lack of data on the yield and angular distribution as a function of proton energy. It is judged that the neutron flux (primary group+small admixture of the second group) incident on the lead sample was determined to an accuracy of 15 percent.

The incident neutron flux is attenuated to some extent in traversing the lead. Taking the total cross section of lead as 7 barns it is calculated that 20 percent of the incident neutrons undergo a primary collision so that the average primary flux throughout the sample is about 90 percent of the incident flux. However, roughly half of the primary collisions are diffraction scattering in which the neutron energy is not appreciably changed, and this part of the secondary flux is as effective as the primary flux for excitation of the metastable state. On the other hand, the efficiency with which the decay of the metastable state is detected is considerably larger for that part of the lead sample adjacent to the anthracene crystal which is the region of minimum neutron flux. After considering these effects, we decided to take the effective neutron flux as 90 percent of the incident flux.

The efficiency of the anthracene scintillation counter for the detection of the decay of the metastable state excited in the lead sample was determined as follows. The long-lived radioactive nucleus Bi^{207} decays primarily[12,13] to the metastable state of Pb^{207} and is, therefore, a convenient source of γ rays with energies identical to those detected in the experiment. A source of Bi^{207} of small lateral dimensions ($\frac{1}{8}$ in. diameter) was prepared by evaporation to dryness of a solution of bismuth nitrate deposited on a thin polystyrene film. The strength of this source was established to 10 percent. Next, the lead sample (a cylinder 1 inch in diameter and $\frac{3}{8}$ in. thick) was replaced by three lead disks of 1 inch diameter and $\frac{1}{8}$ in. thickness. The source was placed at different points in the lead sample by sandwiching it between the lead disks and the efficiency for detection of the decay of the metastable state systematically determined at various points throughout the lead sample. The bias on the counter was set so that only the higher energy 1.07-Mev γ ray was detected because large background rates (in part due to the 479-kev γ ray from Be^7 build-up in target) were encountered at lower bias setting during the actual experiment. The overall efficiency for detection of the γ rays excited in the lead sample was (1.20 ± 0.25) percent.

The total internal conversion coefficient of the 1.07-Mev γ ray is taken to be 0.12 ± 0.01.[14] The range in the lead of the fast electrons from internal conversion is so short that the metastable states which decay by internal conversion are detected with a rather poor efficiency. It is estimated that 0.5 percent of the decays by internal conversion are detected. Consequently, the counts registered by the detector are 95 percent the result of gamma-ray detection and 5 percent the result of fast electron detection.

III. RESULTS

The cross section for the excitation of the metastable state of Pb^{207} as a function of neutron energy is given in Fig. 2(a). The experimentally observed cross section for normal lead has been multiplied by 4.76 to obtain

[12] Friedlander, Wilson, Ghiorso, and Perlman, Phys. Rev. **91**, 498(A) (1953).

[13] E. C. Campbell and F. Nelson, Phys. Rev. **91**, 499(A) (1953).

[14] F. K. McGowan and E. C. Campbell, Phys. Rev. **92**, 523 (1953).

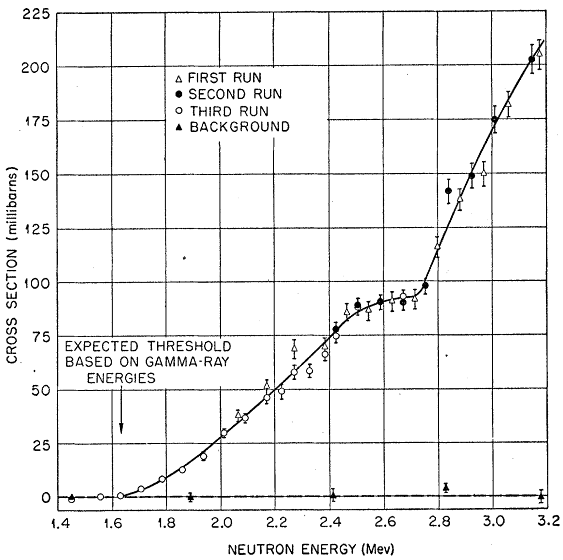

FIG. 2(a). Cross section for the excitation of the metastable state of Pb^{207}. The observed cross section for normal lead has been multiplied by 4.76 to obtain the cross section for Pb^{207} (isotopic abundance 21 percent). The errors shown are the statistical errors. The absolute cross section is judged to be accurate to ± 40 percent.

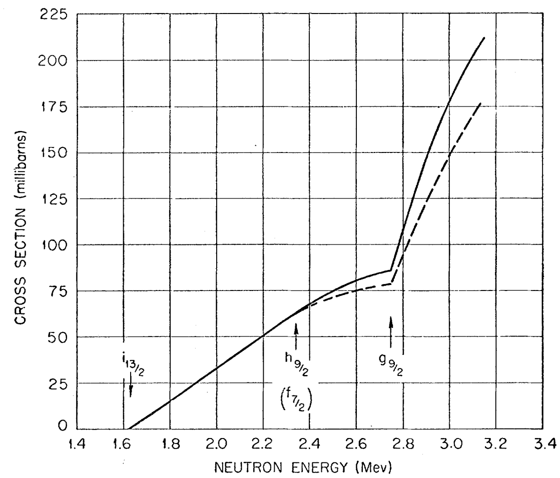

FIG. 2(b). Theoretical cross section calculated by the use of the strong interaction theory of nuclear reactions. The solid curve is based on the assumption of $h_{9/2}$ and $g_{9/2}$ states and the dashed curve is based on the assumption of $h_{9/2}$, $f_{7/2}$, and $g_{9/2}$ states.

the cross section for Pb^{207} (isotopic abundance 21 percent). Three different runs were made. The first run gave absolute cross sections about 8 percent higher on the average than those of the other two runs. To present a less confused picture of the shape of the curve, the points for the first run have been lowered by 8 percent.

Since the anthracene detector was periodically subject to a high flux of fast neutrons, it was necessary to investigate the possibility of activities, other than that of the lead, contributing to the counting rate of the detector. The lead cylinder was replaced by a tantalum cylinder of equal thickness in grams/cm^2. The resulting points are shown in Fig. 2(a) as background points. It is seen that counts caused by activities other than that in lead are relatively unimportant, being the equivalent of about 6 millibarns of cross section. The level given by the background points is taken as the zero of the ordinate scale.

To make certain that the activity in the lead itself was the 0.8-sec decay of the metastable state, a half-life determination at the highest neutron bombarding energy was carried out by varying the time interval between the cutoff of the neutron flux and the start of the counting time. These data are presented in Fig. 3. The decay follows a straight line on semilog plot (half-life of 0.8 sec) down to an intensity which is a few percent of the initial intensity.

From the consideration of the sources of errors it is judged that the determination of the absolute cross section is accurate to ± 40 percent.

IV. DISCUSSION

As previously mentioned, Pb^{207} differs from doubly magic Pb^{208} by one neutron and, therefore, the low-lying states are expected to be of the simple, single particle type which are available to a neutron hole in the 82–126 shell, viz., $p_{1/2}$, $p_{3/2}$, $f_{5/2}$, $f_{7/2}$, $h_{9/2}$, and $i_{13/2}$. Experimental information and assignments are shown in Fig. 4. The $p_{1/2}$, $f_{5/2}$, and $i_{13/2}$ states are well established. The location of the $f_{7/2}$ state is not known. One would expect electron capture in Bi^{207} to decay to the $f_{7/2}$ state if this were energetically possible since the reasonable assignment of $h_{9/2}$ for the ground state of Bi^{207} makes this an allowed transition. It is therefore likely that the $f_{7/2}$ level is a little above the 2.34-Mev level.

In addition to the information given by the study of the decay of Tl^{207}, Bi^{207}, and Po^{211}, we have the work of

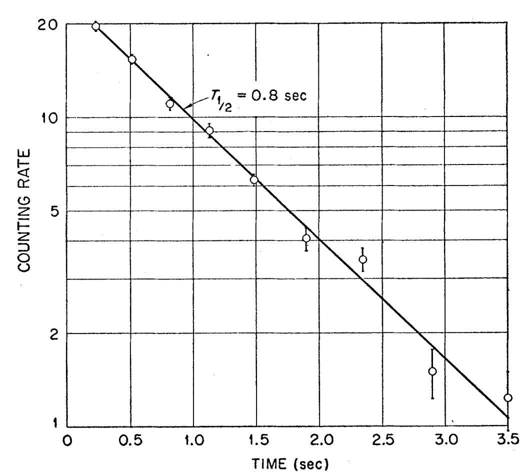

FIG. 3. Half-life measurement of the activity induced in the lead sample. $E_n = 3.17$ Mev.

Harvey[15] on the reactions $Pb^{206}(d,p)Pb^{207}$ and $Pb^{208}(d,t)Pb^{207}$. The levels identified from this study are indicated by the symbols (d,p) and (d,t). New states were found at higher excitation energies. Harvey suggested the assignment $g_{9/2}$ and $i_{11/2}$ for the states at 2.75 and 3.60 Mev. The $g_{9/2}$ and $i_{11/2}$ states are of the type expected in the shell beyond 126 nucleons and are expected to be located at higher excitation energies than those corresponding to a hole in the 82 to 126 shell.

The region of several hundred kev above the threshold for excitation of the metastable state is probably free of levels. In this region we can compare the experimental cross section with the theoretical cross section for direct excitation of the metastable state by inelastic neutron scattering. Direct excitation requires the transfer of 6 units of angular momentum and a change of parity. Taking the locations and assignments for the levels given in Fig. 4, we have calculated the cross section predicted by the strong interaction theory. The nuclear radius for lead was taken to be 8.0×10^{-13} cm (8.0 for the parameter X_0).

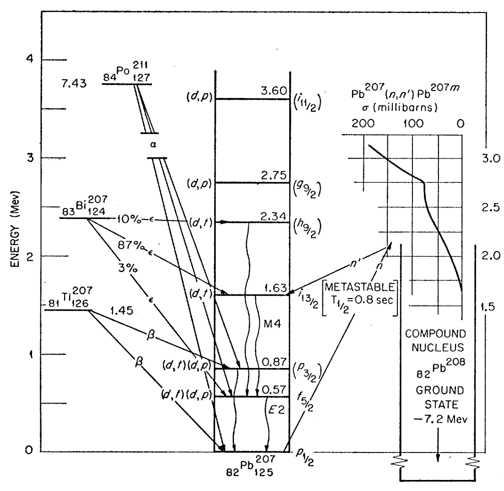

FIG. 4. Energy level diagram summarizing the formation on the low-lying levels of Pb^{207}. Note: The schematic curve of the excitation cross should be increased by 10 percent to agree with curve presented in Fig. 2(a).

Figure 5 shows the calculated cross section together with two runs of the experimental cross section near threshold. The general agreement with respect to shape and absolute cross section is good. The experimental points suggest more curvature near threshold but this may be at least in part attributed to the finite energy spread used to measure the cross section. The agreement in absolute cross section is well within the errors of the experimental determination. It might be mentioned that the inclusion in the calculation of the competition offered by the other low-lying states (0.57 and 0.87 Mev) is quite important. If these states had been

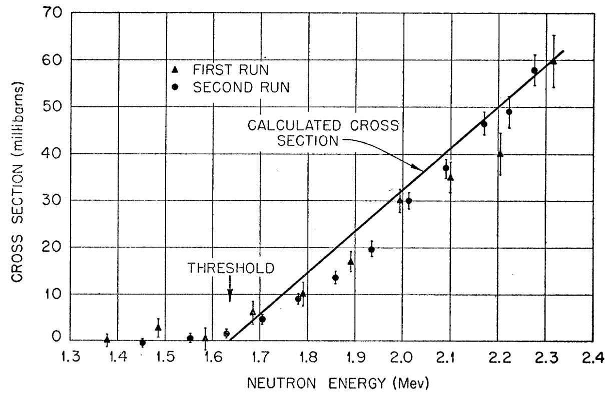

FIG. 5. Calculated cross section based on the strong interaction theory of nuclear reactions together with two runs of the experimental cross section near threshold.

omitted, the calculated cross section would have been, on the average, about a factor of 3 larger.

At higher neutron energies, states above the metastable state will be excited by inelastic scattering. As the incident neutron energy is raised above the threshold for excitation of a new state the cross section for excitation of the metastable state is modified. The cross section for direct excitation is always adversely affected by the onset of inelastic scattering to a new level because of the increased competition. However, since the measured cross section includes indirect as well as direct excitation, the cross section actually may show a rather abrupt increase with the advent of a new state if this state subsequently decays to the metastable state.

After the initial almost linear increase with neutron energy, the experimental cross section levels off at about 2.5 Mev. Now, the existence of a state of 2.34 Mev is well established and its character is quite likely $h_{9/2}$. It is known that this state by-passes the metastable states in the subsequent decay to the ground state.[16] Therefore the excitation of this state would tend to decrease the cross section for excitation of the metastable state.

At 2.75 Mev, the experimental curve shows an abrupt rise and the natural inference is that a new state is excited which feeds the metastable state. Such a state must have a fairly high spin to ensure at least partial decay to the metastable state ($i_{13/2}$) instead of completely by-passing it in favor of the other low-lying states. Harvey found a level at 2.75 Mev and suggested the assignment $g_{9/2}$. A state of the type $g_{9/2}$ can decay to the metastable state by an $E2$ transition whereas decay to the $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ states requires less favorable types of transitions. However, it is difficult to decide to what extent decay to the $h_{9/2}$ and $f_{7/2}$ states ($E1$ transitions) would compete with the $E2$ transition.

We have extended the calculated cross section to higher neutron energies on the assumption that there

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

[16] N. Lazar (private communication).

is a level at 2.34 Mev of the type $h_{9/2}$ which completely by-passes the metastable state and that there is a level at 2.75 Mev of the type $g_{9/2}$ which decays predominantly to the metastable state. The calculated curve is given in Fig. 2(b) as the solid line. The dashed curve shows the calculated cross section with the assumption that there is also an $f_{7/2}$ level (taken to be superimposed on the $h_{9/2}$ level for calculational simplicity since its exact location is not known) which by-passes the metastable state in its subsequent decay. It is seen that the experimental cross section is reasonably well represented by the calculated curves.

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Gamma Radiation from the Inelastic Scattering of Protons by F^{19}†

C. A. Barnes*

Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received November 4, 1954)

The absolute cross section for the excitation of the 109-kev and 197-kev excited states of F^{19}, by the inelastic scattering of protons, has been studied as a function of bombarding energy up to 1750 kev by detecting the resultant gamma radiation in scintillation counters. Most of the resonances for the various $F^{19}(p,\alpha)O^{16}$ reactions appear as resonances for the excitation of one or both of these low-lying states. A detailed study of the angular distributions of the two gamma rays, together with the direct measurements of the lifetimes of these states by Thirion, Barnes, and Lauritsen, and the Coulomb excitation work of Sherr, Li, and Christy, leads to the assignments: 109-kev state, $J=\frac{1}{2}$, odd parity; 197-kev state, $J=5/2$, even parity. The nonresonant yield of 197-kev gamma rays is approximately that expected from Coulomb excitation at low incident proton energies. The nonresonant yield of 109-kev gamma rays exceeds the expected Coulomb excitation. In conjunction with the recent measurements of the elastic scattering of protons by F^{19} made by Peterson, Webb, Hagedorn, and Fowler, in this laboratory, and older measurements of the $F^{19}(p,\alpha)O^{16}$ reactions, the resonant inelastic cross sections allow a new determination of the partial widths for the various modes of decay of the Ne^{20} compound nuclear states.

I. INTRODUCTION

THE bombardment of F^{19} by protons up to energies $\sim$2 Mev can lead to the following reactions:

$$F^{19}+p\rightarrow Ne^{20*}\rightarrow \alpha_{0,\pi,1,2,3}+O^{16} \quad (1)$$

$$\rightarrow \gamma+Ne^{20} \quad (2)$$

$$\rightarrow p_0+F^{19} \quad \text{(elastic scattering)} \quad (3)$$

$$\rightarrow p_{1,2}+F^{19*} \quad \text{(inelastic scattering to first and second excited states of } F^{19}\text{)}. \quad (4)$$

The first of these reactions[1,2] can leave O^{16} in its ground state, in a pair-emitting state at 6.05-Mev excitation, or in gamma-ray emitting states at 6.13, 6.9, and 7.1 Mev. The detailed study of this reaction has made possible the assignment[2,3] of spin and parity to many of the levels in Ne^{20} and O^{16} involved in the reactions.

Reaction (2) shows resonances at proton energies of 669, 874, 935, 980, 1092, 1290, 1324, 1346, 1372, and 1422 kev.[2,4]‡ Elastic scattering of protons (reaction 3) has recently been investigated[5,6] up to 1.8 Mev and gives directly or confirms the spin and parity of many of the Ne^{20} states.

Prior to the present investigation, the inelastic scattering of protons by fluorine has been studied at 7.17-Mev and 8-Mev incident proton energy.[7] Several levels at energies >1.37 Mev in F^{19} were excited, but the resolution in these experiments was insufficient to resolve proton groups to the low-lying levels first reported by Mileikowsky and Whaling.[8] These levels have recently been excited by inelastic scattering of neutrons[9] and by inelastic scattering of α particles.[10,11]

† Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

* On leave of absence from the University of British Columbia.

1 Streib, Fowler, and Lauritsen, Phys. Rev. **59**, 253 (1941); Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946); Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).

2 F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

3 W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 840 (1939); J. R. Oppenheimer and J. S. Schwinger, Phys. Rev. **56**, 1066 (1939); W. R. Arnold, Phys. Rev. **79**, 170 (1950); **80**, 34 (1950); Barnes, French, and Devons, Nature **166**, 145 (1950); C. Y. Chao, Phys. Rev. **80**, 1035 (1950); J. Seed and A. P. French, Phys. Rev. **88**, 1007 (1952); Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950); Devons, Goldring, and Lindsey, Proc. Phys. Soc. (London) **A67**, 134 (1954).

4 S. Devons and H. G. Hereward, Nature **162**, 331 (1948); R. M. Sinclair, Phys. Rev. **93**, 1083 (1954); T. M. Hahn and B. D. Kern, University of Kentucky report, August 31, 1954 (unpublished).

‡ See note added in proof in the caption of Fig. 1.

5 Peterson, Barnes, Fowler, and Lauritsen, Phys. Rev. **94**, 1075 (1954).

6 Webb, Hagedorn, Fowler, and Lauritsen, Phys. Rev. **96**, 851(A) (1954).

7 Cowie, Heydenburg, and Phillips, Phys. Rev. **87**, 304 (1952); Arthur, Allen, Bender, Hausman, and McDole, Phys. Rev. **88**, 1291 (1952).

8 C. Mileikowsky and W. Whaling, Phys. Rev. **88**, 1254 (1952).

9 R. B. Day, Phys. Rev. **89**, 908(A) (1953).

10 Sherr, Li, and Christy, Phys. Rev. **94**, 1076 (1954); **96**, 1258 (1954).

11 N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 748(A) (1954) and Phys. Rev. **94**, 1232 (1954); G. A. Jones and D. H. Wilkinson (private communication).