(d,p) Reactions in the Pb Isotopes and Their Interpretation*

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Q values and differential cross sections have been measured for nuclear states excited by the $Pb^{206}(d,p)Pb^{207}$, $Pb^{207}(d,p)Pb^{208}$, and $Pb^{208}(d,p)Pb^{209}$ reactions. The known properties of the Pb^{206} ground state, the low-lying states of Pb^{207}, and the Pb^{208} ground state are used to confirm the possibility of a stripping interpretation for these reactions. This interpretation is used to suggest possible assignments for the other observed states in Pb^{207} and Pb^{209}; in particular, the ground state of Pb^{209} is consistent with a $g_{9/2}$ assignment. The first excited state of Pb^{209} does not seem to behave like a single-particle state.

INTRODUCTION

STRIPPING reactions are well established as a spectroscopic tool in the study of light nuclei. The successful interpretation of such reactions relies upon experimental conditions where Coulomb effects or additional nuclear effects, such as compound-nucleus formation, are not important. Recent investigations in medium-weight nuclei[1] and in light nuclei[2] show distorted angular distributions which are quite sensitive to changes in the deuteron bombarding energy, in contrast to expectations for stripping. Cross sections displaying these characteristics have been analyzed in a light nucleus[3] as the result of interference between a compound-nucleus reaction amplitude and a stripping amplitude. Such a two-amplitude picture might also be an interpretation of the distorted distributions observed in medium-weight nuclei, but an analysis of the reactions is very difficult because of the level density in these nuclei. Coulomb distortions would also be important for these reactions.

The experiment reported here is a study of (d,p) reactions in heavy nuclei. The specific energy-dependent nuclear distortions, which seem to present such difficulties for medium-weight elements, are expected to be less serious in the heavy elements. In particular, the high-level density in the compound-nucleus should give a cancellation of interference terms between the compound-nucleus reaction amplitude and the stripping amplitude and yield a compound-nucleus amplitude which varies slowly with energy. If this occurs, then it is possible that the angular distributions will be characterized by just the properties of the initial and final states of the reaction although they will be strongly influenced by Coulomb distortions. The experiment consists then of a measurement of differential cross sections for (d,p) reactions involving known nuclear states, an examination of the consistency of the data with the supposition that the initial and final states alone determine the reaction, and finally, an effort to use this interpretation to determine the properties of several unknown nuclear states.

The lead isotopes, Pb^{206}, Pb^{207}, and Pb^{208} were used for this study. Their low-lying level structure has been investigated[4,5] and orbital angular momentum and spin assignments have been made for the ground and first four excited states of Pb^{207}. The ground-state assignments of the other isotopes are known.[5] These nuclei are near doubly-magic Pb^{208} and their states are expected to behave like simple shell-model states. This expectation has led to a considerable amount of theoretical work on the different nuclear states of the isotopes[6,7] and several of the predictions can be compared with the experimental results.[7]

There is an additional interest in the $Pb^{208}(d,p)Pb^{209}$ reaction. This reaction should show the order and energy separation of the possible angular momentum states of the first neutron outside of the closed shell of 126 neutrons. Attempts to extend the independent-particle model interpretations of nuclear states beyond Pb^{208} depend upon the energy positions assigned to the various angular momentum states of the 127th neutron; this would affect, in particular, a detailed understanding of the Bi^{210} (RaE) β decay which depends upon the construction of a wave function for the decaying state.

APPARATUS AND PROCEDURE

The 10.85-Mev deuteron beam of the Indiana University cyclotron was brought out to the target chamber through a pair of magnetic quadrupole lenses and a 32-degree sector magnet. The target chamber, beam collection, and beam integration have all been described previously.[8,9] In this experiment, the beam spot on the

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[1] L. L. Lee and J. P. Schiffer, Phys. Rev. **107**, 1340 (1956).
[2] See reference 3 of Lee and Schiffer[1]; also see J. B. Marion and G. Weber, Phys. Rev. **102**, 1355 (1956); Phys. Rev. **103**, 167 (1956).
[3] M. T. McEllistrem, Phys. Rev. **111**, 596 (1958).
[4] D. E. Alburger and A. W. Sunyar, Phys. Rev. **99**, 695 (1955).
[5] I. Bergstrom and G. Andersson, Arkiv Fysik **12**, No. 19, 416 (1956). These authors have summarized the experimental information for the states of nuclei near Pb^{208}.
[6] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952); D. E. Alburger and M. H. L. Pryce, Phys. Rev. **95**, 1482 (1954); M. H. L. Pryce, Nuclear Phys. **2**, 226 (1956/57); W. W. True, Phys. Rev. **101**, 1342 (1956).
[7] W. W. True and K. W. Ford, Phys. Rev. **109**, 1675 (1958); M. J. Kearsley, Phys. Rev. **106**, 389 (1957); Nuclear Phys. **4**, 157 (1958).
[8] Rasmussen, Miller, and Sampson, Phys. Rev. **100**, 181 (1955).
[9] J. R. Rees and M. B. Sampson, Phys. Rev. **108**, 1289 (1957).

target was about one-eighth of an inch wide and one-fourth of an inch high.

Outgoing protons passed through a magnetic spectrometer, also described in an earlier paper,[8] and were detected by a CsI (Tl) scintillation crystal and photomultiplier. Sufficient absorber was introduced before the crystal to stop all charged particles except protons. Throughout these measurements the spectrometer was operated with a momentum resolution of 0.35% and with a solid angle of 4.0×10^{-3} steradians. The angle between the spectrometer and the incident deuteron beam was varied from 12.5 degrees to 142 degrees. Measurements were taken at 5-degree intervals for all of the reactions except $Pb^{206}(d,p)Pb^{207}$, where 10-degree intervals were taken at large angles. A complete proton momentum spectrum was taken at each angle, including oxygen and carbon contamination groups. The angle was then changed and the procedure was repeated. The outgoing proton groups that were studied had energies between 10 Mev and 16 Mev.

Four different targets were used; natural lead, Pb^{206}, Pb^{207}, and Pb^{208}. The first two of these were prepared by evaporation of the metal onto thin (~0.004 mil) gold leaf.[10] Separated isotopes of Pb^{207} and Pb^{208} were obtained from Oak Ridge in the form of PbO, and the targets were prepared by electrolyzing the metal onto thin silver foils from a solution of PbO dissolved in dilute perchloric acid.[11] Oxygen contamination of the electrolyzed targets made it necessary to carry out the electrolysis, including the drying of the targets after removal from the bath, in a helium atmosphere. In spite of this precaution, the oxygen contamination was sufficiently serious to prevent observation of the $Pb^{208}(d,p)Pb^{209}$ reaction to the first excited state of Pb^{209} at laboratory angles forward of 75 degrees.

Target thicknesses were between 2.5 and 3 mg/cm² of lead and were determined by measuring the yield of elastically scattered 22-Mev alpha particles at forward angles. This cross section has been shown to have the Rutherford angular dependence at laboratory angles forward of 90 degrees.[9] The alpha particles were too energetic to be analyzed by the magnetic spectrometer, and were counted instead by a crystal spectrometer mounted in the target chamber.

ENERGY MEASUREMENT

Two types of measurements were used in determining the Q-values for the different states. In order to determine absolute Q-values it was necessary to know the beam energy at the time of the Q-value measurement. This was done by using the well-known Q-values for the oxygen and carbon stripping reactions.[12] The second type of measurement, giving relative Q-values, was carried out by using adjacent final states in the reaction being studied. The difference in the Q-values of the two states can be well determined even if the value of the beam energy is uncertain by 0.5 to 1.0% (provided the beam energy remains constant throughout the measurement).

Acceptable measurements of absolute Q-values and of relative Q-values required uninterrupted operation of the cyclotron. Absolute Q-values were determined at the more forward angles only (less than seventy degrees) while relative Q-values were determined at all angles. The minimum number of measurements of any absolute or relative Q-value was six and the maximum was twenty.

The nonlinear correction to the magnetic spectrometer's fluxmeter was discussed in a previous paper[13] and is probably the most important source of uncertainty. Recently, this correction has been remeasured and extended to higher energies by measuring the energies of elastically scattered alpha particles from several elements. The importance of the correction was minimized in this work by the proximity of the measured groups to one another.

Table I lists the excitation energies and Q-values that were found in the present work. The individual measurements were consistent with one another well within the final quoted uncertainty of ±0.02 Mev.

TABLE I. Excitation energies, peak angles, peak differential cross sections and total cross sections. All angles ±1 degree, all cross sections ±22%.

Residual nucleus	E_x (Mev)	θ (degrees)	$d\sigma/d\omega$ (mb/sterad)	σ (mb)
Pb^{207}, $Q=4.51$ Mev	0.00	65	0.31	2.01
	0.57	89	0.06	0.37
	0.90	64	0.09	0.62
	2.71	103	1.51	
	3.61	111	0.76	
	4.37	98	5.16	
	4.62	97	4.76	
Pb^{208}	0.00	65	0.19	1.07
Pb^{209}, $Q=1.71$ Mev	0.00	102	1.63	
	0.79	?	0.13	
	1.58	93	7.75	

CROSS-SECTION UNCERTAINTIES

The representative error bars displayed on the angular distribution curves are indicative of errors in relative yield only. A comparison, for example, of peak cross sections for two final states of the $Pb^{206}(d,p)Pb^{207}$ reaction would be determined within limits set by these errors. The errors include the effect

[10] Radiogenic lead, 88% Pb^{206}, was kindly sent to us by Professor H. H. Barschall of the University of Wisconsin and was used for the Pb^{206} target.

[11] Isotopic purity of the Pb^{207} and Pb^{208} samples is given by R. E. Bell and H. M. Skarsgard, Can. J. Phys. **34**, 745 (1956). These authors discuss also methods of preparation of electrolyzed targets.

[12] D. M. Van Patter and W. Whaling, Revs. Modern Phys. **29**, 757 (1957).

[13] Miller, Carmichael, Gupta, Rasmussen, and Sampson, Phys. Rev. **101**, 740 (1956).

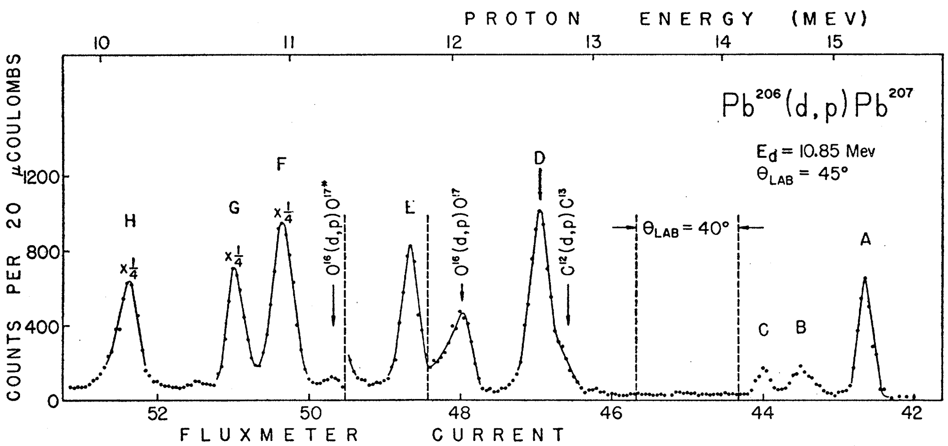

FIG. 1. A typical proton momentum spectrum for $Pb^{206}(d,p)Pb^{207}$. Proton groups to the states of Pb^{207} are identified by capital letters above the groups. Pb^{207} states corresponding to groups labeled *A*, *B*, *C*, *D*, *E*, *F*, *G*, and *H* are at excitation energies of 0.00, 0.57, 0.90, 2.71, 3.61, 4.37, 4.62, and 5.20 Mev, respectively. The positions of expected contaminant groups are indicated. Vertical dashed lines separate regions taken on different days or under different experimental conditions. All of the data at lower proton energies are plotted to one-quarter scale.

of statistics, target nonuniformities, background subtraction, and in some cases, the unfolding of overlapping proton groups. Measurements at laboratory angles forward of 90 degrees were made with the target at 45 degrees to the deuteron beam and in "transmission". The target was in "reflection" for measurements at the back angles. Broadening of the proton momentum spectra because of target thickness became important in the "reflection" position and uncertainties in the separation of overlapping proton groups were much larger (see Fig. 7).

Angle settings for the angular distributions are uncertain by six-tenths of a degree. This uncertainty arises mainly from an indeterminacy of the zero angle of about one-half degree.

A comparison of relative cross sections between targets involves an additional error of ±16% that must be included with the uncertainties shown on the individual angular distributions. This error arises in the measurement of relative target thicknesses which, as mentioned earlier, involved the elastic scattering of alpha particles from the target into a crystal spectrometer mounted in the target chamber. Uncertainties in relating the scattering yield to the Rutherford cross section and target thickness for a particular target were about 11.5%, and these have been combined in an rms manner for the comparison of yields from two different targets.

Finally, absolute cross sections involve all of the uncertainties already mentioned, and in addition, involve absolute beam integration errors and measurement of the relative solid angles of the crystal spectrometer and the magnetic spectrometer. The absolute cross sections given in Table I and as the ordinates of the angular distributions have a total uncertainty of ±22%.

RESULTS

Figure 1 shows a typical proton momentum spectrum. All of the lettered groups in the figure are from the $Pb^{206}(d,p)Pb^{207}$ reaction. The abscissa (Fluxmeter Current) is inversely proportional to the proton momentum. More than 15 hours of running time with a 0.25-microampere deuteron beam were required for this spectrum.

All of the nuclear states that were studied are listed in Table I and, except for the $Pb^{207}(d,p)Pb^{208}$ reaction, are shown in the energy-level scheme of Fig. 2. The dashed levels in Fig. 2 were not seen in the (d,p) reaction and their energies are those given by Alburger and Sunyar.[4] All of the other energies shown in Fig. 2 are the results of our measurements. No energy measurements were made for the $Pb^{207}(d,p)Pb^{208}$ reaction.

The configuration and spin assignments given in Fig. 2 are also from Alburger and Sunyar. A search was made for proton groups to the two dashed levels, but they were not detected. At a laboratory angle of 90 degrees the group to the 1.63-Mev level of Pb^{207} must have an intensity less than one percent that of the

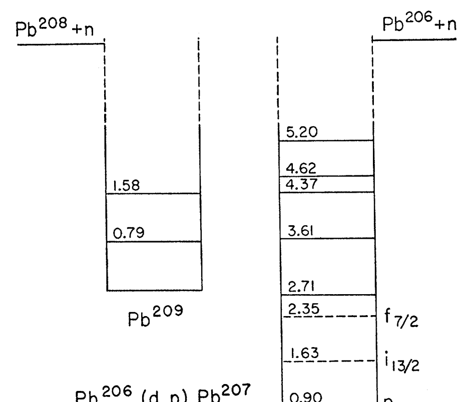

FIG. 2. Energy levels of Pb^{207} and Pb^{209}. The dashed levels do not appear in the (d,p) reaction. Harvey's method of plotting the levels relative to the neutron binding energy is used (reference 20), and shows the possible correspondence of several Pb^{207} nuclear states with the states in Pb^{209}.

ground-state group, while the group to the 2.35-Mev level must have an intensity less than five percent that of the ground-state group.

There are two striking features of our results. First, nearly all of the angular distributions show angular maxima and fall off very rapidly at forward angles. Second, the variation in the observed cross section is very large. Peak cross sections for the different observed states varied between 0.06 mb/sterad and 7.75 mb/sterad, a change in cross sections by a factor of more than one hundred. Table I lists the peak angles of the angular distributions, the peak differential cross sections, and a few total cross sections.

DISCUSSION

(a) Known Nuclear States

Properties of the initial and final states of the reaction were known for four of our experimental angular distributions. If a stripping reaction is assumed, then three of these distributions would involve p-wave neutron capture. These are the distributions for the ground-state and 0.90-Mev state of Pb^{207} shown in Fig. 3, and the distribution for the ground state of Pb^{208} shown in Fig. 4. All three of these distributions have maxima at a laboratory angle of 65 degrees; they also have the most pronounced maxima observed. The fourth angular distribution is for the 0.57-Mev state of Pb^{207} and is shown in Fig. 4. This distribution would involve f-wave neutron capture and has a maximum at 89 degrees. The outgoing proton energies for the four distributions are between 14 Mev and 16 Mev.

There are several features of these angular distributions which we feel are consistent with our assumption of a stripping process, and inconsistent with the statistical assumption for a compound-nucleus process. First, the asymmetrical angular distributions are not in agreement with Wolfenstein's predictions for a compound-nucleus process.[14] Second, the angular distributions for p-wave neutron capture agree well with one another except at the back angles. This agreement is expected for a stripping process. Third, the movement of the maximum to larger angles for f-wave neutron capture is similar to the behavior of stripping reactions in light nuclei. The appearance of angular maxima at large angles for the Coulomb-distorted stripping reactions is indicated by the calculations of Tobocman and Kalos[15] and of Biedenharn *et al.*[16] The interesting feature is, of course, the possibility that the angular distributions are still representative of the neutron orbital angular momentum transfers even though the distributions are strongly influenced by Coulomb forces.

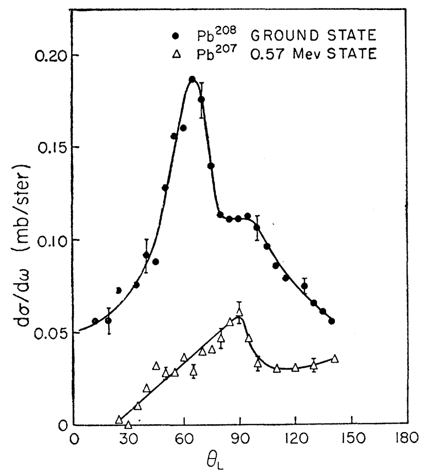

FIG. 4. Proton angular distributions leading to the ground state of Pb^{208} and the $f_{5/2}$ state of Pb^{207}. The ground-state distribution is for p-wave neutron capture and should be compared with the distributions in Fig. 3. The peaking of the f-state distribution at larger angles than the p-state distribution is in agreement with stripping effects observed in light nuclei.

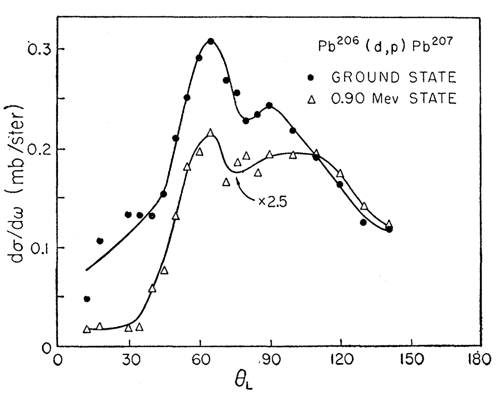

FIG. 3. Proton angular distributions leading to the $p_{1/2}$ (ground) and $p_{3/2}$ states of Pb^{207}. The two distributions are quite similar and suggestive of a stripping mechanism for the reaction.

The supposition of a stripping process can also be tested in a study of the relative cross sections to the four states of known properties. Several theoretical calculations of the level structure of different lead isotopes have been made.[6,7] In particular, the levels of Pb^{205} and Pb^{206} have been treated theoretically by Kearsley and by True and Ford.[7] A result of their calculations has been a mixed-configuration wave function for the ground state of Pb^{206}. The True and Ford wave function has the form

$$\psi_{206}=a(p_{1/2})^{-2}+b(f_{5/2})^{-2}+c(p_{3/2})^{-2}+d(i_{13/2})^{-2},$$

where the absolute values of the coefficients a, b, c, and d are 0.865, 0.306, 0.377, and 0.127, respectively. If one now assumes that the ground state and low-lying excited states of Pb^{207} are pure single-hole configurations, then it is possible to obtain predictions of relative cross sections for different final states of the

[14] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).

[15] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

[16] Biedenharn, Boyer, and Goldstein, Phys. Rev. **104**, 383 (1956).

$Pb^{206}(d,p)Pb^{207}$ reaction from this wave function. To compare these predictions to our data, we refer to the reaction formalism of Auerbach and French[17] and French and Raz,[18] who have studied (d,p) reactions in light elements and in the calcium isotopes. We compare the cross-section ratios by assuming that only the spin statistical factors and the neutron capture probabilities vary from reaction to reaction. This is a valid comparison if only final states resulting from the same neutron capture l-value are compared and if changes of ± 1 Mev in outgoing proton energies near 15 Mev do not materially affect the cross sections. Our comparisons will be between peak cross sections which should be more closely related to a stripping process than the total cross sections. Comparisons using total cross sections and comparisons using peak cross sections agree within the experimental error.

The ratio of the cross section to the 0.9-Mev state of Pb^{207} to that to the ground state of Pb^{207} should be, except for statistical factors, $|c|^2/|a|^2$. We find $|c|^2/|a|^2=0.14\pm0.01$. The theoretical value of True and Ford[7] is 0.19.

Since the ground state of Pb^{207} is assumed to be a pure $p_{1/2}$ neutron hole state, the ratio of the $Pb^{206}(d,p)Pb^{207}$ ground-state cross section to that of $Pb^{207}(d,p)Pb^{208}$ yields a value for $|a|^2$. We find $|a|^2=0.88\pm0.15$. Then $a=0.94\pm0.08$ and $c=0.35\pm0.05$. True and Ford give $a=0.865$ and $c=0.377$.

Further quantitative comparisons of our data with the True and Ford wave function would require a better understanding of the influence of different factors on the cross section. However, several qualitative remarks can be made. The $(f_{5/2})$ level at 0.57 Mev in Pb^{207} was observed; the $(f_{7/2})$ level at 2.35 Mev in Pb^{207} was not observed. This would be predicted by True and Ford. The failure to observe the $(i_{13/2})$ level at 1.63 Mev in Pb^{207} is consistent with the True and Ford wave function. Finally, comparable cross sections for the 0.57-Mev state of Pb^{207} and the 0.90-Mev state of Pb^{207} agree with the approximate equality of b and c.

(b) Possible Assignments of the other Observed States

The observed energy levels of Pb^{207} and Pb^{209} are plotted in Fig. 2 relative to the binding energy of the last neutron. The ground state and low-lying excited states of Pb^{209} are expected to be different angular momentum states of the 127th neutron which lies outside of the closed shell of 126 neutrons. Possible angular momentum states of the last neutron in Pb^{207} bound to a "Pb^{206}" core should correspond closely to the single-particle states of Pb^{209}. Figure 2 indicates a correspondence between the ground state of Pb^{209} and the 2.71 Mev state of Pb^{207}, a correspondence between the 0.79 Mev state of Pb^{209} and the 3.61 Mev state of Pb^{207}, and a correspondence between the 1.58 Mev level of Pb^{209} and the 4.37-Mev state or the 4.62-Mev state of Pb^{207}. The angular distributions and relative intensities to the different states can be used to test these possible correspondences. We shall also attempt to choose among possible spin assignments for these states by assuming a stripping mechanism for the reactions.

The angular distributions for the 2.71-Mev and the 3.61-Mev states of Pb^{207} are shown in Fig. 5. The large cross sections are suggestive of single-particle states. The lowest single-particle neutron states expected in this region are $g_{9/2}$ and $i_{11/2}$.[19] Our observations of known groups indicate that the larger peak angle of the 3.61-Mev state is representative of a higher neutron angular momentum transfer. This is also in agreement with the relative intensities of the two states. The 2.71-Mev and the 3.61-Mev states of Pb^{207}, if they are single-particle states, are then expected to be $g_{9/2}$ and $i_{11/2}$, respectively.

The angular distribution to the ground state of Pb^{209} is shown in Fig. 6 and agrees very well with the angular distribution and cross-section magnitude to the 2.71-Mev state in Pb^{207}. The correspondence of these two states appears to establish their single-particle character, and our earlier arguments indicate a $g_{9/2}$ assignment.

Establishment of the single-particle nature of the 2.71-Mev state in Pb^{207} strengthens our suggestion that the 3.61-Mev state is also a single-particle state. However, the angular distribution for the 0.79-Mev state in Pb^{209} (see Fig. 6) is quite inconsistent with the

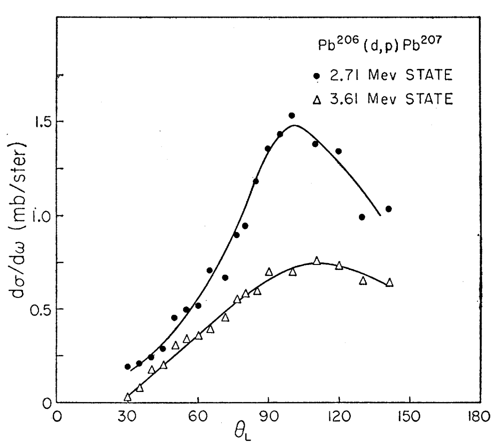

FIG. 5. Angular distributions leading to the fifth and sixth known excited states of Pb^{207}. The distribution for the 2.71-Mev state is nearly identical with the distribution for the ground state of Pb^{209} (Fig. 6).

[17] T. Auerbach and J. B. French, Phys. Rev. **98**, 1276 (1955).

[18] J. B. French and B. J. Raz, Phys. Rev. **104**, 1411 (1956). Our calculations have assumed a differential cross section similar to that given by French and Raz [Eq. (1)], but our $\phi_l(\theta)$ would be modified by Coulomb effects. Details of this cross-section expression are in Auerbach and French.[17]

[19] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

measurements for the Pb^{207} 3.61-Mev state. The character of the 0.79-Mev state is apparently quite different from that of the other states studied. Our data indicate very little angular dependence of the cross section and a much smaller magnitude for the cross section than would be expected for a single-particle state. The failure to find a correspondence between the Pb^{209} 0.79-Mev state and the Pb^{207} 3.61-Mev state also casts doubt upon our earlier interpretation of that Pb^{207} state.

The angular distribution of the 1.58-Mev state in Pb^{209} is shown in Fig. 6. Once again, the large cross section is suggestive of a single-particle state. The single-particle states that are expected from the shell model are $g_{7/2}$ and $d_{5/2}$.[19] While the Pb^{209} ground-state angular distribution (presumably for a $g_{9/2}$ state) peaks at a slightly larger angle than the 1.58-Mev angular distribution, the latter distribution is not inconsistent with a $g_{7/2}$ assignment for the 1.58-Mev state. The f-wave neutron capture angular distribution in Fig. 4 also supports a $g_{7/2}$ assignment for the state. There are, however, several strong arguments against this assignment. First, if the state is a $g_{7/2}$ state and if the $g_{9/2}$ assignment for the ground state is correct, then the g-state splitting is 1.6 Mev, slightly smaller than the 1.8 Mev f-state splitting in Pb^{207}. The g-state splitting is expected to be larger than the f-state splitting. Second, the cross section, when compared to the ground-state cross section, appears to be larger than is expected for a g state. Third, the outgoing proton energy of 11 Mev is quite different from the 15-Mev energy of the protons examined in the f-wave neutron capture. Proton energies below the Coulomb barrier are expected to increase Coulomb distortions of the angular distributions and to move the peaks of the distributions to larger angles. For these reasons we prefer to suggest a $d_{5/2}$ assignment for the 1.58-Mev state of Pb^{209} assuming, of course, that it is a single-particle state.

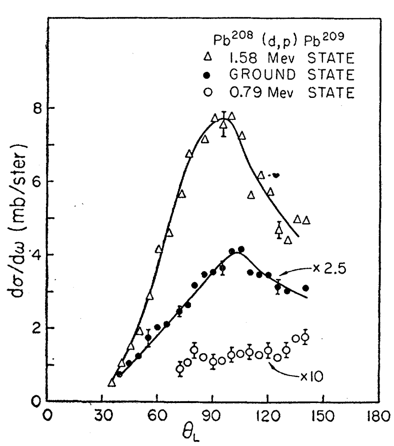

FIG. 6. Angular distributions for the three lowest known states in Pb^{209}. The 0.79-Mev state appears to differ from the other single-particle states. The behavior of the ground state is quite similar to that of the 2.71-Mev state of Pb^{207}.

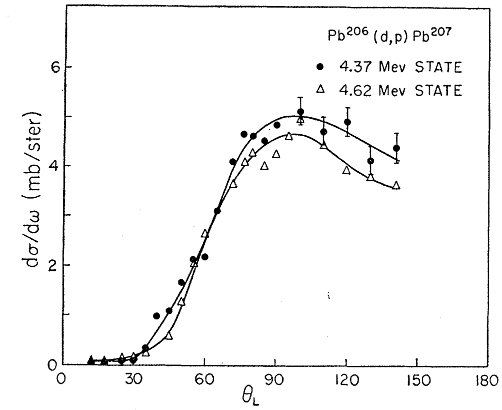

FIG. 7. Proton angular distributions leading to two of the higher excited states in Pb^{207}. The two states appear to have very similar properties.

The angular distributions of the 4.37-Mev and the 4.62-Mev states of Pb^{207} in Fig. 7 are quite similar and are presumably representative of the capture of neutrons with the same orbital angular momentum. This possibility seems to be ruled out by the small energy separation of the two states. The p-state splitting and the f-state splitting in Pb^{207} indicate that energy separations of more than 1 Mev should be expected for this type of doublet. The data might represent two single-particle states with different orbital angular momenta. In that case, corresponding states should be seen in Pb^{209}. The angular distribution of the Pb^{209} 1.58-Mev state is similar to the angular distributions of these Pb^{207} states; however an exact correspondence between either one of the Pb^{207} states and the Pb^{209} state is ruled out by the larger cross section of the 1.58-Mev state.

A suggestion made to us by Professor K. W. Ford appears to offer a plausible explanation of the two identical states in Pb^{207} and also a possible correspondence with the 1.58-Mev state of Pb^{209}. The appearance of core-excited proton states in Pb^{208} at excitation energies above 2.6 Mev implies the existance of similar states in Pb^{207} and Pb^{209} at similar excitation energies. These states would not be seen in a (d,p) stripping reaction. However, if one of them happens to have the same spin and parity as a neutron particle state and nearly coincides with it in energy, then the two states should mix strongly with approximately equal neutron state and proton state amplitudes. The stripping reaction would then excite both states, their cross sections should be about equal, and they should have identical angular distributions. This is in agreement with the experimental measurements for the 4.37-Mev and 4.62-Mev states of Pb^{207}.

A correspondence between the cross section to the 1.58-Mev state of Pb^{209} and the sum of the cross sections to the 4.37-Mev and 4.62-Mev states of Pb^{207} is implied by Ford's suggestion. Our earlier interpretation of the 1.58 Mev state as a single-particle state also requires some kind of correspondence between this state and some state or states of Pb^{207}. The sum of the peak cross sections of the Pb^{207} states is 9.9 mb/sterad while the peak cross section of the 1.58-Mev state is 7.75 mb/sterad. The observed ratio of the two cross sections, including the experimental error, is 1.3 ± 0.4 and should be unity for corresponding states. The experimental data are therefore not in good agreement with this assumption of corresponding states. However, the discrepancies between the different experimental data do not appear to be sufficiently large to rule out the possible interpretation offered here.

(c) Comparisons with Other Experiments

The electron decay of Bi^{207} to the low-lying states of Pb^{207} has been studied by Alburger and Sunyar.[4] Our experimental angular distributions and relative cross sections for the ground state and first two excited states are in agreement with their configuration assignments.

An extensive survey of (d,p) and other reactions in several lead isotopes has been carried out by Harvey.[20] His Q-value and differential cross section measurements were carried out at a fixed angle. Several of our Q-value measurements appear to disagree with his results although the combined uncertainties are large enough to account for the discrepancies. On the basis of his relative cross sections for the different states (at one laboratory angle) and using the j-j coupling scheme by Klinkenberg,[19] Harvey assigned single-particle or single-hole configurations to all of his observed states in Pb^{207} and Pb^{209}. In particular, his assignments for the 2.71-Mev, 3.61-Mev, 4.37-Mev, and 4.62-Mev states of Pb^{207} were $g_{9/2}$, $i_{11/2}$, $d_{5/2}$, and $g_{7/2}$. His assignments for the ground, 0.79-Mev, and 1.58-Mev states of Pb^{209} were $g_{9/2}$, $i_{11/2}$, and $d_{5/2}$, and the possible correspondence of these states with states in Pb^{207} was pointed out. Our experimental results indicate that the 0.79-Mev state of Pb^{209} does not correspond to the 3.61-Mev state of Pb^{207}. Furthermore, our experimental results do not seem to permit simple unmixed configuration assignments for the 4.37-Mev and 4.62-Mev states of Pb^{207}. A possible interpretation of this doublet and its relation to the Pb^{209} 1.58-Mev state has been offered.

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

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Electrodisintegration of Be^9 and C^{12}†

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Yields from the reactions $Be^9(e,e'n)$ and $Be^9(\gamma,n)$, as well as the relative yields from $C^{12}(e,e'n)C^{11}$ and $C^{12}(\gamma,n)C^{11}$, were measured under conditions which permitted a comparison of the relative effects of electrons and bremsstrahlen from electrons in producing nuclear reactions. The primary electron energies were from 6 to 17 Mev in the case of Be, and 24 to 145 Mev in the case of C. Comparison of the experimental results with the theory of electrodisintegration gives information about the multipole order of the electromagnetic transitions involved. The Be^9 results agree with theory if the reaction mechanism is predominantly electric-dipole. For C^{12}, a mixture of 92% electric-dipole with 8% electric-quadrupole intensities gives agreement with theory over the energy range 28–145 Mev, provided that the finite size of the C nucleus is taken into account. The method of considering the finite nuclear size in the theory is presented, and the results previously obtained by Reagan for the reactions $F^{19}(e,e'2p)N^{17}$ and $F^{19}(\gamma,2p)N^{17}$ are shown to be in good agreement with the modified theory for an electric-quadrupole transition.

I. INTRODUCTION

The direct interaction of the electromagnetic field of an electron with the nuclear charges and currents is closely related to the interaction of photons with the nucleus. One important difference arises from the fact that when a nucleus absorbs the energy of a photon, the momentum transfer is fixed along the direction of the incident photon; whereas in transferring energy to the nucleus the electron scatters, giving rise to a distribution of momentum transfers. To the approximation that the nuclear size can be neglected, the relative effects of photons and electrons in producing nuclear reactions can be evaluated without knowledge of the nuclear wave functions other than the specification of the multipole order of the

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