Levels in Bi^{210} from the $Bi^{209}(d,p)$ Reaction*†

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Q values and differential cross sections have been measured for nuclear states in Bi^{210} excited by the $Bi^{209}(d,p)$ reaction. A previously unobserved group with $Q=2.35\pm0.03$ Mev has been found, corresponding to a state with probable proton-neutron assignment $(h_{9/2}g_{9/2})$. The observed Q value for this state is in good agreement with the Q value expected for the $1-$ ground state of RaE. Groups of states with mean excitation of 0.41, 0.88 and 1.4, 2.02, 2.56, 2.81, 3.15, and 4.03 Mev have been found, and neutron assignments of $g_{9/2}$, $i_{11/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, $d_{3/2}$, and $(h_{11/2})$ have been suggested. A comparison with theoretical calculations by Newby and Konopinski for the $(h_{9/2}g_{9/2})$ group of states gives further support to their observation that a calculation of levels in the neighborhood of Pb^{208} is far less accurate when the extra-core interaction type is proton-neutron than when it is neutron-neutron or proton-proton.

I. INTRODUCTION

NUCLEI with mass number close to 208 are of particular interest because of their relative simplicity. Since Pb^{208} has a closed proton shell and a closed neutron shell, the study of nearby nuclei is less complicated than other medium and heavy nuclei, both from the standpoint of experiment and theory. Thus, individual particle model calculations[1] have been more successful in the nuclear lead region than elsewhere among medium and heavy nuclei. Most of the experimental knowledge in this region is obtained from decay scheme studies,[2] but since many levels cannot be studied by α-, β-, and γ-ray spectroscopy, high-resolution nuclear-reaction data can be expected to be of importance. A very suitable reaction for investigation is $Bi^{209}(d,p)Bi^{210}$, since only one excited state in Bi^{210} is reached in the Pb^{210} β decay, and nothing is known of the states produced in the α decay of At^{214}.

Since Bi^{210} has one proton and one neutron outside closed shells, a study of its levels may yield information about the neutron-proton interaction in a heavy nucleus. Quantitative comparisons of theory and experiment have previously been attempted only in the lead isotopes where the interaction type is neutron-neutron. As shown by Newby and Konopinski,[3] the calculations become much more complex in the proton-neutron case, and (due to an apparent necessity to include tensor forces) are more inaccurate.

Another reason for interest in the $Bi^{209}(d,p)Bi^{210}$ reaction is that the results might throw some light on the order of the single-particle neutron levels above neutron number 126. Most of the direct experimental information on these levels comes from the $Pb^{208}(d,p)Pb^{209}$ reaction. However, several uncertainties exist as to the interpretation of the Pb^{209} levels. It might be expected that, because of the proton interaction, a study of the Bi^{210} levels could be of help in the interpretation of the single-particle neutron levels even though the proton-neutron interaction can be taken into account only in an approximate way.

II. PREVIOUS EXPERIMENTAL KNOWLEDGE

A. Radioactive Decay

Radioactive decay studies reveal very little about the states in Bi^{210}. There are, in fact, only three low-lying states which are known. The RaE β-decaying state is believed[4,5] to be $1-$, and an α-decaying state, probably of high spin, has been found[6,7] very near this $1-$ state. Experiment has as yet been unable to determine which of these is the ground state.[7] However, in this paper the $1-$ state will be referred to, for convenience, as the ground state. It is also known from the β decay of Pb^{210} that a $0-$ state exists 0.047 Mev above the $1-$ β-decaying state of Bi^{210}.[8]

One expects the configuration assignments for the extra proton and neutron outside the Pb^{208} core in the ground state of Bi^{210} to be the same as in other cases for the 83rd proton and 127th neutron. The spins of the odd A bismuth isotopes are all 9/2,[9] so that the 83rd proton has an $h_{9/2}$ assignment in agreement with the shell model. The assignment for the 127th neutron is less certain. The nucleus Pb^{209} must have a spin of 7/2, 9/2,

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or 11/2, and the assignment is believed[8] to be $g_{9/2}$ in agreement with the shell model. Further evidence that the new shell starts with a $g_{9/2}$ neutron comes from Tl^{208}, whose ground state and 0.040-Mev excited state have probable[8] assignments of 5+ and 4+, respectively. Since the Tl isotopes all have an $(s_{1/2})^{-1}$ proton configuration, these spins can arise only from the interaction of a $g_{9/2}$ neutron with the unpaired $s_{1/2}$ proton.

Single-particle neutron states in Pb^{209} should have corresponding states (actually multiplets, due to the n-p interaction) in Bi^{210}. Two states which are ascribed to neutron excitation have been observed at energies of 1.56 and 2.01 Mev above the ground state in Pb^{209}, produced by the β decay of Tl^{209}.[10] The 2.01-Mev state was given an assignment of $d_{3/2}$ on the ground that it is fed by an $E1$ gamma transition from the 2.13-Mev state. Since the 2.13-Mev state is the final state in all the observed β decay, it is believed to be predominantly a $(p_{1/2})^{-1}$ core-excited neutron state.

B. (d,p) Reactions

States in Bi^{210} have been observed previously in (d,p) reactions by Harvey,[11] who also studied the states in Pb^{207}, Pb^{208}, and Pb^{209}. Neutron configuration assignments were made on the basis of shell-model predictions taking the relative sizes of the cross sections into consideration. Corresponding states in the different nuclei were given the same assignments. One noticeable feature of Harvey's data was the presence of three states in each nucleus which exhibited very large cross section. Each of these states occurred with approximately the same neutron binding energy in each nucleus. The four groups observed in the $Bi^{209}(d,p)Bi^{210}$ reaction had excitation energies of 0.45, 2.09, 2.66, and 3.21 Mev. The neutron configurations assigned to these states were $g_{9/2}$, $d_{5/2}$, $g_{7/2}$, and $d_{3/2}$, respectively. The ground-state group was not observed (see part C below), and no group corresponding to the $i_{11/2}$ state in Pb^{209} was found.

A more recent investigation of the $Pb^{206}(d,p)Pb^{207}$ and $Pb^{208}(d,p)Pb^{209}$ reactions has been made[12] in which angular distributions of the protons leading to several states were studied. Interpretations made primarily on the basis of stripping theory suggested assignments in agreement with those made by Harvey for the $g_{9/2}$ and $d_{5/2}$ states. However, in this experiment no levels with excitation energies higher than 1.58-Mev were studied in Pb^{209}.

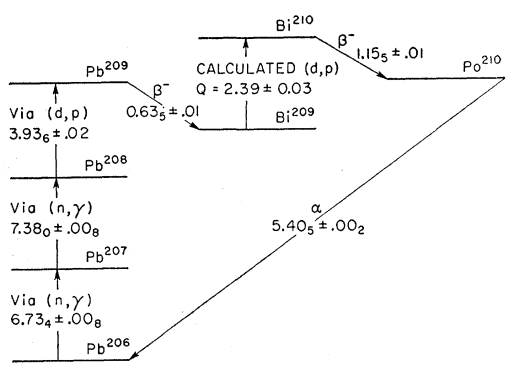

FIG. 1. The closed mass-cycle illustrating the expected Q for the $Bi^{209}(d,p)Bi^{210}$ reaction (references 8 and 12). A new group found in the present investigation has a measured $Q=2.35\pm0.03$ Mev, in agreement with the expected ground-state value of 2.39 ± 0.03 Mev. The error quoted for the expected value is the rms error of all of the contributing measurements shown.

C. The Ground-State Transition

As soon as reaction Q values in the lead region became available, it was pointed out[13–15] that an error of between 0.4 and 0.5 Mev existed in a closed cycle including neutron binding energies and β- and α-decay energies. This cycle is shown in Fig. 1. It was suggested that neither the most energetic proton group observed in the $Bi^{209}(d,p)Bi^{210}$ reaction[14] nor the broad γ ray from the $Bi^{209}(n,\gamma)Bi^{210}$ reaction[15] represented the transition to the ground state but rather to a state (or group of states) of about 0.45-Mev excitation. The expected Q value for the ground state of the $Bi^{209}(d,p)Bi^{210}$ reaction calculated from the data given in the figure is 2.39 ± 0.03 Mev.

A search[16] for protons of higher energy gave an upper limit of 3% for the intensity of the ground-state transition relative to the observed $Q=1.94$-Mev group.

III. EXPERIMENTAL PROCEDURE

The experimental arrangement used in this study was similar to that previously described.[12] 11-Mev deuterons from the Indiana University cyclotron passed through a half inch "snout slit," a strong-focusing magnetic-quadrupole lens, a 32-degree sector magnet, and a series of defining slits before entering the target chamber. For most of the measurements the beam intensity on the target was about 0.25 microampere, concentrated in a spot about $\frac{1}{8}$ in. wide by $\frac{1}{4}$ in. high. Beam collection and integration have been previously described.[17,18]

Protons from reactions in the target passed through a 20-inch radius, 180° double-focusing magnetic spectrometer[17] and were detected by a 20-mil CsI(Tl) crystal placed behind the image slits of the spectrometer. Absorbing foils were introduced between the slits and the crystal to stop all charged particles except protons. A complete proton spectrum over the momentum range of interest was obtained at 12 laboratory angles between 28° and 142.5°. Another experiment in progress pre-

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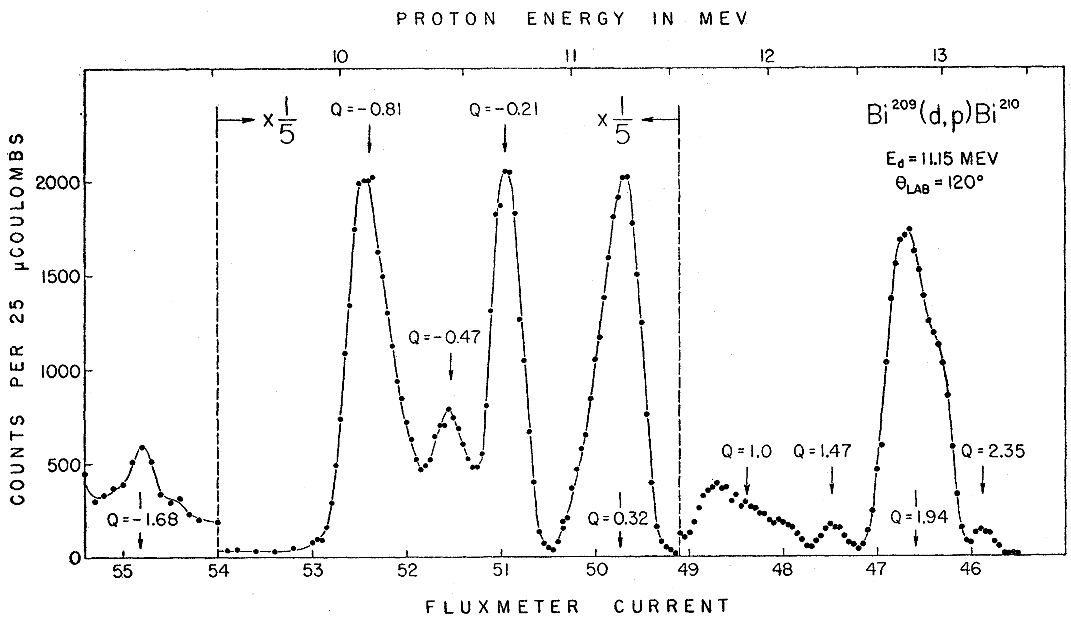

FIG. 2. A typical proton spectrum obtained for the $Bi^{209}(d,p)Bi^{210}$ reaction for angular distribution purposes using normal resolution conditions described in the text. All of the groups shown represent states in Bi^{210}. The intense groups between the dashed lines are plotted to one-fifth scale.

vented the accumulation of data at angles less than 28°, but the cross section was expected[12] to be very small and without structure in this region. For the angular distribution measurements the acceptance solid angle of the spectrometer was set at 3.35×10^{-3} steradian, and the momentum resolution at 0.32%. One spectrum was obtained under higher resolution conditions, as will be described in detail in the following section.

Elastic deuterons scattered from heavy targets are too energetic to be focused directly by the spectrometer. Therefore, the beam energy was determined by observing proton groups with well-known Q's from the $Be^9(d,p)$ reaction.[19] A measurement of the energy of a proton group from bismuth then allowed the Q value of the latter reaction to be calculated. In a typical run, a known proton group from a beryllium target was first observed, then a portion of the spectrum from a bismuth target, followed by the known group again. This procedure minimized possible effects of beam-energy shifts or other time-dependent effects. In general, the beryllium group closest to the portion of the bismuth spectrum under investigation was used for beam-energy determination in order to minimize possible errors due to spectrometer nonlinearities.[20]

All of the bismuth measurements were carried out on a 2 mg/cm² bismuth target prepared by evaporation onto a thin Zapon backing. The 0.32 mg/cm² beryllium target was also an evaporated target prepared for an earlier experiment.[21] Target thicknesses were determined by using the spectrometer to measure the energy lost by alpha particles from a ThB deposit in traversing each target.

IV. RESULTS

Figure 2 shows the spectrum of proton groups observed from the $Bi^{209}(d,p)$ reaction at a laboratory angle of 120°. At this angle the contaminant groups are essentially negligible, so that all of the proton groups shown in Fig. 2 are due to bismuth. As the laboratory angle was decreased, contaminant groups from oxygen and carbon became more troublesome since the bismuth cross sections were decreasing. In a few cases at more forward angles, contaminant subtractions were required to estimate certain bismuth cross sections. Fortunately, contaminant effects were the worst at the least interesting (forward) angles.

The angular distributions for most of the proton groups observed are plotted in Figs. 3 and 4. Their general character is quite similar to that observed previously in the Pb isotopes at this bombarding energy.[12] Since quantitative theoretical Coulomb corrections to the simple stripping theory require extensive machine analysis, the discussion of the present paper is guided instead by the previous experiment[12] in which certain known states were excited. A detailed discussion of the conclusions drawn from these angular distributions is given below.

An examination of Fig. 2 reveals that certain of the

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observed groups clearly do not represent transitions to single states. On the other hand, there is a clear separation between most of the broad groups themselves. Further, it was found that the shapes of the broad groups do not seem to change with angle, indicating that the unresolved groups in a particular peak all have the same angular distribution.[22] These rather striking results are clarified experimentally and theoretically in subsequent sections.

Table I lists the Q values of the groups observed in the present study, the corresponding excitation energies of the residual nucleus Bi^{210}, the magnitude of the cross section at the peak of the angular distribution, and the angle at which this peak occurs. Since in most cases an improvement in resolution did not resolve further states, each Q value was calculated from the proton energy at the center of the half-maximum of the appropriate group. In some cases, however, this does not represent the Q value of the "center of gravity" of the observed group. The Q values quoted for Bi^{210} in Table I and indicated in Fig. 2 represent the appropriate mean values of all suitable measurements taken at the twelve angles. Overall errors in these Q's are ± 0.03 Mev, based on the internal consistency of the various measurements and including a reasonable allowance for possible systematic errors. Errors in the absolute magnitudes of the cross sections quoted in Table I and plotted in Figs. 3 and 4 are about $\pm 20\%$, due primarily to uncertainty in the target thickness. Since the same bismuth target was employed for all of the angular distribution measurements, the *relative* values of the cross sections shown in Figs. 3 and 4 are believed to be accurate to $\pm 5\%$.

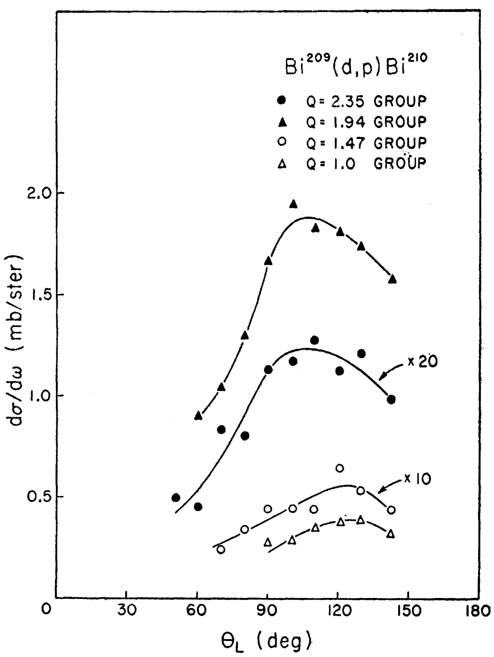

FIG. 3. Proton angular distributions for the four most energetic groups shown in Fig. 2. Note the scale factors indicated for the weak $Q=2.35$- and 1.47-Mev groups. There is marked similarity between the $Q=2.35$- and 1.94-Mev groups (suggested captured neutron assignment $g_{9/2}$), and between the $Q=1.47$- and 1.0-Mev groups (suggested neutron assignment $i_{11/2}$).

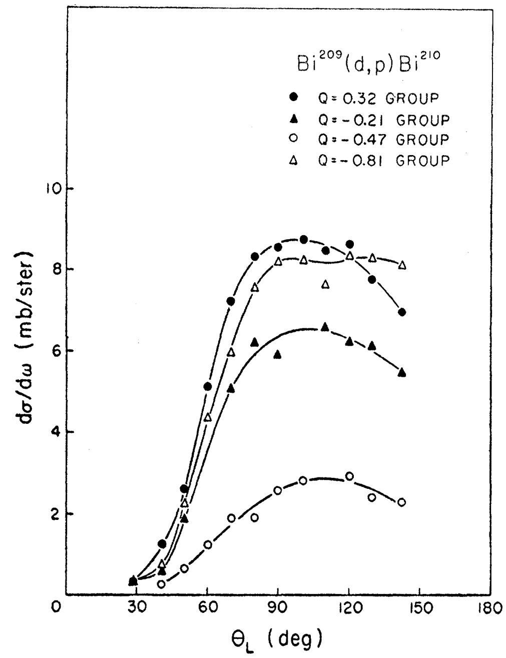

FIG. 4. Proton angular distributions for the four intense groups between the dashed lines in Fig. 2. The assignments suggested in the text for the captured neutron are: $Q=0.32$ group, $d_{5/2}$; $Q=-0.21$ group, $s_{1/2}$; $Q=-0.47$ group, $g_{7/2}$; and $Q=-0.81$ group $d_{3/2}$.

In an attempt to resolve further structure in the broad groups shown in Fig. 2, one spectrum was obtained under higher resolution conditions. The horizontal and vertical beam-defining slits were narrowed until the beam spot on the target, which represents the "object" for the spectrometer optics, was less than $\frac{1}{8}$ in. by $\frac{1}{8}$ in. In addition, the spectrometer image slits were closed from $\frac{1}{4}$ in. to $\frac{1}{8}$ in., representing about 0.17% momentum resolution assuming a point source. Since

TABLE I. Q values, excitation energies of the residual nucleus, peak differential cross sections, and laboratory angles at which the peak cross sections occur, for states of Bi^{210} studied in the present investigation.

Q (Mev)	E_{exc} (Mev)	$d\sigma/d\Omega$ (mb/sr)	θ (degrees)
2.35	0	0.06	108
1.94	0.41	1.88	107
1.47	0.88	0.06	124
~1.0	~1.4	0.39	126
0.32	2.02	8.70	96
−0.21	2.56	6.51	103
−0.47	2.81	2.9	110
−0.81	3.15	8.28	96
−1.68	4.03	···	···

[22] If this were not true, the angular distributions obtained for the broad groups and shown in Figs. 3 and 4 would be of no significance.

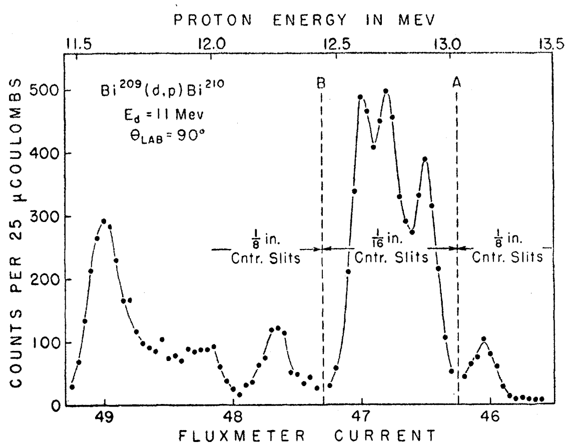

FIG. 5. The high-energy portion of the proton spectrum of Fig. 2 repeated at a different angle under higher resolution conditions described in the text. The region between the dashed lines labelled "A" and "B" was run with the spectrometer counter slits reduced to $\frac{1}{16}$ in. instead of $\frac{1}{8}$ in., so that the number of counts in that region should be approximately doubled to compare with the rest of the spectrum. The principal gain in information over Fig. 2 occurs in the observed splitting into three groups of the $Q=-1.94$-Mev multiplet between "A" and "B". A comparison of this energy region with theory is made in Fig. 8.

the target thickness correction for 13-Mev protons was only about 20 kev, a thinner target was not necessary. Under these conditions, the spectrum shown in Fig. 5 was obtained. It will be noted that the broad group centered at $Q=1.94$ Mev does split into three prominent peaks, and the most energetic group of the entire spectrum ($Q=2.35$ Mev) is more cleanly resolved. Aside from these modifications, the spectrum does not change markedly from that of Fig. 2, indicating that much higher resolution would be required to resolve further structure. Comparing the results in Fig. 5 to the expected theoretical spectrum,[3] with some modifications to be mentioned later, the overall energy resolution (including spectrometer resolution, target thickness, and beam spread) appears to be about 0.7%, or 90 kev for 13-Mev detected protons.[23] The major contribution to this result is probably energy inhomogeneity of the beam.

V. DISCUSSION

A. Basis for Interpretation of Results

A leading principle in the interpretation of the data has been stripping theory. An attempt[12] to confirm the possibility of a stripping interpretation for (d,p) reactions in the lead region at 11-Mev bombarding energy gave results that appeared to be clearly related to the theory. However, although the angular distributions of the protons did not show strong statistical features, they were not simple Butler curves.

Stripping theory as originally formulated[24] is expected to apply only if Coulomb effects are relatively unimportant. In general, other things being equal, the "uncharged" theory predicts that the angle corresponding to the first peak in the cross section increases, and the peak cross section decreases, as the angular momentum transfer increases. Further, for states of the same configuration and reduced width, the cross section should vary as $2J+1$, where J is the spin of the final state, provided the energy and angle for which the comparison is made are the same.

Coulomb effects are certainly serious in the present experiment, however, in which 11-Mev deuterons were used to bombard Bi^{209} nuclei for which the Coulomb barrier is about 14 Mev. Numerical calculations have shown[25,26] that one expects (d,p) angular distributions to be peaked at more backward angles and to be smeared out by the Coulomb effects. Proton angular distributions leading to the states in the Pb isotopes show[12] these features. They indicate that, although the peak angle appears to increase and the peak cross section appears to decrease with the angular momentum l_n of the captured neutron, interpretation of l_n from either the peak angle or the peak cross section alone is very difficult.

In experiments performed in lighter nuclei, analysis has shown[27] that the effects of specifically nuclear distortions of the stripping amplitude tend to have the opposite effect from the Coulomb distortions, and frequently restore the appearance of a simple Butler stripping angular distribution. However, as might be expected, the angular distributions found previously in the Pb isotopes[12] appear to be dominated by the Coulomb effects.

Shell model states expected in the region above the Pb^{208} core have also been used as a guide in making assignments to the observed levels. Although the spacings and order are not well known, the single-particle neutron states expected[28] in this region are $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, $d_{5/2}$, $g_{7/2}$, $s_{1/2}$, and $d_{3/2}$. The shell model also predicts that the spin-orbit splittings between pairs of states with orbital angular momentum l should be proportional to the appropriate ratios of $2l+1$.

In addition to these "single particle" considerations, calculations in the spirit of the "individual particle model"[1] could be expected to be useful in the interpretation of the data. Although calculations in the zero-range approximation were made, and finite-range calculations[3] were available for some of the configurations, no complete theoretical calculation exists with which experimental data can be compared. However, the results of the zero-range approximation in predicting the widths of the groups of states arising from different neutron

[23] This is consistent with the results of more recent unpublished measurements on isolated states taken with the same equipment under essentially the same experimental conditions.

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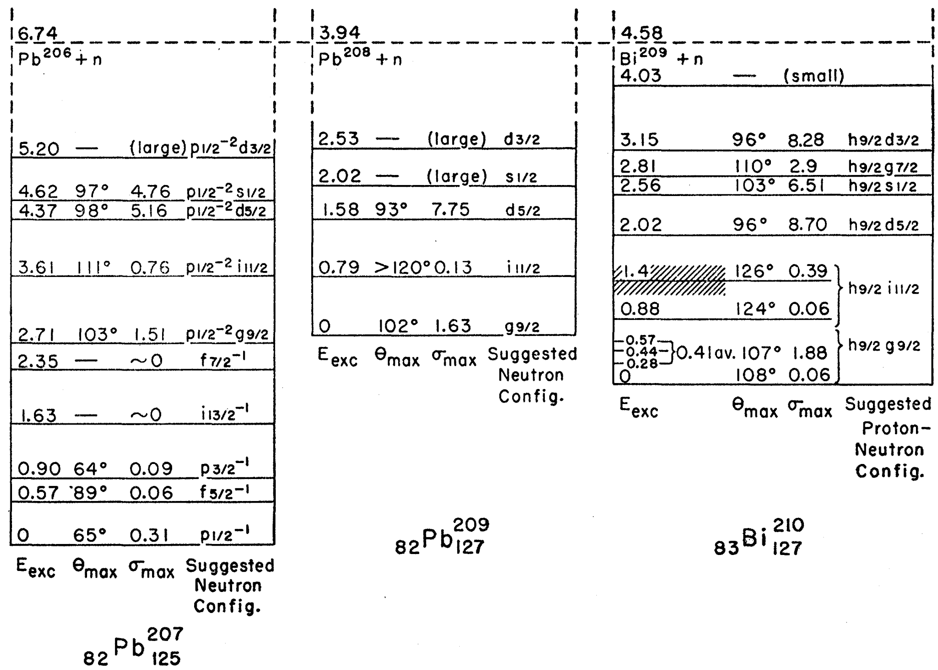

FIG. 6. Energy levels of Pb^{207}, Pb^{209}, and Bi^{210} as obtained in the present and earlier (reference 12) investigations at Indiana University. The levels are plotted so that the neutron binding energy in each nucleus coincides (reference 11) in order to emphasize the locations of corresponding states in the three nuclei. On each state is listed the excitation energy, the laboratory angle at which the maximum cross section appears in the angular distribution, the corresponding maximum value of the cross section, and the suggested proton and/or neutron assignment of the missing or extra nucleons relative to doubly-magic Pb^{208}. Where angular distributions were not measured, a rough indication of the observed size of the cross section relative to the average of the other states is indicated in parentheses.

configurations were used in the interpretation of the data, and the result of the finite-range calculation for the $(h_{9/2}g_{9/2})$[29] configuration was used in the manner described later.

B. Interpretations

Figure 6 shows a summary of the states observed at Indiana University in (d,p) experiments in the lead region. This figure gives the excitation energies, peak angles in the angular distributions, peak cross sections, and suggested configuration assignments of the observed states.[30] The figure is plotted so that equal neutron binding energies in the various nuclei coincide,[11] allowing ready identification of corresponding states.

As shown in Fig. 2, a group with $Q=2.35\pm0.03$ Mev was found in the $Bi^{209}(d,p)$ reaction. Its Q value is not significantly different from the value of 2.39 ± 0.03 Mev expected from the mass cycle already described (Fig. 1). The significance of the angular distribution of this peak (Fig. 3) will be discussed in the next section.

The group with $Q=1.94$ Mev in Fig. 2 (average Bi^{210} excitation energy $E_x=0.41$ Mev) has a peak cross section of 1.88 mb/sr and a peak angle of 107°, as shown by the angular distribution in Fig. 3. The suggested neutron assignment of $g_{9/2}$ for this state agrees fairly well both in peak cross section and peak angle with the Pb^{207} and Pb^{209} results.[12]

The proton group observed with $Q=1.47$ Mev ($E_x=0.88$ Mev) does not appear to be part of the $g_{9/2}$ neutron configuration. The angular distribution shows a peak angle of 124°, which is suggestive of a larger l_n, and a peak cross section of 0.06 mb/sr. The broad group with Q of about 1.0 Mev ($E_x=1.4$ Mev) peaks at 126°. Since the next neutron state expected from the shell model is $i_{11/2}$, the most plausible interpretation is that these states are both from the $(h_{9/2}i_{11/2})$ configuration. The peak angle of these states is about 125° compared to 111° for Pb^{207} and >120° for Pb^{209}, and the sum of the peak cross sections for these states is 0.45 mb/sr compared to 0.13 mb/sr in Pb^{209} and 0.76 mb/sr in Pb^{207}. In this vicinity are also expected states with a $j_{15/2}$ neutron configuration. Such states might very well contribute to part of the cross section of the group ascribed to $i_{11/2}$.

The angular distributions of the four groups with Q values of 0.32, −0.21, −0.47, and −0.81 Mev are shown in Fig. 4. The group with $Q=0.32$ Mev ($E_x=2.02$ Mev) has a peak angle of 96° and a peak cross section of 8.70 mb/sr. A very similar angular distribution is exhibited by the $Q=-0.81$-Mev group ($E_x=3.15$ Mev), which has a peak angle of 96° and a peak cross section of 8.28 mb/sr. On the basis of the large peak cross sections, peak angles, and energy separation of these groups, the most reasonable assignments are $d_{5/2}$ for the 2.02-Mev excited state and $d_{3/2}$ for the 3.15-Mev excited state. The $d_{5/2}$ assignment is in agreement with previous[12] assignments in Pb^{207} and Pb^{209}.

The group with $Q=-0.21$ Mev ($E_x=2.56$ Mev) was assigned as $g_{7/2}$ by Harvey,[11] and the corresponding

[29] In a symbol of the form $(h_{9/2}g_{9/2})$, used frequently in the rest of this paper to describe configurations of Bi^{210}, the first assignment is that of the proton outside the Pb^{208} core and the second is that of the neutron.

[30] This figure includes excitation energies for two higher states in Pb^{209} obtained from the $Pb^{208}(d,p)$ reaction. These states were not studied in the earlier work (reference 12), and so were included in the present investigation for comparison purposes. Angular distributions for these two states were not attempted.

state in Pb^{209} was assigned[10] as $d_{3/2}$ in the study of the decay of Tl^{209}. The peak cross section for this group is 6.51 mb/sr, which is more than three times as large as the $g_{9/2}$ group. Further, the peak angle of 103° is smaller than that for the $g_{9/2}$, although it might be expected to be larger since the outgoing proton energy here is smaller. Thus, the assignment of a g neutron appears doubtful. A $d_{3/2}$ assignment on the other hand would give a d-state splitting which is smaller than that of the known p-state splitting in this region. The only remaining neutron state of expected high cross section suggested by the shell model is $s_{1/2}$. An $(h_{9/2}s_{1/2})$ configuration gives rise to only two states, $J=4$ and $J=5$, which are 50 kev apart according to the zero-range calculation. This would explain the fact that the experimental width of the $Q=-0.21$-Mev group is less than that of any other group observed in the experiment. Furthermore, the arguments supporting a $d_{3/2}$ assignment for this state in the study of the Tl^{209} decay are also valid for an $s_{1/2}$ interpretation. If this interpretation is correct, the peak angle is larger and the peak cross section is smaller for the $s_{1/2}$ than for the d states. A possible explanation is that the principal maximum in the angular distribution has not been observed.[31]

The group with $Q=-0.47$ Mev ($E_x=2.81$ Mev) most likely represents the $g_{7/2}$ state. Its peak angle of 110° and peak cross section of 2.9 mb/sr are in fair agreement with the $g_{9/2}$ state. No state corresponding to this group has been observed in Pb^{209} or the other lead isotopes. An explanation for this might be that in Pb^{209} the $g_{7/2}$ state has an excitation close to that of the state which has been assigned $d_{3/2}$ and has not been resolved, while in Bi^{210} the $(h_{9/2}g_{7/2})$ interaction is larger than that of $(h_{9/2}d_{3/2})$ so that the two groups are resolved. Zero-range calculations support this suggestion.

Due to the small cross section, large background, and the presence of carbon and oxygen contaminants, no angular distribution has been obtained for the $Q=-1.68$-Mev group ($E_x=4.03$ Mev). The next shell-model state expected is $h_{11/2}$, which starts a new shell. The energy separation between the shells (i.e., from $d_{3/2}$ to $h_{11/2}$) obtained in zero deformation by Nilsson[28] is about one Mev. Experimentally the separation between the 4.03-Mev state and the supposed $d_{3/2}$ state is 0.88 Mev. This suggests $(h_{9/2}h_{11/2})$ as a possible assignment for the state at 4.03-Mev excitation.

As shown by Harvey,[11] the nuclei Pb^{207}, Pb^{208}, Pb^{209}, and Bi^{210} all have three states with neutron binding energies between about 1.5 and 2.5 Mev which are strongly excited by (d,p) reactions. In experiments using better resolution than that available to Harvey, the same three prominent groups have also been observed at this laboratory.[32] A possible explanation given by McEllistrem et al.[12] for the central large state in Pb^{207} does not appear adequate to explain the corresponding states in the other nuclei. It seems more probable that each of the three states in each nucleus is a separate single-particle neutron state. Corresponding states in the three nuclei investigated here have similar binding energies, peak cross sections, and (where measured) peak angles in the angular distributions. Thus, if the $s_{1/2}$ neutron interpretation suggested for the 2.56-Mev state in Bi^{210} is correct, it would appear that the same assignment is more probable for the 4.62-Mev state in Pb^{207}.

C. Comparison with Calculations

The first attempt to calculate levels in the lead region was made by Pryce,[33] who introduced a simple approximate method which later was very valuable in constructing the level scheme of Pb^{206}.[34] In a more exact calculation utilizing the same strength of internucleon force as observed in the two-body system, True and Ford[35] obtained a mean discrepancy from experiment of 57 kev for 13 levels in Pb^{206}.

Recently Newby and Konopinski,[3] using the method of True and Ford, have attempted to calculate the levels involved in the RaE β decay. In the case of Po^{210} with two protons outside the Pb^{208} core, good agreement with experimentally-known levels was obtained. However, in the case of Bi^{210}, with a neutron and a proton outside the same core, the calculation proved to be much more involved. A pure central force could not account for the positions of the known 1− and 0− states. When tensor force effects were calculated approximately, however, they were able to show that the result was in the right direction to reproduce the observed order of 1− and 0− levels.

Figure 7 shows the levels below 2-Mev excitation in Bi^{210} calculated by Newby and Konopinski with a finite-range central force. They have shown that the tensor force moves the $(h_{9/2}g_{9/2})_{0-}$ level up, and the $(h_{9/2}i_{11/2})_{1-}$ level at 830-kev excitation down, while the $(h_{9/2}g_{9/2})_{1-}$ level at 400-kev excitation is little affected. Their conclusion is that the ground-state configuration is $(h_{9/2}i_{11/2})_{1-}$. However, the $(h_{9/2}g_{9/2})_{1-}$ assignment is not excluded, and the most straightforward interpretation of the present experiment favors this configuration as shown below. No calculation of the effect of the tensor force on the rest of the levels has been made. Nevertheless, a comparison of this level spectrum with the observed proton spectrum of Fig. 5, obtained with a resolution of about 90 kev, is of interest. As shown in Fig. 3, the most energetic proton group ($Q=2.35$) has an angular distribution very similar to that of the group with $Q=1.94$ Mev ($E_x=0.41$ Mev). This suggests that the two groups arise from the same neutron configuration, i.e., $g_{9/2}$. The peak cross section of the most energetic group is experi-

[31] For an example of the apparent suppression of a forward peak by Coulomb effects, see I. Slaus, Nuclear Phys. **10**, 457 (1959).

[32] In the present work and in reference 12 Pb^{208} has not been investigated at this laboratory, except for the ground state.

[33] M. H. L. Pryce, Proc. Phys. Soc. (London) **A65**, 773 (1952).

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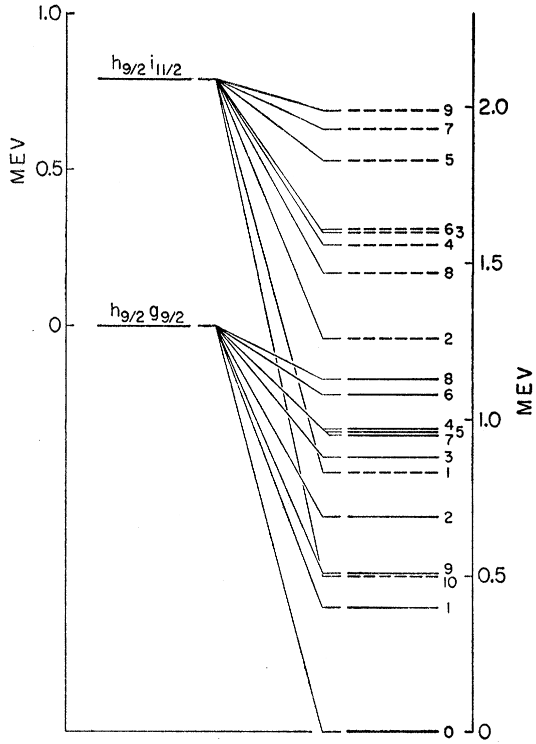

FIG. 7. The expected positions of the energy levels of Bi^{210} for the proton-neutron configurations $(h_{9/2}g_{9/2})$ and $(h_{9/2}i_{11/2})$, as obtained by Newby and Konopinski (reference 3) using a finite-range central-force type of calculation.

mentally 3% of the total of the two groups. On the basis of stripping theory, the cross sections for states with spins 0, 1, and 2, formed from an $(h_{9/2}g_{9/2})$ configuration, should be 1%, 3%, and 5%, respectively, of the total cross section. Thus, the most probable assignment for the observed $Q=2.35$ group is $(h_{9/2}g_{9/2})_{1-}$. It then seems most likely that this group represents excitation of the known (RaE) 1− ground state since its Q value is in agreement with that calculated for the ground state and its cross section is consistent with the spin one assignment. If this interpretation is valid, the observed group must also contain the known 0− state of 47-kev excitation. Since this state must arise from the $(h_{9/2}g_{9/2})$ configuration, the expected cross section for the group becomes 4%, which is not significantly different from the experimental 3%. When such a state is subtracted, the Q value calculated for the $(h_{9/2}g_{9/2})_{1-}$ state is increased by about 0.01 Mev to 2.36 Mev.

The possibility that the 1− β-decaying state is of the $(h_{9/2}i_{11/2})$ configuration has been suggested.[36,3] In this event, if the two 1− states lie close together and mix weakly or not at all, the $Q=2.35$-Mev group represents an excited state. The difference between the measured Q value and the Q value expected from the mass cycle places the observed state at an excitation energy of 40±60 kev.

[36] G. E. Lee-Whiting, Phys. Rev. **97**, 463 (1955).

If the two 1− states mix strongly (i.e., with approximately equal amplitudes in each state), two possibilities exist. If the two mixed states are less than 50 kev apart, the observed peak represents both. However, it seems unlikely that two strongly mixed states would lie within 50 kev of each other because of their mutual repulsion. If the two mixed states are greater than about 200 kev apart, the upper one would lie under the main body of the $(h_{9/2}g_{9/2})$ configuration and would not have been detected. In the latter case the ground state has been observed, and the 3% measured cross section is in agreement with the expected cross section of $2\frac{1}{2}$%. Both states would have been observed if their energy separation were between about 50 and 200 kev and they are strongly mixed. Finally, as discussed above, the possibility that the group represents a superposition of the $(h_{9/2}i_{11/2})_{1-}$ state and a high-spin state of the $(h_{9/2}i_{11/2})$ configuration is ruled out by its angular distribution.

It is clear from Fig. 7 that the $(h_{9/2}g_{9/2})_{9-}$ level lies well below any other level of this configuration with

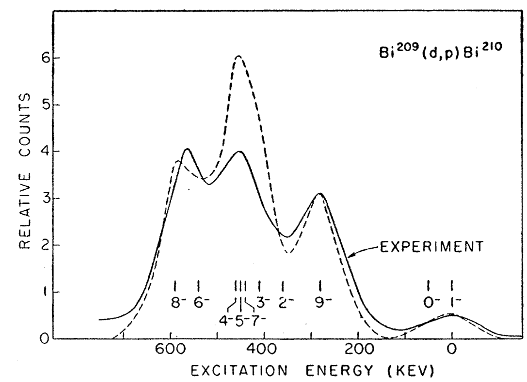

FIG. 8. A comparison of the higher-resolution experimental results of Fig. 5 and the theoretical results of Fig. 7, modified by the present authors in a manner described in the text.

appreciable cross section. If one assumes that the tensor force effects are not too large, it is natural to identify the first excited state of appreciable cross section, the 0.28-Mev state in Figs. 5 and 6, with the 9− state. Furthermore, the remaining high spin states fall into two groups, 4−, 5−, 7−, and 8−, 6−, which could correspond to the peaks at 0.44 and 0.57-Mev excitation, respectively.

The experimental spectrum is compared with the theoretical one in Fig. 8. The theoretical curve was obtained by normalizing the predicted peaks to the experimental ones, keeping the theoretical level order the same, and folding in the experimental resolution. The level scheme obtained in this way is shown in Fig. 9. Normalization of the absolute scale was made by estimating that part of the binding energy originating from the n-p interaction for the 1− ground state in the same manner as True and Ford. This value turns out to be 0.75 Mev compared to the 0.9-Mev result of the central-force calculation.

The major result of this comparison (aside from the effect on the 0− and 1− levels already mentioned) has been to move the spin 9 state up by about 0.32 Mev. The qualitative agreement is good, but some rearrangement would be necessary in order to fit the two peaks of 0.44- and 0.57-Mev excitation. However, this is to be expected since the states here are very close, and even small tensor-force effects are of importance.

When examined with better resolution, no great improvement was obtained for the $(h_{9/2}i_{11/2})$ part of the spectrum. It appears to agree fairly well with the level order calculated by Newby and Konopinski. The cross section of the 0.88-Mev state is 13% of the cross section for all the states that are believed to belong to this configuration. This is in agreement with the cross section expected for the spin 8 state, which would have to be

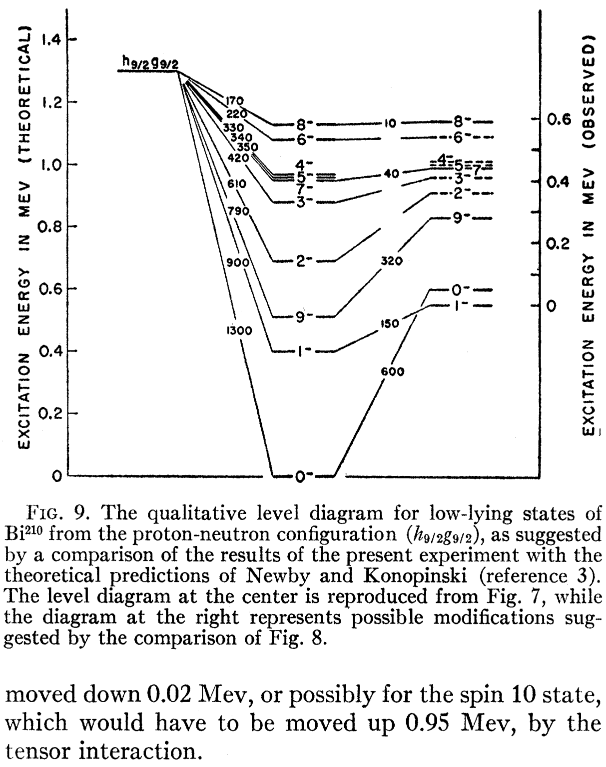

FIG. 9. The qualitative level diagram for low-lying states of Bi^{210} from the proton-neutron configuration $(h_{9/2}g_{9/2})$, as suggested by a comparison of the results of the present experiment with the theoretical predictions of Newby and Konopinski (reference 3). The level diagram at the center is reproduced from Fig. 7, while the diagram at the right represents possible modifications suggested by the comparison of Fig. 8.

moved down 0.02 Mev, or possibly for the spin 10 state, which would have to be moved up 0.95 Mev, by the tensor interaction.

No evidence has been found for the high-spin α-decaying state near the ground state. On the basis of the above interpretation such a state cannot be of the $(h_{9/2}g_{9/2})$ configuration, since the cross section of the $Q=2.35$-Mev group puts an upper limit of one on the spin for that configuration. The possibility that the $Q=2.35$ Mev group is of the $(h_{9/2}i_{11/2})$ configuration (e.g., of spin 10) is, as mentioned above, not likely if the angular distribution of the group has been interpreted correctly. Thus, the most likely configuration for the high-spin state appears to be $(f_{7/2}g_{9/2})$, for which the cross section is expected to be very low in this reaction.[37]

VI. CONCLUSIONS

With the possible exception of two states, interpretation on the basis of stripping theory of the neutron states observed in (d,p) reactions in the lead region appears meaningful. Although the suggested $i_{11/2}$ neutron state in each nucleus is consistent with other states in Q value, peak angle, and order of magnitude of the peak cross section, the exact value of the peak cross section varies considerably from nucleus to nucleus. The second difficulty arises from the magnitudes of the peak angle and peak cross section of the suggested $s_{1/2}$ state. The reason for these quantities being in disagreement with those of other states is not known, but it may be related to the large Coulomb effects.

The predicted ground state of Bi^{210} has been observed for the first time in a particle reaction. The observed group has a measured Q value of 2.35 ± 0.03 Mev. Its cross section of 3% of the total cross section for the proton-neutron configuration $(h_{9/2}g_{9/2})$ is consistent with its being due primarily to the $(h_{9/2}g_{9/2})_{1-}$ state. With this interpretation, the most probable Q value for the $Bi^{209}(d,p)Bi^{210}$ reaction to the 1− ground state alone is 2.36 ± 0.03 Mev, in agreement with the value of 2.39 ± 0.03 Mev calculated from known binding and disintegration energies in this region.

A previously unobserved group has been found at an excitation of 2.81 Mev in Bi^{210}. The neutron assignment suggested here is $g_{7/2}$. The failure to observe a corresponding group in Pb^{209} may be due to the proximity of this state to the 2.53-Mev $(d_{3/2})$ state. A zero-range calculation of the proton-neutron interaction for the $(h_{9/2}d_{3/2})$ and $(h_{9/2}g_{7/2})$ configurations suggests that the states would be resolved in Bi^{210} if this were true.

Using the interpretation already discussed, the present experiment suggests that the most probable order of the single-particle neutron levels in Bi^{210} is $g_{9/2}$, $i_{11/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$. The data give no information on the $j_{15/2}$ state. It is also of interest to note that the present interpretation of these and earlier lead results yield spin-orbit level splittings as follows: p states, 0.9 Mev (Pb^{207}); d states, 0.83 Mev (Pb^{207}), 0.95 Mev (Pb^{209}), and 1.13 Mev (Bi^{210}); f states, 1.78 Mev (Pb^{207}); and g states, 2.4 Mev (Bi^{210}). Except possibly for a small value of the d-state splitting, these numbers are in qualitative agreement with the expectation that the spin orbit splitting should be proportional to $2l+1$.

The data suggest that there is little, if any, overlapping of states from different neutron configurations. Comparison of the $(h_{9/2}g_{9/2})$ configuration with central-force calculations based on the low-energy properties of the neutron-proton system shows that the central force overestimates the effect of this interaction. However,

[37] In the above discussion, it has in general been assumed that configuration mixing is too small to affect the cross sections appreciably. The general similarity of the observed cross sections leading to states of Pb^{209} and Bi^{210} seems to justify this assumption. However, it should be kept in mind that the mixing of even a relatively small amount of the configuration $(h_{9/2}g_{9/2})$ into an $(f_{7/2}g_{9/2})$ wave function for example can drastically increase the expected cross section for a state of the latter assignment.

qualitative experimental agreement is obtained with the level order predicted by the central force for the states of the $(h_{9/2}g_{9/2})$ configuration.

VII. ACKNOWLEDGMENTS

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Note added in proof.—Recently Blomqvist and Wahlborn, Arkiv Fysik (in print), have calculated energy levels in the lead region using a diffuse potential of the Woods-Saxon type. They obtain the same single-particle level order as is suggested in the present work.

It has been suggested by Golenetskii et al., Z. Eksp. Teor. Fiz. S.S.S.R. **37**, 560 (1959), that no α-decaying state exists close to the ground state. Instead, a 9− state at about 0.22 Mev excitation is proposed, in good agreement with the present suggestion of a 9− state at about 0.28 Mev.

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Total Gamma Absorption in C^{12}, N^{14}, O^{16}, and Al^{27} at 20 Mev*

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Total gamma absorption cross sections were measured of C^{12} from 20.0 to 21.2 Mev, and of N^{14}, O^{16}, and Al^{27} from 20.0 to 20.5 Mev using monochromatic gamma rays. A direct absorption technique was used, utilizing $T^3(p,\gamma)He^4$ photons, varied in energy by changing the energy of the incident protons. The C^{12} cross section showed structure with possible resonances at 20.15 Mev, 20.46 Mev, and 20.92 Mev, with integrated cross sections of 1.1, 1.0, and 6.6 Mev millibarns, respectively. O^{16} showed a sharply rising cross section suggesting a strong resonance above about 20.3 Mev. The cross sections of N^{14} and Al^{27} were smooth over the energy interval investigated.

INTRODUCTION

ONE of the most striking features of photonuclear reactions is the "giant-resonance" region of photon absorption. This resonance is ascribed principally to electric-dipole absorption. Experiments in this energy region have usually measured the various partial cross sections, principally the (γ,p) and the (γ,n) reactions, using heterogeneous bremmstrahlung photons. Several of these experiments have indicated fine structure in the "giant resonance" absorption by light elements.[1] Attempts to investigate such structure[2] using monochromatic gamma rays have not been generally successful. The present experiment is a further attempt to measure the detailed total photon absorption in the giant resonance region using monochromatic gamma rays.

EXPERIMENT

Figure 1 shows a simplified schematic diagram of target, absorbers, detectors, and associated electronic circuitry. An electrostatic accelerator provided protons

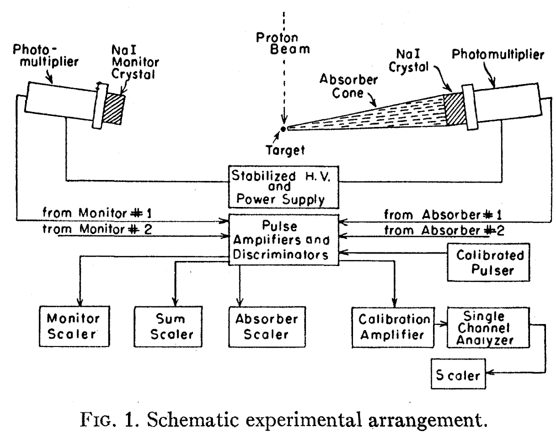

FIG. 1. Schematic experimental arrangement.

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† Now with the Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania.

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