Levels of Tl^{206} as Observed at High Resolution with the $Tl^{205}(d,p)Tl^{206}$ Reaction*

JOHN R. ERSKINE
Argonne National Laboratory, Argonne, Illinois
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The energy level structure of Tl^{206} has been investigated with the $Tl^{205}(d,p)Tl^{206}$ reaction induced with a 12-MeV beam from a tandem Van de Graaff. The proton spectrum was studied with a broad-range magnetic spectrograph at scattering angles from 20° to 90°. A ground-state Q value of 4.276 ± 0.005 MeV was measured for this reaction. Forty-four levels were observed. Below 1.5-MeV excitation energy, levels were found at 263, 305, 635, 650, 802, 998, 1117, and 1335 keV excitation. On the basis of the differential-cross-section and angular-distribution measurements, the ground state and 305-keV state appear to belong to the $s_{1/2}p_{1/2}$ configuration with spins of $J=0$ and 1, respectively. The 263- and 650-keV states probably are the $J=2$ and 3 members, respectively, of the $s_{1/2}f_{5/2}$ configuration. The 635- and 802-keV states probably are the $J=2$ and 1 members, respectively, of the $s_{1/2}p_{3/2}$ configuration. Data on the $Pb^{207}(d,p)Pb^{208}$ reaction were taken to aid in the interpretation of the data.

INTRODUCTION

THALLIUM 206 is one of the four odd-odd nuclei immediately adjacent to the doubly magic nucleus Pb^{208}. The low-lying energy-level structure of Tl^{206}, as well as that of Bi^{210}, Bi^{208}, and Tl^{208}, should be reasonably well accounted for by the jj-coupling shell model. For these odd-odd nuclei one expects that the relatively simple picture of an odd neutron and odd proton (either particle or hole) moving in the various shell-model orbits and interacting through a certain residual interaction can explain the dominant features of the low-lying energy levels.

Two of these odd-odd nuclei, Bi^{210} and Bi^{208}, have been previously studied with high resolution in charged-particle reactions.[1,2] In both of these studies, the resolution used had been sufficient to pick out most of the individual final states. Probable spin assignments were made on the basis of the relative differential cross section. These results for Bi^{210} have been theoretically analyzed by Kim and Rasmussen.[3] They made use of a jj-coupled odd-group model with configuration mixing and a residual nucleon-nucleon interaction that included tensor forces. Kim and Rasmussen were able to obtain good agreement between the observed energy-level structure of Bi^{210} and the calculated level structure when the residual interaction closely resembled the free-nucleon interaction. Using this two-body interaction which worked for Bi^{210}, Kim and Rasmussen[4] then predicted the energy-level structure of Bi^{208}. In a subsequent detailed experimental study[2] of Bi^{208} by means of the $Bi^{209}(d,t)Bi^{208}$ reaction, the observed energy-level structure of Bi^{208} was found to be in remarkably good agreement with the theoretical predictions of Kim and Rasmussen.

The present investigation was made to obtain a better picture of the energy-level structure of Tl^{206} than was previously available. Presumably, the simple jj-coupled shell-model picture will work here as well. Some information on the level structure of Tl^{206} has previously been obtained by Rusinov *et al.*[5] who studied the alpha decay of the Bi^{210} isomer. The Tl^{206} level structure was calculated theoretically by Kharitonov *et al.*[6] To some extent, these theoretical results guided Rusinov *et al.* in the interpretation of their experimental results. Walen and Bastin-Scoffier[7] have interpreted the data on the alpha decay of Bi^{210} in a different way from Rusinov *et al.* Recently, Mukherjee[8] has examined the $Tl^{205}(d,p)Tl^{206}$ reaction with 60-keV resolution.

EXPERIMENTAL PROCEDURE

The 12-MeV deuteron beam from the Argonne tandem Van de Graaff was used to produce the (d,p) reaction. Protons from the reaction were analyzed with a broad-range magnetic spectrograph which has been described elsewhere.[2] The targets were made by evaporating Tl_2O_3 enriched to 99% in Tl^{205} onto self-supporting carbon foils. The targets were quickly transferred from the evaporator to the scattering chamber to prevent deterioration. Target thicknesses were about 50 μg/cm.[2] Exposures were made at scattering angles ranging from 20° to 60° and at 90°. The over-all energy-resolution width obtained in the data was about 15 keV. A solid-state detector was used to monitor the deuterons elastically scattered from the Tl^{205} in the target. The number of counts recorded by the monitor was used to normalize the data recorded at the various angles as well as to obtain absolute scattering cross sections. The latter were measured by using the known solid angle of the spectrograph and the known solid angle of the monitor together with elastic

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[1] J. R. Erskine, W. W. Buechner, and H. A. Enge, Phys. Rev. **128**, 720 (1962).
[2] J. R. Erskine, Phys. Rev. **135**, B110 (1964).
[3] Y. E. Kim and J. O. Rasmussen, Nucl. Phys. **47**, 184 (1963).
[4] Y. E. Kim and J. O. Rasmussen, Phys. Rev. **135**, B44 (1964).
[5] L. I. Rusinov, Yu. N. Andreev, S. V. Golenetskii, M. I. Kislov, and Yu. I. Filimonov, Zh. Eksperim. i Teor. Fiz. **40**, 1007 (1961) [English transl.: Soviet Phys.—JETP **13**, 707 (1961)].
[6] Yu. I. Kharitonov, L. A. Sliv, and G. A. Sogomonova, Nucl. Phys. **28**, 210 (1961).
[7] R. J. Walen and G. Bastin-Scoffier, Nucl. Phys. **16**, 246 (1960).
[8] P. Mukherjee (to be published).

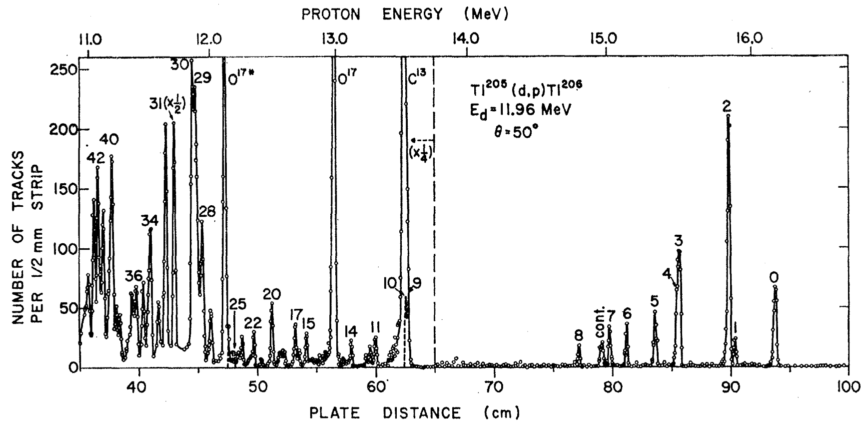

FIG. 1. Spectrum of protons observed at 50° from a Tl^{205} target bombarded with 11.96-MeV deuterons. At this angle, groups 9, 10, and 26 are obscured by contaminant groups. The shapes of the obscured groups, as inferred from data at other angles, have been drawn in under the contaminant groups.

scattering cross sections obtained through the use of the optical potentials reported by Perey and Perey[9] and by Melkanoff *et al.*[10] A computer program was used to unfold some of the doublets observed in the data. The computer was given a single group as a standard peak and asked to find the best fit to the data by adjusting the doublet spacing and relative amplitudes.

The data on the $Pb^{206}(d,p)Pb^{207}$ were obtained with the same procedure as above. A target of lead enriched to 99.8% in Pb^{206} was used.

EXPERIMENTAL RESULTS

The proton spectrum recorded at a scattering angle of 50° is shown in Fig. 1. A ground-state Q value of 4.276 MeV was obtained for the $Tl^{205}(d,p)Tl^{206}$ reaction. Forty-four energy levels were observed. Table I lists the excitation energies of the Tl^{206} levels together with their reaction Q values, absolute differential cross sections at 50°, and l values suggested by the angular-distribution measurements. For completeness, Table I also contains the suggested values of the total angular momentum and configurations for the various levels. These assignments will be discussed below. Angular distributions from 20° to 60° measured for the first five groups are given in Fig. 2. Because of poor statistics,

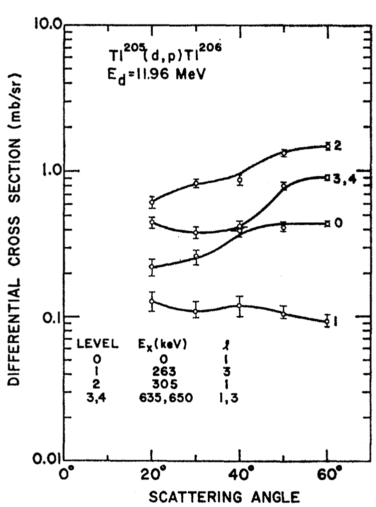

FIG. 2. Angular distribution from 20° to 60° of the lowest excited states observed in the $Tl^{205}(d,p)Tl^{206}$ reaction. The curves through the points are hand drawn to guide the eye. The l-value assignments are based on arguments given in the text.

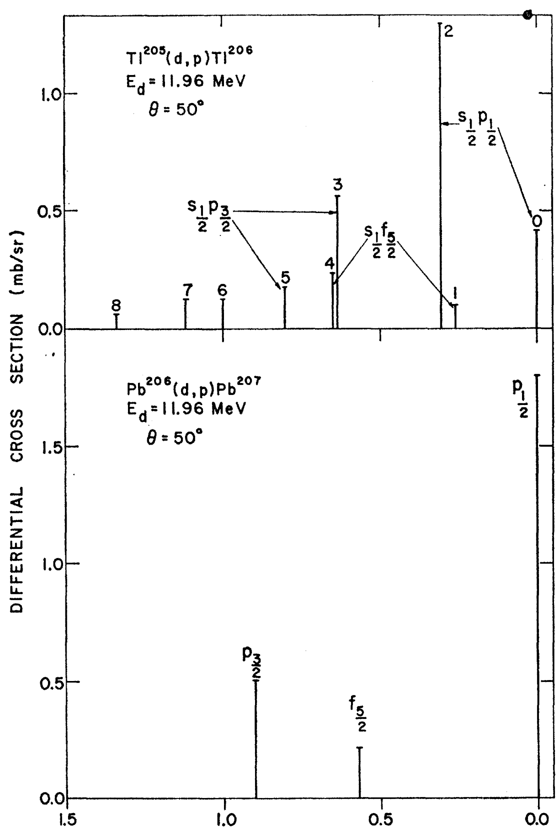

FIG. 3. A comparison of proton spectra from the $Tl^{205}(d,p)Tl^{206}$ and $Pb^{206}(d,p)Pb^{207}$ reactions taken at the same scattering angle and bombarding energy. The data are presented in the form of a bar graph in which the absolute differential cross sections of the reactions leading to the various excited states are plotted on an energy scale at the appropriate excitations. The levels are labeled with the configuration assignments discussed in the text.

[9] C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).
[10] M. A. Melkanoff, T. Sawada, and N. Cindro, Phys. Letters **2**, 98 (1962).

TABLE I. Excitation energies, Q values, l values, and suggested spins and configurations for the Tl^{206} levels formed through the $Tl^{205}(d,p)Tl^{206}$ reaction.

Level	E_x[a] (MeV)	Q[b] (MeV)	$d\sigma(50°)$[c] (mb/sr)	l[d]	Suggested assignment[e] J^π	Configuration
0	0.0	4.276	0.42	1	0^-	$s_{1/2}p_{1/2}$
1	0.263	4.013	0.11	3	2^-	$s_{1/2}f_{5/2}$
2	0.305	3.971	1.30	1	1^-	$s_{1/2}p_{1/2}$
3	0.635	3.641	0.56	(1)	2^-	$s_{1/2}p_{3/2}$
4	0.650	3.626	0.24	(3)	3^-	$s_{1/2}f_{5/2}$
5	0.802	3.474	0.18		1^-	$s_{1/2}p_{3/2}$
6	0.998	3.278	0.13			
7	1.117	3.159	0.13			
8	1.335	2.941	0.06			
9	2.581	1.695	1.1		(5^+)	$(s_{1/2}g_{9/2})$
10	2.594	1.682	1.0		(4^+)	$(s_{1/2}g_{9/2})$
11	2.828	1.448	0.43			
12	2.868	1.408	0.30			
13	2.896	1.380	0.18			
14	3.014	1.262	0.38			
15	3.363	0.913	0.48			
16	3.424	0.852	0.24			
17	3.452	0.824	0.62			
18	3.538	0.738	0.24			
19	3.564	0.712	0.18			
20	3.638	0.638	0.92			
21	3.717	0.559	0.11			
22	3.784	0.492	0.51			
23	3.874	0.402	0.45			
24	3.900	0.376	0.21			
25	3.938	0.338	0.19			
26	3.976	0.300	0.35			
27	4.126	0.150	0.81			
28	4.200	0.076	2.1			
29	4.238	0.038	4.0		(3^+)	$(s_{1/2}d_{5/2})$
30	4.273	0.003	4.4		(2^+)	$(s_{1/2}d_{5/2})$
31	4.426	−0.150	7.0		(1^+)	$(s_{1/2}s_{1/2})$
32	4.491	−0.215	3.5		(0^+)	$(s_{1/2}s_{1/2})$
33	4.555	−0.279	0.94			
34	4.622	−0.346	2.0			
35	4.680	−0.404	1.2			
36	4.739	−0.463	1.2			
37	4.775	−0.499	1.1			
38	4.879	−0.603	0.77			
39	4.904	−0.628	0.89			
40	4.941	−0.665	3.0			
41	5.015	−0.739	2.2			
42	5.055	−0.779	2.9			
43	5.091	−0.815	2.4			
44	5.140	−0.864	1.3			

[a] The uncertainties in the excitation energies are ±2 keV for levels 1, 2, and 3, ±5 keV for levels 4–8, and no greater than ±7 keV for the other levels.
[b] The uncertainty in the ground-state Q value is ±5 keV. The uncertainties in the other Q values are the combined uncertainties of the ground-state Q value and of the excitation energies.
[c] The uncertainties in these absolute differential cross sections are about 20%; but relative to each other the differential cross sections of levels 0–8 have uncertainties of only about 10%.
[d] These assignments of the l values of the captured neutron are based on the angular-distribution data. The values in parentheses are less certain.
[e] These spin and configuration assignments are discussed in the text. The assignments in parentheses are less certain.

groups Nos. 3 and 4 could not be accurately unfolded at all angles; hence only the angular distribution of the combined group is given. Angular distributions of the higher excited states were also obtained, but poor statistics severely limited the usefulness of these data in distinguishing between the various possible l values. Figure 3 is a bar graph of the absolute differential cross sections at 50° of the $Tl^{205}(d,p)Tl^{206}$ reaction leading to the various levels in Tl^{206}. The bars are drawn at the appropriate excitation energies for the levels on an energy scale. Data taken on the $Pb^{206}(d,p)Pb^{207}$ reaction are presented in the same way in Fig. 3. These bar-graph graphs are simply related to the proton spectra from these reactions and will be used below in a comparison between the levels of Tl^{206} and Pb^{207}. Both spectra were recorded at the same bombarding energy and at the same scattering angle.

The uncertainties in the Q values are estimated to be 5 keV; those in the excitation energies are estimated to be 2–7 keV as specified in footnote *a* of Table I. The uncertainties in the absolute differential cross sections for both the thallium and lead reactions shown in Fig. 3 are estimated to be about 20%, but are somewhat smaller when the cross sections are taken as relative measurements within one spectrum.

DISCUSSION

Comparison of the Energy Levels with Previous Studies

Several energy-level diagrams of the lower excited states of Tl^{206} are given in Fig. 4. Three level diagrams are shown: the levels observed in the present high-resolution study, the levels observed in the alpha-decay study of Bi^{210} by Rusinov *et al.*[5] and the levels reported by Mukherjee[8] who used the (d,p) reaction. The levels at 301 and 262 keV, observed by Rusinov *et al.*, are in excellent agreement with the levels at 305 and 263 keV seen in the present (d,p) study. No evidence was obtained for the existence of a ground-state doublet suggested by Rusinov *et al.* and by Kharitonov *et al.*[6] Such a doublet would probably have been observed in the present data if the doublet spacing had been greater than 7 keV and if both members of the doublet had the same intensity. It is not clear whether or not the levels reported at 610 and 720 keV by Rusinov *et al.* have been observed in the present (d,p) study since these energies do not quite agree with the present measurements within the stated uncertainties. The 290- and 640-keV

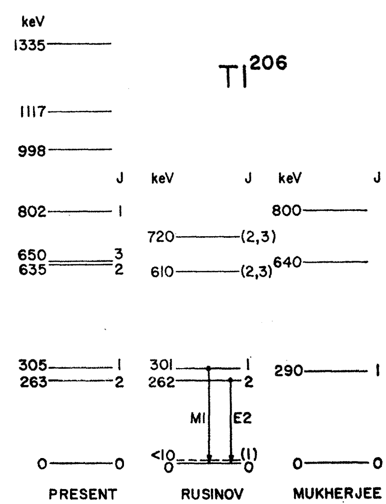

FIG. 4. Energy level diagrams of the low-lying levels in Tl^{206}. Energy levels observed in the present (d,p) study are presented along with levels reported by Rusinov *et al.* (Ref. 5) and Mukherjee (Ref. 8). Spin assignments from the various studies have been included.

levels reported by Mukherjee are evidently unresolved doublets corresponding to those observed at 263 and 305 keV and at 635 and 650 keV in the present study.

Interpretation of Observed Energy Levels

According to the simple *jj*-coupled shell model, six energy levels below 1-MeV excitation in Tl^{206} should be strongly excited in the (d,p) reaction. These states are formed by coupling a $s_{1/2}$ proton hole with a $p_{1/2}$, $f_{5/2}$, or $p_{3/2}$ neutron hole. One expects three sets of doublets and would like to identify them, if possible, with six states in Tl^{206}. Of course, the situation could be more complicated; one should be alert to other possibilities such as the existence of low-lying states formed by coupling the next excited proton hole (the $d_{3/2}$ state at approximately 0.37-MeV excitation) to the odd neutron.

The present data furnish three kinds of evidence to aid in the above identification: (1) angular distributions (for some of the levels) which should give the l value of the captured neutron, (2) relative differential cross section measurements which can be used to identify the ordering of the spins in the various doublets through the use of the $(2J+1)$ rule, and (3) absolute differential-cross-section measurements which can be compared with absolute cross-section measurements on the $Pb^{206}(d,p)Pb^{207}$ reaction leading to states of known[11] spin and parity. The latter reaction is almost identical to the $Tl^{205}(d,p)Tl^{206}$ reaction except that in the lead reaction the $s_{1/2}$ proton hole is filled.

The best interpretation of the present data seems to be the following. The ground state and 305-keV level in Tl^{206} are the $J=0$ and $J=1$ members of the $s_{1/2}p_{1/2}$ configuration.[12] The 263- and 650-keV states are the $J=2$ and $J=3$ members of the $s_{1/2}f_{5/2}$ configuration. And finally the 635- and 802-keV levels are the $J=2$ and $J=1$ members of the $s_{1/2}p_{3/2}$ configuration.

The arguments for this interpretation of the experimental data are as follows. The present data in Fig. 2 show that the angular distribution of group No. 1 is significantly different from the angular distribution of groups 0 and 2. The angular distribution of level No. 1 actually falls between 20 and 60° whereas levels 0 and 2 have angular distributions which rise near 50 and 60°. Since the ground state of Tl^{206} is most probably an $s_{1/2}p_{1/2}$ state, it is reasonable to identify angular distributions 0 and 2 as having the shape associated with $l=1$. Since only p and f neutron-hole states are expected near the Tl^{206} ground state, the other angular distribution (level No. 1) probably has the shape characteristic of $l=3$. This identification is somewhat supported by $l=1$ and $l=3$ angular distributions measured by Miller, Wegner, and Hall[13] for the $Pb^{206}(d,p)Pb^{207}$ reaction at 10.8-MeV bombarding energy. In going from 35° to 80° scattering angle, the cross section of their $l=1$ angular distribution rises much more rapidly than the cross section of their $l=3$ angular distribution. The angular distribution of group No. 1 might not correspond to a pure $l=3$ shape since there is the possibility of admixing the $s_{1/2}f_{5/2}$ configuration into the $d_{3/2}p_{1/2}$ configuration. This would give an $l=1$ component to the angular distribution (see Discussion).

The arguments leading to configuration and spin assignments based on the differential cross sections are best illustrated in Fig. 3. Here both the Tl^{206} and the Pb^{207} spectra (taken at a common observation angle of 50° and bombarding energy of 12 MeV) are plotted in a modified way on a bar graph. The absolute differential cross sections of the reactions leading to the various levels are plotted at the appropriate excitations on an energy scale. The presence of the $s_{1/2}$ proton hole in the Tl^{206} should produce a splitting of the various states of the neutron. This means that the ground state of Pb^{207} (a $p_{1/2}$ state) should appear in the Tl^{206} spectrum as two states with relative cross sections which are proportional to $(2J+1)$. Since the $s_{1/2}p_{1/2}$ configuration can have a spin of either 0 or 1, the cross sections of the two members of the $s_{1/2}p_{1/2}$ configuration in Tl^{206} should be in a 1:3 ratio. Levels 0 and 2 have the proper relative cross section for this identification and both appear to be $l=1$ states from the shapes of their angular distributions. In addition, the sum of the absolute differential cross sections for levels 0 and 1 is about the same as the absolute cross section of the Pb^{207} ground state. The $f_{5/2}$ state in Pb^{207} at 570 keV should be split into two levels with an intensity ratio of 5:6 in correspondence with the spins 2 and 3. Level No. 1 in Tl^{206} has about the proper absolute cross section to identify it as the $J=2$ member of the $s_{1/2}f_{5/2}$ configuration. Furthermore, the shape of the angular distribution of level No. 1 indicates that it is an $l=3$ transition. The $J=3$ member of the $s_{1/2}f_{1/2}$ configuration is probably the state at 650 keV (level No. 4) since it has about the right intensity. The angular distribution of unresolved levels 3 and 4 shown in Fig. 2 does not fully resemble the shape of either the $l=3$ angular distribution (No. 1), or the $l=1$ angular distributions (Nos. 0 and 2) but appears to be a combination of both shapes. This is consistent with assigning one of these two levels (No. 4) as the $J=3$ state from the $s_{1/2}f_{5/2}$ configuration. The other level (No. 3) probably is a p state and may be one member of the $s_{1/2}p_{3/2}$ configuration. Since this level has a larger differential cross section than any of the next four excited states, it probably is the $J=2$ rather than the $J=1$ member of this configuration. It is not clear where the $J=1$ member of the $s_{1/2}p_{3/2}$ configura-

[11] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 59-3-125.

[12] In this notation for the configuration, the proton-hole state is written on the left and the neutron-hole state is written on the right. The usual -1 exponent indicating a hole state will not be added.

[13] D. W. Miller, H. E. Wegner, and W. S. Hall, Phys. Rev. 125, 2054 (1962).

tion is. It may be the 802-keV state, although higher excited states cannot be ruled out.

The above identifications are consistent with some earlier reports on the properties of Tl^{206}. Rusinov *et al.*[5] found that the 263- and 305-keV levels are de-excited through $E2$ and $M1$ gamma-ray transitions (Fig. 4). This agrees with the spin assignment based on the present (d,p) data. Walen and Bastin-Scoffier[7] have examined published reports of the alpha decay of metastable Bi^{210} and Bi^{210} (Ra E) leading to Tl^{206}. On the basis of the observed intensities of the alpha transitions, and of the doublet separations known for other thallium isotopes, they suggest that the ground state and 305-keV state belong to the $s_{1/2}p_{1/2}$ configuration and that the 263-keV state is the $J=2$ member of the $s_{1/2}f_{5/2}$ configuration, in agreement with the present interpretation from the (d,p) data but in disagreement with the interpretation of Rusinov *et al.* The study of the $Tl^{205}(d,p)Tl^{206}$ reaction by Mukherjee[8] is for the most part consistent with the above interpretation based on the present (d,p) data. What disagreement there is between the two (d,p) studies can probably be traced to the lower resolution obtained in Mukherjee's data.

The energy levels observed at 998, 1117, and 1335 keV may belong to configurations in which the proton hole is a $d_{3/2}$ state. No spin assignments or configuration assignments could be made for any of these levels.

Among the higher excited states in Tl^{206} will be states which are formed by an $s_{1/2}$ proton hole coupling with an odd neutron in the neutron shell above the gap at 126 neutrons. These states should be the strongest states observed in the (d,p) reaction at high excitation energy, if configuration mixing effects are not too strong. (The latter effects tend to fragment and reduce the (d,p) cross sections of the above two-particle levels by mixing them with levels not easily excited in (d,p) reactions.) It is likely that configuration-mixing effects do not completely obscure the highly excited states in Tl^{206} mentioned above since in Bi^{210} (a similar nucleus) a relatively simple interpretation was possible for many of the highly excited states observed in the (d,p) spectrum.[1] In particular, the $h_{9/2}s_{1/2}$ doublet found in Bi^{210} at 2.54 MeV excitation appears to be relatively undisturbed by configuration mixing.

In the $Pb^{208}(d,p)Pb^{209}$ reaction the $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, $d_{5/2}$, $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ neutron single-particle states are observed[14,15] with Q values of 1.709, 0.931, 0.30, 0.143, −0.322, −0.783, and −0.829 MeV, respectively. States in Tl^{206} formed by coupling these neutron states with a $s_{1/2}$ proton hole should have about the same Q value. It is on this basis and on the basis of the observed differential cross sections that one can speculate about the configurations of some of the observed Tl^{206} levels. The most obvious identifications are the following. The 13-keV doublet formed by levels 9 and 10 at a Q value of about 1.69 MeV may be the $s_{1/2}g_{9/2}$ configuration. The 35-keV doublet formed by levels 29 and 30 at a Q value of about 0.020 MeV may be the $s_{1/2}d_{5/2}$ configuration. And the $s_{1/2}s_{1/2}$ configuration may be identified with levels 31 and 32 at $Q=-0.150$ and -0.215 MeV, respectively. Extremely tentative spin assignments for states Nos. 9, 10, 29, 30, 31, and 32 are given in Table I. These have been made under the assumption of a rule for the ordering on the spins in doublets proposed by de-Shalit and Walecka.[16] This rule will be discussed immediately below.

Comparison with Theoretical Calculations

The above suggestions of the spin ordering in the $s_{1/2}p_{1/2}$, $s_{1/2}f_{5/2}$, and $s_{1/2}p_{3/2}$ doublets are in agreement with a theoretical rule proposed by de-Shalit and Walecka.[16] "In the odd configuration $[j_1,j_2{}^n(J_n=j_2)]$ in which $j_1=1/2$, the ground-state total angular momentum has even or odd values of J according to whether the parity of the configuration is negative or positive." Practically no exceptions to this rule are known. The spins of 0, 2, and 2, respectively, predicted by this rule for the ground states of the above configurations, agree with the spins suggested by the (d,p) data.

The doublet splittings obtained from the present (d,p) data (305, 387, and 167 keV for the $s_{1/2}p_{1/2}$, $s_{1/2}f_{5/2}$, and $s_{1/2}p_{3/2}$ configurations, respectively) are quite large in comparison with the theoretical calculations of Kharitonov *et al.*,[6] who predict that these splittings are in the order of a few tens of kilovolts. This disagreement is not too surprising since their results for Bi^{210} reported in the same paper are in disagreement with the observed levels.

Silverberg[17] has carried out a shell-model calculation of Tl^{206} in which he includes tensor forces and a hard core in the two body interaction. His calculations are easily able to give a 305-keV splitting for the $s_{1/2}p_{1/2}$ doublet in agreement with the present interpretation. For the $s_{1/2}f_{5/2}$ doublet, however, his calculations (for various choices of interaction parameters) do not agree as well. The calculated doublet splitting is too small and the mean excitation energy of the doublet is too large.

In a shell-model calculation of Tl^{206}, Kim[18] used virtually the same theory as he used in his calculations of Bi^{210} (Ref. 3) and Bi^{208} (Ref. 4) except that contributions from tensor forces to off-diagonal matrix elements were neglected. The latter should have only a small effect on the eigenvalues. Kim used the same residual interaction that gave such good results for Bi^{210} and Bi^{208}. He included two single-particle states for the proton ($s_{1/2}$ and $d_{3/2}$) and five single-particle states for

[14] J. R. Erskine and W. W. Buechner, Bull. Am. Phys. Soc. **7**, 360 (1962).
[15] P. Mukherjee and B. L. Cohen, Phys. Rev. **127**, 1284 (1962).
[16] A. de-Shalit and J. D. Walecka, Nucl. Phys. **22**, 184 (1961).
[17] L. Silverberg, Arkiv Fysik **20**, 355 (1962).
[18] Y. E. Kim (private communication).

TABLE II. Eigenfunctions and excitation energies of Tl^{206} energy levels. From the calculations of Kim (Ref. 18).

J	Excitation energies (MeV)	Eigenfunctions $s_{1/2}p_{1/2}$	$d_{3/2}p_{1/2}$	$s_{1/2}f_{5/2}$	$s_{1/2}p_{3/2}$	$d_{3/2}f_{5/2}$	$d_{3/2}p_{3/2}$	$s_{1/2}f_{7/2}$	$d_{3/2}f_{7/2}$
0	0.0	0.99993					−0.01148		
	1.394	0.01148					0.99993		
1	0.066	0.98803	−0.06704		−0.02801	0.13506	0.01650		
	0.708	0.06218	0.94738		0.08141	0.06847	−0.29546		
	1.001	−0.00128	−0.08952		0.98074	0.17208	0.02282		
	1.281	−0.13948	−0.00462		−0.17318	0.96598	0.13199		
	1.519	0.02169	0.29993		0.02643	−0.11992	0.94577		
2	0.485		0.74885	−0.62162	−0.02085	0.19276	0.12283		0.01139
	0.901		0.58311	0.60567	0.45952	−0.28242	0.02788		0.03802
	0.926		−0.29470	−0.37337	0.87231	0.02548	0.00498		0.11018
	1.448		0.03626	0.31210	0.12771	0.93474	−0.08041		−0.06901
	1.689		−0.10485	0.08905	−0.00810	0.06240	0.98814		0.02637
	2.589		0.00711	0.04481	−0.10533	0.06926	−0.03495		0.99037
3	0.920			0.99490		0.08730	0.03300	−0.00869	0.03732
	1.435			−0.03955		0.73801	0.65226	0.15780	−0.05861
	1.499			−0.08401		0.66534	0.73731	−0.08044	0.01263
	2.633			0.02565		−0.07097	0.16933	0.86513	−0.46603
	3.099			−0.02997		−0.00167	0.03417	0.46915	0.88195
4	1.077					0.99905		−0.01703	0.04016
	2.585					0.00538		0.96165	0.27424
	3.136					−0.04329		−0.27376	0.96082

the neutron ($p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $f_{7/2}$, and $i_{13/2}$). The results of his calculation are shown in Table II, where the excitation energies and eigenfunctions for Tl^{206} are given. Kim finds that for Tl^{206} the doublet splittings are 66, 19, and 75 keV for the $s_{1/2}p_{1/2}$, $s_{1/2}f_{5/2}$, and $s_{1/2}p_{3/2}$ configurations, respectively. These splittings are only a small fraction of those observed.

Part of the reason for these serious discrepancies here and in the calculations of Silverberg and of Kharitonov *et al.* is suggested by the wave functions in Table II. The calculations show that the $J=2$ states from the $d_{3/2}p_{1/2}$ and $s_{1/2}f_{5/2}$ configurations are strongly intermixed. Under these circumstances it would be very difficult to obtain detailed agreement with the experimental energies unless the off-diagonal matrix elements and the zeroth-order energies were just right.

The strong admixing suggested by Kim's calculations reduces the certainty of the identification of the 263-keV state in Tl^{206} with the $J=2$ state from the $s_{1/2}f_{5/2}$ configuration; this 263-keV state could be the $J=2$ state from the $d_{3/2}p_{1/2}$ configuration. This probably is not the case since the observed angular distribution of the 263-keV state definitely does not have an $l=1$ shape. (The predicted differential cross sections for both $J=2$ states from the above configuration arise about 80% from $l=1$ and 20% from $l=3$. This estimate is based on Kim's wave functions for Tl^{206}, Silverberg's wave function for the Tl^{205} ground state,[17] and reasonable estimates for the ratio of $l=1$ to $l=3$ intrinsic single-particle cross sections.) Furthermore, such strong admixing would require that the proton spectrum should include a second group with about the same cross section as the 263-keV state. It is unlikely that such a group would have been missed.

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