Levels of Bi^{209} Observed in the $Pb^{208}(He^3,d)$ Reaction*

JOHN BARDWICK AND ROBERT TICKLE
Cyclotron Laboratory, Department of Physics, The University of Michigan, Ann Arbor, Michigan 48105
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The level structure of Bi^{209} has been studied using the $Pb^{208}(He^3,d)Bi^{209}$ reaction at 44.2 MeV. A distorted-wave-approximation analysis of angular distributions for the seven strong levels observed indicates that the following levels contain almost the full shell-model strength: g.s., $1h_{9/2}$; 0.90 MeV, $2f_{7/2}$; 1.61 MeV, $1i_{13/2}$; 2.83 MeV, $2f_{5/2}$; and 3.12 MeV, $3p_{3/2}$. The level at 3.64 MeV contains about two-thirds of the $3p_{1/2}$ strength. Our analysis did not provide a conclusive explanation for the level at 4.42 MeV. Angular distributions were also measured for three states weakly excited at 2.61, 4.52, and 4.58 MeV. A number of other states were weakly excited in the region between 3.4 and 4.4 MeV.

I. INTRODUCTION

THE nuclear structure of Bi^{209} is of considerable interest because it contains information relating to the positions of the proton shell-model states beyond $Z=82$ and because it affords us an opportunity to study the coupling between the single-particle motions and the excited states of the Pb^{208} core.

The locations of the proton and neutron single-particle and single-hole states are an essential ingredient in shell-model calculations of nuclear structure in the lead region. The neutron states have been determined by the (d,p) and (d,t) reactions[1] on Pb^{208} and the Pb^{208} $(t,\alpha)Tl^{207}$ reaction[2] has provided information concerning the location and identification of the proton single-hole states.

Very recently, several publications have appeared in the literature concerning the proton particle states in Bi^{209}. These states have been studied by Woods *et al.*[3] and Wiedenthal *et al.*[4] using the $Pb^{208}(He^3,d)$ reaction and also by Lilley and Stein[5] using the $Pb^{208}(\alpha,t)$ reaction. From these publications our knowledge of the proton single-particle states in Bi^{209} can be summarized briefly as follows: ground state, $1h_{9/2}$; 0.90 MeV, $2f_{7/2}$; 1.61 MeV, $1i_{13/2}$; 2.83 MeV, $2f_{5/2}$; and 3.12 MeV, $3p_{3/2}$. Results of distorted-wave computations and a careful inspection of the spectrum indicate that most of the single-particle strength is contained in these levels because they have spectroscopic factors near unity. The $3p_{1/2}$ strength seems to be fragmented. It appears that some of this strength, perhaps 60–80%, is contained in a level at 3.64 MeV. Interesting questions relate to the whereabouts of the remaining $3p_{1/2}$ strength, to the explanation of an unbound level at 4.42 MeV that is rather strongly excited in the proton transfer reaction, and to the effect of particle-vibration coupling on the structure of Bi^{209}. In this paper we present our results from a study of the $Pb^{208}(He^3,d)Bi^{209}$ reaction at 44.2 MeV.

II. EXPERIMENTAL PROCEDURE

He^3 ions, accelerated to 44.2 MeV by the University of Michigan 83-in. sector-focused cyclotron, were used to bombard a self-supporting target 0.75 mg/cm² thick and enriched to 99.3% in Pb^{208}. To determine the target thickness, the intensities of the deuteron groups at 35° from the enriched target were compared with the intensities of the corresponding groups from two self-supporting lead targets of natural isotopic abundance. The latter targets were then cut, weighed, and the enriched target thickness calculated using the relative isotopic compositions.

The deuterons were analyzed in momentum using one of the three available magnetic spectrographs and were recorded in nuclear track plates (Ilford K-2 with 100-μ emulsions) placed at the image surface. After development, the plates were scanned by microscope in ½-mm swaths at 1-mm intervals to record the number of deuteron tracks. Other than the uncertainty in cross sections due to statistics, the most probable sources of error were inaccuracies in the track counting, target thickness, and in the spectrograph solid angle as a function of position along the image surface. After

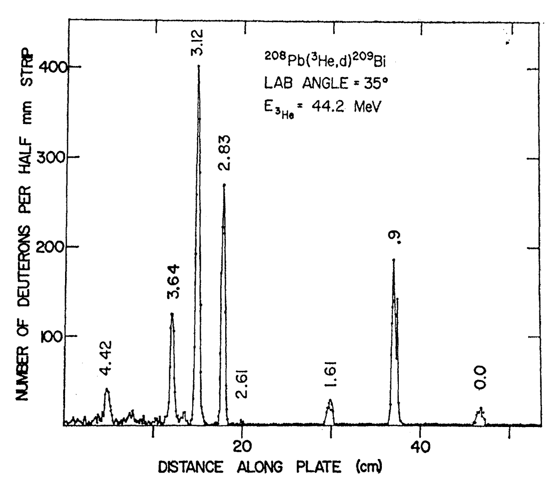

FIG. 1. Deuteron spectrum at 35° from the $Pb^{208}(He^3,d)Bi^{209}$ reaction.

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[1] G. Muehllehner, A. S. Poltorak, W. C. Parkinson, and R. H. Bassel, Phys. Rev. 159, 1039 (1967); P. Mukherjee and B. L. Cohen, *ibid.* 127, 1284 (1962).
[2] S. Hinds, R. Middleton, J. H. Bjemegaard, O. Hansen, and O. Nathan, Nucl. Phys. 83, 17 (1966).
[3] R. Woods, P. D. Barnes, E. R. Flynn, and G. J. Igo, Phys. Rev. Letters 19, 453 (1967).
[4] B. H. Wildenthal, B. M. Preedom, E. Newman, and M. R. Cates, Phys. Rev. Letters 19, 960 (1967).
[5] J. S. Lilley and N. Stein, Phys. Rev. Letters 19, 709 (1967).

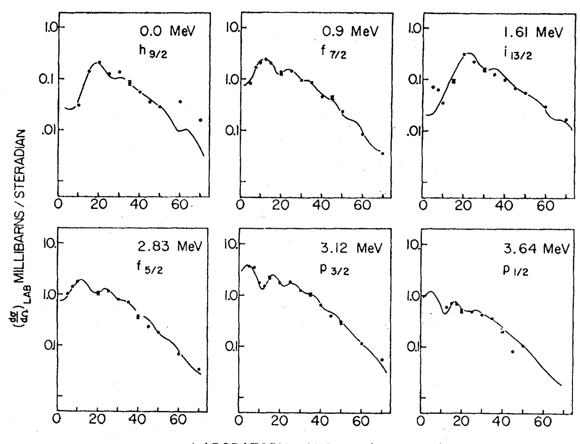

FIG. 2. Angular distributions of deuteron groups from $Pb^{208}(He^3,d)Bi^{209}$ at a He^3 energy of 44.2 MeV. The solid curves are the normalized reduced cross sections σ_{lj} obtained from the DWA analysis.

careful consideration of each source of error, it is estimated that the absolute cross sections are accurate to about 15%. Beam currents were typically 130 nA. Each exposure of 400 μC covered approximately 5 MeV in excitation. Figure 1 shows a deuteron spectrum recorded at 35°. The resolution is approximately 50 keV.

III. RESULTS AND DISCUSSION

The angular distribution for each of the strong deuteron groups was measured in the angular range from 5°–70° and the results are shown in Fig. 2. The solid curves are distorted-wave-approximation (DWA) predictions from the computer code JULIE[6] using the parameters listed in Table I. These parameters are identical to those used by Wiedenthal *et al.*[4] to analyze the $Pb^{208}(He^3,d)Bi^{209}$ reaction at 51 MeV. Although they represent the best parameters of the several sets we tested in that they result in good fits to the experimental angular distributions and give spectroscopic factors close to the anticipated values, we use these parameters hesitantly in view of the fact that they yielded only fair fits to elastic scattering data at energies not entirely appropriate to our bombarding energy.

Results from the DWA analysis are given in Table II. The spectroscopic factors S_{lj} were determined from the measured differential cross sections $d\sigma/d\Omega$ using the equation

$$d\sigma/d\Omega=4.4(2J+1)S_{lj}\sigma_{lj}(\theta),$$

in which 4.4 is the normalization factor given by Bassel,[7] J is the angular momentum of the level excited in Bi^{209}, and $\sigma_{lj}(\theta)$ is the reduced cross section obtained from the DWA calculation. Considering the experimental uncertainties and the applicability of the

[6] We are indebted to R. M. Drisko for making the distorted-wave code JULIE available to us.

[7] R. H. Bassel, Phys. Rev. **149**, 791 (1966).

TABLE I. Parameters used in the DWA calculations of the reduced cross sections shown in Figs. 2 and 3.

	V_0 (MeV)	W_0 (MeV)	r_0 (F)	r_c (F)	a (F)	r_0' (F)	a' (F)	W_D (MeV)
He^3 [a]	175	17.5	1.14	1.40	0.723	1.60	0.81	0.0
Deuteron[b]	111	0.0	1.05	1.25	0.859	1.24	0.794	17.7
Bound state[c]			1.24	1.25	0.65			

[a] These parameters are similar to those obtained from He^3 elastic scattering on Y and Zr at 43.7 MeV. See E. F. Gibson, B. W. Ridley, J. J. Kraushaar, and M. E. Rickey, Phys. Rev. **155**, 1194 (1967).

[b] Obtained from an analysis of 52-MeV elastic scattering on Pb^{208} given by B. Duelli, F. Hinterberger, G. Mairle, U. Schmidt-Rohr, P. Tunek, and G. Wagner [Phys. Letters **23**, 485 (1966)].

[c] The depth of the bound-state potential was adjusted to obtain the appropriate binding energy. $\lambda=6$ was used for the strength of the spin-orbit potential. See Ref. 4 for a brief discussion of this choice.

DWA parameters mentioned previously, the spectroscopic factors are probably accurate to not better than 15–20%. We obtain too much $f_{7/2}$ strength, which indicates an error in our determination of the cross section for this level or perhaps reflects the unsuitability of the DWA parameters. This excess strength is most probably due to the former since all of the spectroscopic factors except this one are in very good agreement with those obtained in Ref. 4.

Our assignments for the first five shell-model states are the same as previous determinations. The level at 3.64 MeV, though partially obscured by impurities at the forward angles, is well fitted by an $l=1$ distribution and therefore must contain some of the $3p_{1/2}$ shell-model strength. The spectroscopic factor for this level is only 0.63, which indicates the $p_{1/2}$ strength is fragmented.

The remaining level in Bi^{209}, which is strongly excited by the (He^3,d) reaction, is an unbound level at 4.42 MeV. Although we have obtained an angular distribution for this level, which is shown in Fig. 3, we are unable to determine the l transfer from the DWA analysis. For comparison, the DWA reduced cross sections σ_{lj} computed for l transfers of 1 and 2 units are shown on the figure. (The reduced cross sections for the levels above 3.8 MeV that are unbound were computed assuming an excitation energy of 3.75 MeV.) Neither of the curves gives a particularly good fit. Efforts to reproduce the data with distributions for $l=3$, $l=4$, and $l=6$ met with even less success. This may be due in part to the fact that we are using a bound wave function for the transferred proton. It is possible that the 4.42-MeV state is an unresolved doublet, but attempts to reproduce the experimental angular distribution with a mixture of $l=1$ and $l=3$ were unsuccessful.

There are at least six additional levels, between 3.41 and 4.58 MeV, that are weakly excited in the (He^3,d) reaction. Angular distributions for the highest two of these states, at 4.52 and 4.58 MeV, are also shown in Fig. 3. Neither angular distribution is reproduced by the DWA calculations although the level at 4.58 MeV does have some similarity to an $l=1$ distribution. The maximum cross sections for these weak states are on the order of 100 μb/sr or less.

The level structure of Bi^{209} affords an opportunity to

TABLE II. Results from the analysis of the $Pb^{208}(He^3,d)Bi^{209}$ angular distributions obtained at 44.2-MeV bombarding energy. The DWA calculations used the parameters given in Table I.

Ex[a]	Shell-model assignment	$d\sigma/d\Omega$ (30°) expt. (mb/sr)	S_{lj}
0.00	$1h_{9/2}$	0.14	0.95
0.90	$2f_{7/2}$	0.96	1.18
1.61	$1i_{13/2}$	0.16	0.88
2.61		0.02	
2.83	$2f_{5/2}$	0.81	1.15
3.12	$3p_{3/2}$	1.25	1.03
3.41[b]			
3.50[b]			
3.64	$3p_{1/2}$	0.43	0.63
3.81[b]			
3.97[b]			
4.08[b]			
4.16[b]			
4.24[b]			
4.42	$(3p_{1/2})$	0.38	(0.46)
4.52			
4.58			

[a] Excitation energies for the single-particle states, except for the 3.12-MeV state, were taken from Ref. 3, which quotes the errors as ±10 keV. The remaining energies were normalized to the above values, introducing an additional uncertainty of ±20 keV. Thus the level at 2.61 MeV is most likely the unresolved doublet reported in Ref. 9 at 2.597 MeV.
[b] Maximum cross section for these levels is about 50 μb/sr.

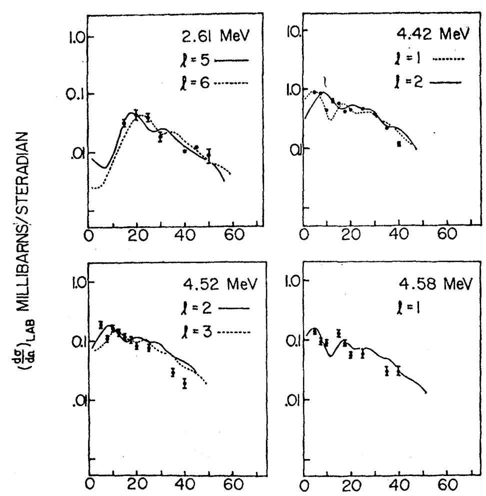

FIG. 3. Angular distributions of deuteron groups from Pb^{208} $(He^3,d)Bi^{209}$ at a He^3 energy of 44.2 MeV. The solid and dotted curves are the normalized reduced cross sections σ_{lj} obtained from the DWA analysis.

study quantitatively the coupling between the single-particle motions and excited states of the Pb^{208} core. For example, according to the weak-coupling model,[8] an $h_{9/2}$ proton may couple to the 3^- octupole vibration at 2.61 MeV in Pb^{208} and form a septuplet of states with an unperturbed energy of 2.61 MeV in Bi^{209}. This particle-vibration septuplet has been almost completely resolved in the recent high-resolution proton-scattering experiment by Hafele and Woods.[9] Because of mixing with other states of the same spin and parity, we expect admixtures of the single-proton configurations in predominantly particle-vibration states and vice versa.

There is a level at approximately 2.6 MeV that is excited very weakly in the (He^3,d) reaction and that can be seen in Fig. 1. The angular distribution for this level is included in Fig. 3. Although the statistics are poor, it definitely seems to be excited by a high l transfer, perhaps $l=5$ or $l=6$. It is probably the same state that is excited in the $Pb^{208}(\alpha,t)$ reaction as reported by Lilley and Stein.[5] Mottelson[10] has recently discussed some of his results from a study of particle-vibration coupling in the lead region. His calculations predict that about 5% of the $1i_{13/2}$ single-particle strength and about 7% of the $1i_{11/2}$ single-particle strength (from the next higher shell) is contained in the $\frac{13}{2}^+$, $\frac{11}{2}^+$ members of the $(h_{9/2},3^-)$ particle-vibration septuplet. Most likely the weak state we observe is $l=6$ and is the unresolved $\frac{13}{2}$, $\frac{11}{2}$ doublet at 2.597 MeV seen in the proton inelastic scattering experiment by Hafele and Woods.[9] The cross section for the state we see at 2.6 MeV is about 13% of that for the $1i_{13/2}$ state, which agrees very well with Mottelson's prediction of about 12%.

The origins of the weakly excited levels between 3.41 and 4.58 MeV and the strong level at 4.42 MeV are not explained by our analysis. If the angular distribution for the 4.42-MeV level does correspond to $l=1$, then this level would contain the remainder of the missing $p_{1/2}$ strength. Another possibility for strongly exciting a level in this region of the spectrum is through an $f_{7/2}$ single-particle admixture in the $J=\frac{7}{2}^-$ member of the $(1i_{13/2},3^-)$ particle-vibration septuplet, which has an unperturbed energy of about 4.2 MeV. This latter possibility was also considered by Mottelson who estimates about 20% of the $f_{7/2}$ strength should be shifted to the $(1i_{13/2},3^-)$ state and hence appear as an $l=3$ transition around 4–5-MeV excitation.

Ellegaard and Vedelsby[11] have recently published their results of a study of Bi^{209}. They also used the (He^3,d) reaction but at a much lower bombarding energy of 20.3 MeV. They suggest that the level at 4.42 MeV is populated by an $l=3$ transition and is hence an $f_{7/2}$ fragment. Our data seem to indicate a lower l transfer.

The angular distributions for the 4.52- and 4.58-MeV levels also appear to be of low l transfer, which would rule out configurations which are excited by mixing with the $i_{13/2}$ or $i_{11/2}$ single-particle states. One possibility is that these states arise from a coupling between the first three proton single-particle states and the 5^- or 4^- levels at 3.19 and 3.47 MeV in Pb^{208}. States of this type would have unperturbed energies between 3.19 and 5.08 MeV, and could be excited through admixtures of single-particle states having the same spin and parity.

[8] A. de-Shalit, Phys. Rev. **122**, 1530 (1961); Phys. Letters **15**, 170 (1965).
[9] J. C. Hafele and R. Woods, Phys. Letters **23**, 579 (1966).
[10] B. R. Mottelson, in Proceedings of the International Conference on Nuclear Structure, Tokyo, Japan, 1967 (unpublished).
[11] C. Ellegaard and P. Vedelsby, Phys. Letters **26B**, 155 (1968).