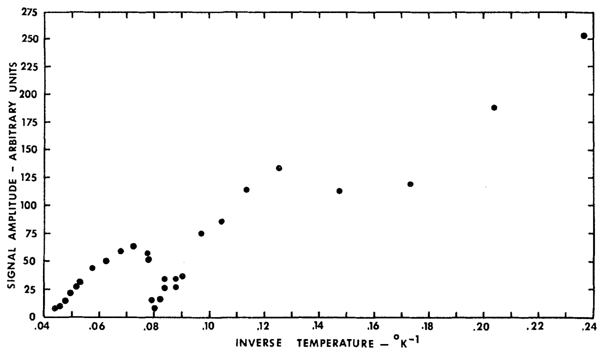

FIG. 3. UPR $\Delta m = \pm 2$ dispersion signal amplitude versus temperature. Conditions as in Fig. 1.

The dispersion signal also shows anomalous behavior between 10 and 13°K. The dispersion signal shows no sign of saturation at low temperatures. This agrees with saturation measurements on UPR absorption and dispersion at 4.2°K.[10] No theory has yet been given to describe the behavior of the UPR dispersion signal under conditions of saturation. The experimental behavior of the UPR absorption and dispersion signals under conditions of saturation is similar to the behavior of the epr absorption and dispersion signals. In the epr case also, the absorption signal saturates much easier than the dispersion signal.[11] The fact that the temperature dependence of the absorption and dispersion signals is qualitatively different suggests that it may be best to use the dispersion mode when searching for new signals.

---

†Work supported in part by the National Science Foundation under Grant No. NSF GP-5070.

*Now at Boeing Scientific Research Laboratories, Seattle, Washington.

[1]E. B. Tucker, in Physical Acoustics, edited by W. P. Mason, (Academic Press, Inc., New York, 1966), Vol. 4A.

[2]R. Guermeur, J. Joffrin, A. Levelut, and J. Penne, Phys. Letters 13, 107 (1964).

[3]D. I. Bolef, J. de Klerk, and R. B. Gosser, Rev. Sci. Instr. 33, 631 (1962).

[4]R. D. Mattuck and M. W. P. Strandberg, Phys. Rev. 119, 1204 (1960).

[5]E. H. Jacobsen and K. W. H. Stevens, Phys. Rev. 129, 2036 (1963).

[6]D. H. McMahon, Phys. Rev. 134, A128 (1964).

[7]E. R. Feher, Phys. Rev. 136, A145 (1964).

[8]R. L. Hartman, E. L. Wilkinson, and J. G. Castle, Jr., Bull. Am. Phys. Soc. 12, 642 (1967).

[9]J. Y. Wong and A. L. Schawlow, Bull. Am. Phys. Soc. 12, 655 (1967).

[10]R. Guermeur, J. Joffrin, A. Levelut, and J. Penne, Phys. Letters 15, 203 (1965).

[11]A. M. Portis, Phys. Rev. 91, 1071 (1953).

PROTON SINGLE-PARTICLE STATES ABOVE $Z=82$, AS OBSERVED WITH THE REACTION ^{208}Pb(^{3}He, d)^{209}Bi AT $E_{^3\mathrm{He}}=51$ MeV *

B. H. Wildenthal,† B. M. Preedom,‡ E. Newman, and M. R. Cates§
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received 11 September 1967)

The location and identification of the proton single-particle states above $Z=82$ is a problem of basic interest[1,2] and the subject of recent[3-5] discussion and investigation. This note presents the experimental angular distributions of the six strong transitions observed to bound states of ^{209}Bi in an investigation of the reaction ^{208}Pb(^{3}He, d)^{209}Bi at $E_{^3\mathrm{He}}=51.26$ MeV. An analysis of these data with local, zero-range distorted-wave (DW) calculations[6] yields a positive identification of the first five of these levels with the $1h_{9/2}$, $2f_{7/2}$, $1i_{13/2}$, $2f_{5/2}$, and $3p_{3/2}$ single-particle states, respectively.

The experiment was performed with the Oak Ridge Isochronous Cyclotron and the associated broad-range spectrograph facility. The target was a 0.47-mg/cm^2 lead foil of isotopic constitution 95% ^{208}Pb, 1.2% ^{207}Pb, and 3.8% ^{206}Pb.[7] The experimental energy resolution (full width at half-maximum) for the ^{209}Bi groups was 60 keV. The major target contaminants were ^{12}C and ^{16}O; the (^{3}He, d) reaction products from these nuclei obscured the particle groups of one or two levels of ^{209}Bi at several angles. The absolute cross sections of the (^{3}He, d) transitions to the levels of ^{209}Bi were established by reference to the elastic yields of Pb(^{3}He, ^{3}He)Pb at $\theta_L=14°$, 16°, 18°, and 25°. The cross sections for this elastic scattering were assumed to be those predicted in an optical-model cal-

Table I. Results of DW analysis of angular distributions of the reaction ^{208}Pb(^{3}He,d)^{209}Bi, $E_{^3\mathrm{He}} = 51.26$ MeV, and the DW parameters for the calculations upon which the spectroscopic factors are based.

Level energy (MeV)	l	J^π	S_{exp}	S(opposite j)
0.00	5	$\frac{9}{2}^-$	1.00	0.68
0.89 ± 0.01	3	$\frac{7}{2}^-$	1.12	1.66
1.60 ± 0.02	6	$13/2^+$	0.94	1.39
2.81 ± 0.03	3	$\frac{5}{2}^-$	1.14	0.78
3.10 ± 0.03	1	$\frac{3}{2}^-$	1.08	2.23
3.61 ± 0.03	(1)	($\frac{1}{2}^-$)	(0.7–0.9)	0.3–0.4

	V_0 (MeV)	W_0 (MeV)	r_0 (F)	r_{0c} (F)	a (F)	r_0' (F)	a' (F)	W_D (MeV)
^{3}He[a]	175	17.5	1.14	1.40	0.723	1.60	1.81	0
Deuteron[b]	111	0	1.05	1.25	0.859	1.24	0.794	17.7
Bound state[c]			1.24	1.25	0.65			

[a]Ref. 11.

[b]Rev. 8.

[c]The bound-state well depths were adjusted to reproduce the respective separation energies of the various levels. $\lambda = 6$.

culation which employed the ^{3}He parameters in Table I. The optical model predictions at these angles are insensitive to the exact values of the parameters used in the calculation as the Coulomb term predominates.

The experimental differential cross sections are shown in Figs. 1 and 2. The curves in these figures are obtained from DW calculations, made with the code JULIE,[8] which employ the parameters listed in Table I. The deuteron parameters are from an analysis[9] of 52-MeV elastic scattering on ^{208}Pb. These parameters are similar to the values obtained for ^{209}Bi and from formulas derived from deuteron elastic scattering at 34.4 MeV.[10] The three sets produce virtually identical DW angular distributions for the present reaction. The ^{3}He parameters used are those obtained by Bassel and collaborators[11] from an analysis of scattering on medium-weight nuclei at energies from 30 to 50 MeV. Their results indicate that these parameters are stable with respect to changes in either the bombarding energy or the target mass.

The excitation energies of the states of ^{209}Bi studied, and their assigned spectroscopic properties, are listed in Table I. Since the magnetic spectrograph is not well calibrated at the high fields employed in the present investigation, the small systematic deviations between our measured energies and the average values[3–5,12,13] found in the literature should not be considered significant. The ground state and the 1.60-MeV level are characterized by l transfers of 5 and 6, respectively, as is illustrated in Fig. 1. The sensitivity with which the ~50 MeV (^{3}He, d) reaction and the associated DW analysis can distinguish between these two cases is also shown in Fig. 1 by a comparison of the data to the predicted distributions for the alternative l transfers, indicated by the dashed lines. The ground-state spin is known[14] to be $\frac{9}{2}^-$ and the 1.60-MeV level is most like-

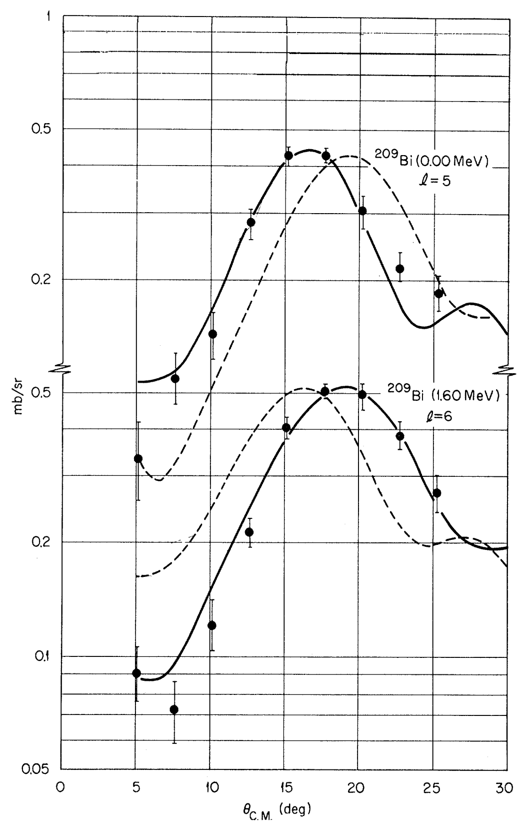

FIG. 1. The experimental angular distributions of the ground state and 1.60-MeV level of ^{209}Bi, excited by the reaction ^{208}Pb(^{3}He, d)^{209}Bi at 51.26-MeV incident energy. The solid curves represent DW calculations for the two states, using the parameters of Table I, with $l = 5$ assumed for the ground state and $l = 6$ assumed for the 1.60-MeV level. The dashed curves represent calculations in which the opposite l values are assumed.

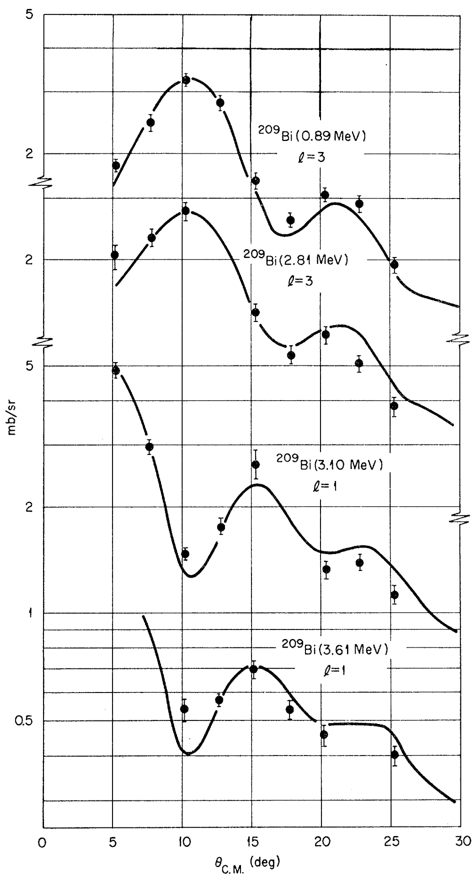

FIG. 2. The experimental angular distributions of the 0.89-, 2.81-, 3.10-, and 3.61-MeV levels of ^{209}Bi, excited by the reaction ^{208}Pb(^{3}He, d)^{209}Bi at 51.26-MeV incident energy. The curves represent DW calculations for the l transfers of 3, 3, 1, and 1, respectively. The parameters of Table I are employed.

ly $13/2^+$. The basis of identification of three other low-lying levels is illustrated in Fig. 2. An inspection of the experimental points and DW curves shows that the states at 0.89 and 2.81 MeV are characterized by $l=3$ transfers and that the 3.10-MeV state is excited with an $l=1$ transfer.

The absolute magnitudes of the angular distributions calculated in the distorted-wave Born approximation for the present reaction, though not their shapes, are quite sensitive to the imaginary well strengths of the optical potentials and to the radius parameter r_0 of the bound-state potential well. Since the ^{3}He potential that is employed lacks the direct experimental verification of the deuteron potential, there is some ambiguity in the absolute values of the predicted cross sections which results from the uncertainty in W_0 (^{3}He). The best value of W_0 appears[11] to be approximately 17.5 MeV. A Coulomb-stripping study[15] on ^{208}Pb suggests that $r_0 = 1.24$ F gives the optimum value for the radius of the bound-state well. The spectroscopic factors for the states of ^{209}Bi that are extracted with calculations which use these parameters are listed in Table I. The normalizing factor[16] for (^{3}He, d) reactions of 4.42 was assumed.

The magnitudes of the predicted cross sections of high l transfers are also sensitive to the strength λ of the spin-orbit component of the bound-state potential. From a study of the $l=5$ and 6 transitions, where the spin-orbit effects are most important, it was found that the usual value, $\lambda=25$, was too large. This finding is consistent with the accepted hypothesis[17] that the radius of the spin-orbit potential is smaller than the radius of the central parts of the potential well. A value $\lambda=6$ was found to give spectroscopic factors with ≈10% scatter about unity.

The spin-orbit term in the bound-state well increases the cross sections for $j=l+\frac{1}{2}$ transitions and decreases those of $j=l-\frac{1}{2}$. Since the effects of this term on the cross sections are in the same direction as the $2j+1$ weighting factor, the predicted cross sections for all l values are significantly j dependent for any strength of λ reasonably larger than 0. Thus, under the reasonable assumption that the states of ^{209}Bi which are strongly populated in the present reaction are essentially pure single-particle states and hence should have spectroscopic factors about equal to one, the spins of the observed levels of ^{209}Bi, as well as the l values, can be assigned. This is shown in Table I where the spectroscopic factors for the opposite assumptions of j are compared with those resulting from the chosen assignments.

A recently published study[4] of the proton single-particle states of ^{209}Bi failed to detect the previously observed,[5] strong, 3.1-MeV level because of an unfortunate positioning of the edges of the emulsion plates. The 3.6-MeV level was consequently assumed to be the $p_{3/2}$ state and the unbound level[4] at 4.4 MeV the $p_{1/2}$ state, with attendant difficulties in interpreting the cross sections. While the present work shows that the 3.1-MeV level should be identified with the $p_{3/2}$ state, it opens the question of the identities of the 3.6- and 4.4-MeV levels. The yield from the 3.6-MeV level is unfortunately masked by the yield from the oxygen target contaminant at 5.0° and 7.5°, the angles which are needed to provide a definite positive or negative identification of an $l=1$ state. The existing experimental points are in best agreement with an $l=1$ calculation, and the spectroscopic factor resulting from an assumed $p_{1/2}$ character for this state is listed in Table I. However, such an assignment, on the basis of the present data, is only tentative. The experimental data for the unbound 4.4-MeV level are also fragmentary because of the same, but more severe, sort of interference from the light-element contaminants. There is some evidence of peaking at forward angles, similar to an $l=1$ shape, but none of the bound-state calculations provides a good fit. The cross sections for the 4.4-MeV level are slightly smaller than those for the 3.6-MeV level at the same angles.

---

*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

†U. S. Atomic Energy Commission Postdoctoral Fellow under appointment from the Oak Ridge Associated Universities.

‡Oak Ridge Graduate Fellow from the University of Tennessee under appointment from the Oak Ridge Associated Universities; present address: Cyclotron Laboratory, Michigan State University, East Lansing, Michigan.

§Oak Ridge Graduate Fellow from Texas A & M University under appointment from the Oak Ridge Associated Universities.

[1]M. G. Mayer and J. H. D. Jensen, Elementary Theory of Nuclear Shell Structure (John Wiley & Sons, Inc., New York, 1955).

[2]A. A. Ross, Hans Mark, and R. D. Lawson, Phys. Rev. 102, 1613 (1956); A. Schröder, Nuovo Cimento 7, 460 (1958); J. Blomquist and S. Wahlborn, Arkiv Fysik 16, 545 (1960).

[3]B. Zeidman, private communication.

[4]R. Woods, P. D. Barnes, E. R. Flynn, and G. J. Igo, Phys. Rev. Letters 19, 453 (1967).

[5]N. Stein and J. S. Lilley, Bull. Am. Phys. Soc. 10, 497 (1965); and Nuclear Physics Laboratory, University of Washington, Annual Report, 1966 (unpublished).

[6]R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240 (unpublished).

[7]The target was prepared by the Stable Isotopes Division of Oak Ridge National Laboratory.

[8]R. M. Drisko (unpublished).

[9]B. Duelli, F. Hinterberger, G. Mairle, U. Schmidt-Rohr, P. Turek, and G. Wagner, Phys. Letters 23, 485 (1966).

[10]E. Newman, L. C. Becker, B. M. Preedom, and J. C. Hiebert, Nucl. Phys. A100, 225 (1967).

[11]E. F. Gibson, B. W. Ridley, J. J. Kraushaar, M. E. Rickey, and R. H. Bassel, Phys. Rev. 155, 1194 (1967).

[12]J. Alster, Phys. Rev. 141, 1138 (1966).

[13]S. Hinds, H. Marchant, J. H. Bjerregaard, and O. Nathan, Phys. Letters 20, 674 (1966).

[14]Nuclear Data Sheets, compiled by K. Way et al. (Printing and Publishing Office, National Academy of Sciences-National Research Council, Washington, D.C.).

[15]M. Dost and W. R. Hering, Phys. Letters 19, 488 (1965).

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

[17]R. M. Drisko, private communication.