^{210}Bi^{m}(d,t) reaction; ^{210}Bi(9^{-}) parentage of states in ^{209}Bi

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Configuration assignments and spectroscopic factors are deduced from angular distribution data on 22 levels or level groupings in ^{209}Bi using the reaction ^{210}Bi$^{m}(d,t)^{209}$Bi at E_d = 17 MeV. Transitions to levels in ^{209}Bi between 2.6 and 6.0 MeV are observed and these levels are interpreted in terms of the coupling of the pure $|h^{\pi}_{9/2},g^{\nu}_{9/2}|_{9^-}$ target state with neutron holes in ^{207}Pb. The j values of the transferred neutron are determined through comparison of the measured angular distributions and energies with angular distributions and energies for the corresponding single-hole states in ^{207}Pb. Levels below 5.0 MeV are assigned $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ neutron hole parentage while the levels above 5.0 MeV all have $f_{7/2}$ neutron hole parentage. The results complement and extend previous inelastic scattering and analog resonance studies on levels below 4.0 MeV excitation in ^{209}Bi. In particular, the summed spectroscopic strength for the $p_{1/2}$ neutron hole parentage states agrees well with the theoretical sum rule limit and measured single-hole strength in ^{207}Pb. The microscopic shell model (in contrast to the weak-coupling model) successfully predicts the observed splitting of spectroscopic strength among the members of the ($|h^{\pi}_{9/2},g^{\nu}_{9/2}|_{9^-} \otimes p^{-1\nu}_{1/2}$) multiplet.

[NUCLEAR REACTIONS ^{210}Bi$^{m}(d,t)^{209}$Bi, E_d=17 MeV. θ_{lab}=12.5°, 20°, 27.5°, 35°, 42.5°, 50°, 57.5°, 72.5°, 87.5°, 100°, 115°. Measured $\sigma(\theta)$ for $E^*(^{209}$Bi) =2700–6000 keV. Deduced $l_j^{-1\nu}$, spectroscopic factors.]

I. INTRODUCTION

The single-particle structure of ^{209}Bi, with one proton beyond the double closed shell nucleus ^{208}Pb, has been studied[1,2] extensively. These studies demonstrated that the ^{209}Bi levels can be almost completely described in terms of the simple shell model. More recent experimental efforts[3-5] have investigated the next level of shell model structure in ^{209}Bi—the two particle–one hole configuration. In this paper we report on results obtained from a study of the ^{210}Bi$^{m}(d,t)$ reaction. This reaction is highly selective in the states that can be excited and this has permitted the 2p-1h structure of many levels in ^{209}Bi to be identified.

States of 2p-1h character are excited in direct inelastic scattering on ^{209}Bi; however, these reactions are most sensitive to the collective excitations of the ^{208}Pb core and thus emphasize the particle-vibration structure of ^{209}Bi. Through studies of this type[6] a multiplet of levels near an excitation energy of 2.6 MeV in ^{209}Bi has been associated with the weak coupling of an $h_{9/2}$ proton to the 3$^-$ state of ^{208}Pb. The success of this weak-coupling or particle-vibration model[7-12] in describing these states has led several groups[4,13-16] to search for multiplets built on other excitations of the ^{208}Pb core. While experimental evidence does exist for structure in ^{209}Bi based upon couplings to the higher excited states of ^{208}Pb, it was pointed out[17] that, for levels in the energy region from 2.8 to 3.6 MeV in ^{209}Bi, an alternate description in terms of the coupling of a neutron hole to the low-lying states of ^{210}Bi provides an equally valid account of the experimental data. The properties of the levels in this energy region were more fully examined by means of isobaric analog studies involving the ^{209}Bi(p,p') reaction,[3] and it was shown that a consideration of the underlying microscopic 2p-1h structure provides a rather complete description of the observed properties of these levels.

The existence of a ^{210}Bi^{m} target[18] provides a means of testing in a definitive way the microscopic model[3] proposed for the levels in ^{209}Bi from 2.8 to 3.6 MeV and of extending our knowledge of the microscopic structure of levels associated with a particular class of 2p-1h configurations. Since the target exists in the 9$^-$ metastable state at an excitation energy of 0.271 MeV, the (d,t) reactions should populate states in ^{209}Bi that can be described as a neutron hole coupled to a 9$^-$ ^{210}Bi core state. Moreover, abundant theoretical[19-21] and experimental[22-27] evidence strongly suggests that this 9$^-$ state is a very pure two particle state whose wave function is dominated by the $|h^{\pi}_{9/2},g^{\nu}_{9/2}|$ component. Thus the present experiment explores states in ^{209}Bi with the $|h^{\pi}_{9/2}$,

$g^{\nu}_{9/2}|_{9^-} \otimes (l_j)^{-1\nu}$ configuration in their structure where $(l_j)^{-1\nu}$ specifies the neutron hole orbital. These neutron hole orbitals are determined for many transitions observed in the $^{210}Bi^m(d,t)$ reaction from both the measured triton angular distributions and the regions of the triton spectra at which single-hole transition strength is expected based upon results from a $^{208}Pb(d,t)$ reaction study.[28] Since this latter reaction on ^{208}Pb was performed at the same incident deuteron energy as the present measurement, a detailed comparison of the single-hole transition strength is presented. The present results are employed in a critical evaluation of the microscopic 2p-1h and weak-coupling descriptions of levels in ^{209}Bi below 3.5 MeV excitation.

II. EXPERIMENTAL PROCEDURES

The fabrication of the $^{210}Bi^m$ target was carried out using the Florida State University Isotope Separator and has been described in detail in Ref. 18. Briefly, an ultrapure sample of ^{209}Bi was exposed to a high flux of neutrons at the Savannah River Laboratories of the U. S. DOE. After the five-day ground state of ^{210}Bi had decayed out, the 2.6×10^6 year 9^- isomer was initially separated at the Oak Ridge Calutron. The resulting separated material consisted of 1.39 mg of $^{210}Bi^m$ with an isotopic abundance of 2.5 at.% in ^{209}Bi. This material was then placed in the ion source of the Florida State University Isotope Separator which had been designed[18] to accomodate extremely small amounts of material. Following retardation, the target (with 99% isotopic purity) was deposited on a 60 $\mu g/cm^2$ carbon backing with a maximum density of material in an oval spot 4 mm $\times$ 2 mm.

In the present experiment the $^{210}Bi^m$ target was bombarded by a 17 MeV deuteron beam from the Yale MP tandem accelerator and the reaction products analyzed by a multigap spectrograph. The technical aspects of this magnet are discussed in Ref. 29. Data were recorded at 22 angles on Ilford 50 μm thick nuclear emulsion plates with the exposure lasting for approximately 50 000 μC of collected charge. A surface barrier detector, located at a laboratory angle of 75°, was used to monitor deuterons elastically scattered from the target and this provided a means of locating the position of maximum $^{210}Bi^m$ thickness on the target. The field of the spectrograph was selected in order to allow tritons and deuterons associated with transitions to levels from 2.5 to 6.0 MeV in ^{209}Bi and from 0.0 to 3.0 MeV in ^{210}Bi, respectively, to fall on the focal plane of the magnet.

Data for 11 angles from 12.5° to 115° were analyzed in detail. The plates were scanned in 0.5 mm steps in the vicinity of the peaks and in 1.0 mm steps over the background region. Since the magnetic field varies slightly from gap to gap in the spectrograph, a peak in each spectrum which could be identified with the 2.987 MeV transition in ^{209}Bi was used to compute the effective field for each gap. The 2.987 MeV transition therefore served as a reference energy[4] for the calibration of the spectra. The effective fields and experimentally measured calibration curves[29] which relate the distance along the plate to the radius of curvature of the magnet were then used to convert plate distance into Q value.

A typical spectrum from the $^{210}Bi^m(d,t)$ measurement is shown in Fig. 1. For ease of presentation, the spectrum is plotted in ΔQ steps of ~6 keV although the data were actually analyzed in steps of ~3 keV. The full width at half maximum (FWHM) for peaks in the spectra varies from ~15 keV at more forward angles to ~30 keV at more backward angles. However, for any given spectrum the resolution was relatively constant over the entire energy range of interest. Excitation energies were obtained from the positions of the $\frac{1}{3}$ heights of the peaks and intensities were extracted by summing the counts over the appropriate ΔQ interval and separating overlapping peaks by making use of the peak shape for the 2.987 MeV transition. Reproducibility of the level energies from angle to angle and the reasonableness of the angular distributions give us confidence in the results in spite of the very thin target. The energies of many transitions in ^{209}Bi have already been measured in inelastic scattering experiments[4] with an uncertainty of less than 5 keV and transitions measured in the present experiment can readily be identified with those derived from the

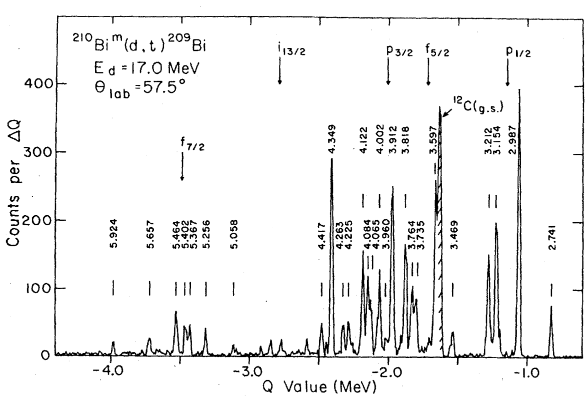

FIG. 1. Triton spectrum from $^{210}Bi^m(d,t)$ measurement. Excitation energies of corresponding states in ^{209}Bi are indicated and arrows show the locations of the unperturbed single-hole transition strength based upon the states of ^{207}Pb.

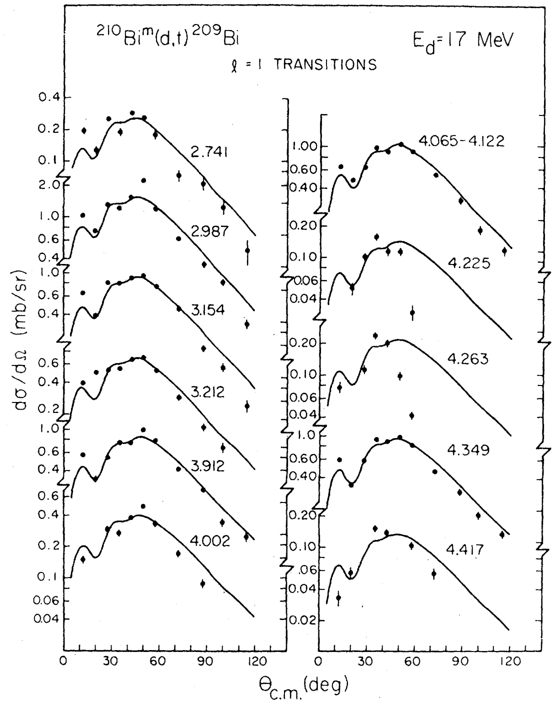

FIG. 2. Triton angular distributions for $l=1$ transitions in ^{209}Bi.

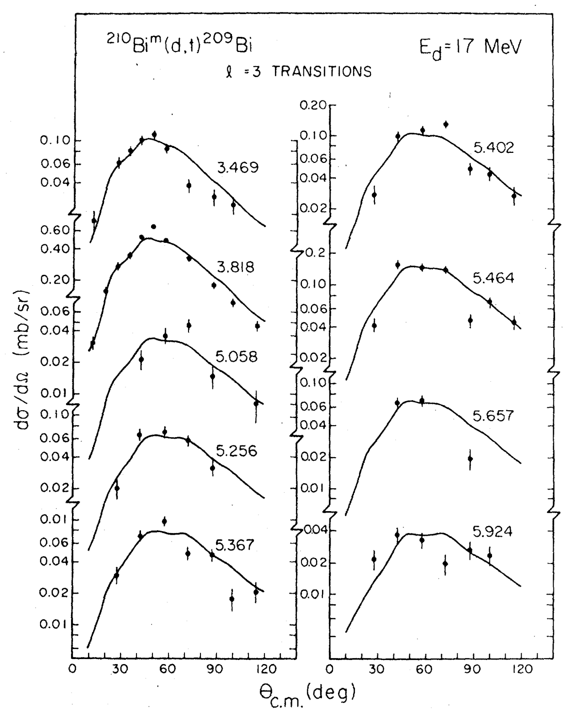

FIG. 3. Triton angular distributions for $l=3$ transitions in ^{209}Bi.

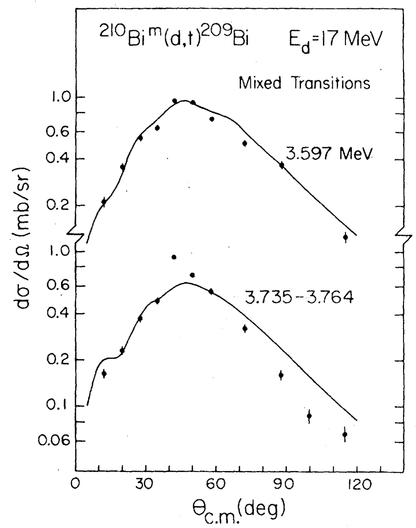

FIG. 4. Triton angular distributions for mixed transitions in ^{209}Bi. See text for discussion.

previous work.

Since the amount of target material relative to the carbon backing foil was quite small, reaction products from the foil and the impurities contained in the foil could give rise to rather large peaks in the spectra. While every attempt was made to identify each of these contaminant peaks, it is possible that not all were identified and some of the large deviations in certain isolated data points in the angular distributions could be a reflection of this problem. The measured angular distributions for the ^{210}Bi(d,t) reaction are shown in Figs. 2–4.

Data for ^{210}Bi(d,d) scattering could only be extracted for angles greater than 110°. However, by comparing the results obtained at these angles with similar data from elastic deuteron scattering on ^{208}Pb and ^{209}Bi, an absolute cross-section normalization was established. As an additional check on the normalization, the elastic deuteron counts obtained with the monitor detector were compared with values for the differential cross section calculated from the deuteron optical potential of Ref. 30. The two methods yielded a consistent value for the target thickness of 3.0 ± 0.3 μg/cm^2 at the beam spot used in this experiment. An uncertainty of 10% is therefore assumed for the absolute cross-section normalization in this work.

III. ANALYSIS

The solid curves in Figs. 2–4 are distorted-wave Born approximation (DWBA) calculations based upon the optical potential used in Ref. 30 and corrected for Q-value dependence. These same parameters were used in the analysis of the ^{208}Pb(d,t) data of Moyer *et al.*[28] The DWBA code DWUCK[31] was used in the present calculations.

Since the shapes of the angular distributions involving spin transfers of $j=l+\frac{1}{2}$ and $j=l-\frac{1}{2}$ are indistinguishable, the angular distributions alone do not permit the identification of the orbital from which the transferred neutron has been picked up. The triton spectrum in Fig. 1 is displayed as a function of reaction Q value and corresponds to an excitation energy region from 2.6 to 6.0 MeV in ^{209}Bi. The arrows along the upper part of the figure indicate the expected location of single-hole transition strength based upon the energies of the single-hole states of ^{207}Pb. If the fragmentation of single-hole strength caused by the presence of the extra-core neutron and proton in the ^{210}Bi^m(d,t) reaction does not spread out the population over too great an energy range, then the single-hole strength should lie close to the unperturbed positions and thus identification of both the l and j of the transferred neutron should be possible.

The energy separation of the $f_{5/2}$ and $f_{7/2}$ neutron hole states is quite large, approximately 2 MeV, and therefore multiplets in ^{209}Bi associated with these two orbitals should be well separated. In the case of the $p_{1/2}$ and $p_{3/2}$ orbitals, though, the energy separation is small (0.85 MeV) and the corresponding multiplets in ^{209}Bi could overlap in energy and indeed by admixed thus causing difficulty in assignment. Fortunately, however, resonance studies[3] of the ^{209}Bi(p,p') reaction have already suggested assignments for many of the levels in ^{209}Bi with structure involving the $p_{1/2}$ hole orbital; three of these levels are populated in the present experiment. These suggested assignments are discussed in terms of the present experimental results in Sec. IV.

The results of the present analysis are summarized in Table I. The l and j values for the transferred neutron have been determined from the angular distributions and the unperturbed positions of the single-hole strength. The corresponding values for the spectroscopic strength are also tabulated. The spectroscopic factors were derived using the normal definition

$$\frac{d\sigma}{d\Omega}=\frac{3.33}{(2j+1)}\,S\sigma_{\rm DWBA}(\theta)\,,$$

where j is the total angular momentum of the transferred neutron. The spin assignments for the six lowest levels have been taken from Refs. 3 and 4.

Finally, the spectroscopic sums and energy centroids are compared with the values for the single-hole states obtained in the ^{208}Pb(d,t) reaction.[28] The energy centroids were calculated using

TABLE I. Summary of results for the ^{210}Bi^m(d,t)^{209}Bi reaction.

Energy [a] MeV	J^π Ref. b	l	S	l_j Ref. c
2.741	$\frac{15}{2}^+$	1	0.14	$p_{3/2}$
2.987	$\frac{19}{2}^+$	1	0.98	$p_{1/2}$
3.135	$\frac{15}{2}^+$, $\frac{11}{2}^+$			
3.154	$\frac{17}{2}^+$, $\frac{9}{2}^+$	1	0.61	$p_{1/2}$
3.212	$\frac{17}{2}^+$	1	0.48	$p_{1/2}$
3.469	$\frac{11}{2}^+$ Ref. d	3	0.27	$f_{5/2}$
3.597	$\frac{19}{2}^+$	1, 3	0.17, 1.95	$p_{3/2}$, $f_{5/2}$
3.735, 3.764		1, 3	0.25, 0.94	$p_{3/2}$, $f_{5/2}$
3.818		3	1.58	$f_{5/2}$
3.912		1	0.71	$p_{3/2}$
3.960				
4.002		1	0.35	$p_{3/2}$
4.021				
4.065, 4.084, 4.122		1	0.92	$p_{3/2}$
4.225		1	0.14	$p_{3/2}$
4.263		1	0.21	$p_{3/2}$
4.349		1	0.97	$p_{3/2}$
4.417		1	0.14	$p_{3/2}$
5.058		3	0.15	$f_{7/2}$
5.256		3	0.32	$f_{7/2}$
5.367		3	0.41	$f_{7/2}$
5.402		3	0.56	$f_{7/2}$
5.464		3	0.83	$f_{7/2}$
5.657		3	0.43	$f_{7/2}$
5.924		3	0.28	$f_{7/2}$

[a] Energies are derived from present study with 2.987 MeV level as a reference energy. Energy uncertainties are 5 keV for levels below 3.60 MeV and 10 keV for levels above 3.60 MeV.

[b] From Table I of Ref. 4.

[c] Orbital and total angular momentum of transferred neutron.

[d] Possible doublet. See text for discussion.

the formula

$$\bar{E}_{l_j}=\frac{\sum_i S^i_{l_j}E^i}{\sum_i S^i_{l_j}}\,,$$

where $S^i_{l_j}$ and E^i are the spectroscopic factor and excitation energy in ^{209}Bi, respectively, corresponding to the pickup of a neutron with orbital and total angular momentum l_j.

IV. CONFIGURATION ASSIGNMENTS

A. The $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration

From angular momentum coupling considerations, the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration is expected to give rise to two states of spin-parity—$\frac{19}{2}^+$ and $\frac{17}{2}^+$. Thirteen transitions with $l=1$ angular distributions are observed and these correspond to the population of states at excitation energies between 2.5 and 4.5 MeV in ^{209}Bi. The states at 2.987, 3.154, and 3.212 MeV have been identified in previous work[3] with the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration with suggested spin assignments of $\frac{19}{2}^+$, $\frac{17}{2}^+$, and $\frac{17}{2}^+$, respectively. These results have been used to separate the $p_{1/2}$ $l=1$ transitions from the $p_{3/2}$ $l=1$ transitions listed in Table I. The energy centroid position and total spectroscopic strength for these three transitions are found to be in remarkable agreement with the experimental results for the $p_{1/2}$ hole state transition derived from the ^{208}Pb(d,t) reaction[30] (see Table II). In summary, the interpretation of the 2.987, 3.154, and 3.212 MeV states in terms of the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration is strongly supported by the present results.

B. The $|^{210}\mathrm{Bi}(9^-)\otimes p_{3/2}^{-1\nu}|$ configuration

The states identified with the $|^{210}\mathrm{Bi}(9^-)\otimes p_{3/2}^{-1\nu}|$ configuration include all the levels excited by $l=1$ transitions which have not been associated with the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration. The spin-parity values expected on the basis of the $|^{210}\mathrm{Bi}(9^-)\otimes p_{3/2}^{-1\nu}|$ configuration are $\frac{15}{2}^+$, $\frac{17}{2}^+$, $\frac{19}{2}^+$, and $\frac{21}{2}^+$. Aside from the level at 2.741 MeV excitation energy, all these levels lie at energies greater than 3.450 MeV. From the angular distribution data it is found that eight of the level groupings (the 2.741, 3.912, 4.002, 4.065–4.122, 4.225, 4.263, 4.349, and 4.417 MeV levels) are excited by $l=1$ transitions while two (the 3.597 and 3.764 MeV levels) are populated by mixed $l=1$ and $l=3$ transitions. The 3.764 MeV peak could be resolved from the 3.735 MeV peak at only a few angles and they were, therefore, analyzed together. At the most forward angles, the cross section for the 3.764 MeV transition is much larger than that for the 3.735 MeV transition and this leads to the identification of the 3.764 MeV transition as the $l=1$ component of the doublet. The results are summarized in Table I. The listed levels can account for 100% of the spectroscopic strength obtained for the $p_{3/2}$ single-hole transition in ^{207}Pb and their energy centroid is only 120 keV above the unperturbed position for the $|^{210}\mathrm{Bi}(9^-)\otimes p_{3/2}^{-1\nu}|$ configuration. The angular distributions for the mixed transitions are consistent with the data and this suggests that no serious misassignment of strength has occurred.

The association of the ten groups discussed above with the $|^{210}\mathrm{Bi}(9^-)\otimes p_{3/2}^{-1\nu}|$ configuration is consistent with the total transition strength and energy centroid for these levels and provides additional support for the division of $p_{1/2}$ and $p_{3/2}$ $l=1$ transitions assumed in this analysis.

TABLE II. Comparison of single-particle transitions for the ^{208}Pb(d,t) and ^{210}Bi(d,t) reactions.

l_j	Energy centroids E_{sp} Ref. a	$\bar{E}$	Spectroscopic strengths S_{sp} Ref. a	$\sum S l_j$
$p_{1/2}$	3.080	3.088	2.1 [b]	2.07
$f_{5/2}$	3.650	3.691	6.8	4.74
$p_{3/2}$	3.930	4.050	4.0	4.0
$i_{13/2}$	4.720		14.5	
$f_{7/2}$	5.420	5.467	7.1	2.98

[a] Aside from E_{sp} and S_{sp} for the $p_{1/2}$ transition, the single-particle results are from the ^{208}Pb(d,t) reaction study of Ref. 28.

[b] From study of Ref. 30.

C. The $|^{210}\mathrm{Bi}(9^-)\otimes f_{5/2}^{-1\nu}|$ configuration

Six states with spin-parities $\frac{13}{2}^+$ through $\frac{23}{2}^+$ are expected for the $|^{210}\mathrm{Bi}(9^-)\otimes f_{5/2}^{-1\nu}|$ configuration. From the angular distributions for transitions to levels below 4.5 MeV, it is found that the 3.469 and 3.818 MeV levels are excited by $l=3$ transitions and the 3.597 and 3.735 MeV levels by mixed $l=1$ and 3 transitions. The 3.735 MeV transition is the second member of the 3.735–3.764 MeV doublet discussed above and it is identified as the $l=3$ component in this unresolved transition. The 1.770 MeV energy separation of the $f_{5/2}$ and $f_{7/2}$ single-hole states (see Fig. 1) suggests that the corresponding levels in ^{209}Bi can be associated with the $|^{210}\mathrm{Bi}(9^-)\otimes f_{5/2}^{-1\nu}|$ and $|^{210}\mathrm{Bi}(9^-)\otimes f_{7/2}^{-1\nu}|$ configurations on the basis of energetics.

For levels associated with the $|^{210}\mathrm{Bi}(9^-)\otimes f_{5/2}^{-1\nu}|$ configuration, the resulting energy centroid is 41 keV higher than the unperturbed value and the total spectroscopic strength is about 30% below the single-hole value obtained from ^{207}Pb. From the ^{209}Bi(p,p') data of Ref. 3, the excitation function for a transition leading to a level at 3.465 MeV is found to exhibit resonance structure at the 6^- analog state and much weaker resonance structure near the 9^-. This level can probably be identified with the 3.469 MeV transition observed in the present measurement. The excitation of this level at the 9^- analog state is consistent with its population in the present (d,t) experiment; however, the present assignment of the 3.469 MeV level as a member of the $|^{210}Bi(9^-)\otimes f_{5/2}^{-1\nu}|$ multiplet is in conflict with the $\frac{11}{2}^+$ spin assignment derived in Ref. 3. This conflict could be resolved if this level is actually a doublet with one member associated with the $|^{210}Bi(6^-)\otimes p_{1/2}^{-1\nu}|$ configuration and the other with $|^{210}Bi(9^-)\otimes f_{5/2}^{-1\nu}|$.

Within the assumptions of the present analysis, the description of all the levels below 4.400 MeV excited by $l=3$ transitions in terms of the $|^{210}Bi(9^-)\otimes f_{5/2}^{-1\nu}|$ configuration provides a consistent explanation of the experimental results.

D. The $|^{210}Bi(9^-)\otimes f_{7/2}^{-1\nu}|$ configuration

Seven levels above an excitation energy of 5.0 MeV are identified in Table I with the $|^{210}Bi(9^-)\otimes f_{7/2}^{-1\nu}|$ configuration. Eight states are predicted for this configuration with spins from $\frac{11}{2}^+$ to $\frac{25}{2}^+$. The transitions associated with the configuration account for only 40% of the predicted single-hole strength and the energy centroid for the levels is 47 keV above the unperturbed position. These results indicate that the $f_{7/2}$ single-hole strength is quite fragmented. Some $f_{7/2}$ strength might reside in transitions to levels above 6.000 MeV in ^{209}Bi; however, this region of the energy spectrum was obscured at most angles in the present measurement by contaminant peaks.

E. The $|^{210}Bi(9^-)\otimes i_{13/2}^{-1\nu}|$ configuration

Angular momentum coupling suggests that 14 states are expected from the configuration $|^{210}Bi(9^-)\otimes i_{13/2}^{-1\nu}|$ with spin-parities from $\frac{5}{2}^-$ to $\frac{31}{2}^-$. Based on the location of the $i_{13/2}$ hole state in ^{207}Pb, we may expect most of the strength from the $|^{210}Bi(9^-)\otimes i_{13/2}^{-1\nu}|$ configuration to lie in the energy region from 4.5 to 5.0 MeV (see Fig. 1). However, the fragmentation of the strength into a minimum of 14 states combined with the intrinsically lower $i_{13/2}$ single-particle cross section makes it very difficult to observe the individual transitions. There are a number of extremely weak fluctuations in the background in the excitation region from 4.5 to 5.0 MeV (see Fig. 1). An attempt was made to extract a summed angular distribution of all of these fluctuations between 4.5 and 5.0 MeV to see if the integrated yield exhibited an $l=6$ distribution. This effort was inconclusive possibly because of the presence of many other weak non-$i_{13/2}$ transitions in this region of the spectrum. Therefore, more sensitive experiments are required to locate the $|^{210}Bi(9^-)\otimes i_{13/2}^{-1\nu}|$ configuration.

V. DISCUSSION

The configurational structure of the ^{210}Bi target state does permit the direct excitation of the $h_{9/2}$ ground state of ^{209}Bi via pickup of a $g_{9/2}$ neutron; however, only the region of excitation above 2.5 MeV in ^{209}Bi was explored in the present experiment. No other single-particle states of ^{209}Bi are expected to be strongly excited in the energy range studied in the present measurement and indeed no evidence is found for such excitations.

Since the structure of the ^{210}Bi target state is dominated by the $|h_{9/2}^{\pi},g_{9/2}^{\nu}|$ configuration, the (d,t) reaction should preferentially excite the 2p-1h states of ^{209}Bi possessing the $\{|h_{9/2}^{\pi},g_{9/2}^{\nu}|_{9^-}\otimes(l_j)^{-1\nu}\}$ configuration in their wave functions. The present results, therefore, provide an extremely sensitive test of the microscopic or shell model description of ^{209}Bi.

The lowest level in ^{209}Bi excited in the present $^{210}Bi^m$ experiment is the 2.741 MeV level. This level has been identified in several experiments[4,6-9,13-17] as the spin $\frac{15}{2}^+$ member of a septuplet of states based upon the coupling of an $h_{9/2}$ proton to the 3^- core state of ^{208}Pb at 2.615 MeV. This latter model assumes that the coupling between the valence particle and the core vibration is weak and thus neglects the microscopic structure of the core state. From the $l=1$ nature of the angular distribution shown in Fig. 2 and total angular momentum coupling considerations, the excitation of this level must proceed via pickup of a $p_{3/2}$ neutron. The spectroscopic factor associated with the transition to this level provides a measure of the amplitude of the $\{|h_{9/2}^{\pi},g_{9/2}^{\nu}|_{9^-}\otimes p_{3/2}^{-1\nu}\}$ configuration in the wave function of this level. On the basis of the weak-coupling model and the random-phase approximation (RPA) wave functions for the ^{208}Pb 3^- state calculated by Gillet *et al.*,[32] it is possible to derive a theoretical value for the spectroscopic factor. With an amplitude for the $|g_{9/2}^{\nu},p_{3/2}^{-1\nu}|$ component in the ^{208}Pb 3^- wave function of 0.42 and employing Racah coefficients to recouple the microscopic orbitals (see Ref. 9), it can be shown that

$$|\langle |h_{9/2}^{\pi},g_{9/2}^{\nu}|_{9^-}\otimes p_{3/2}^{-1\nu}|^{208}\mathrm{Pb}(3^-)\otimes h_{9/2}^{\pi}\rangle_{15/2}|^2=0.147\,.$$

This overlap squared times the statistical factor of $(2J_f+1)/(2J_i+1)$, where J_i and J_f are the target and final state spins, respectively, leads to a weak-coupling model prediction of 0.123 for the spectroscopic factor for the $\frac{15}{2}^+$ state. This result is in excellent agreement with the measured value of 0.165 determined for the 2.741 MeV level.

The next three levels strongly excited in the $^{210}Bi^m(d,t)$ experiment are identified as members of the $|^{210}Bi(9^-)\otimes p_{1/2}^{-1\nu}|$ multiplet. In Ref. 3 the spin assignments for these levels (at 2.987, 3.154, and 3.212 MeV) are given as $\frac{19}{2}^+$, $\frac{17}{2}^+$, and $\frac{17}{2}^+$, respectively. These assignments are consistent with the spin-parities allowed for the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration and are supported by the present experimental results. It is important to note that these spins are in disagreement with spins derived for these same levels in several direct inelastic scattering measurements on ^{209}Bi. In these studies[13-15] a weak-coupling model based on the coupling of an $h_{9/2}$ proton to the 5^- state of ^{208}Pb was assumed. There are ambiguities inherent in this method of determining spins and the present results strongly suggest that some of the spins derived in these studies[13-15] are incorrect. The spin of $\frac{19}{2}^+$ for the 2.987 MeV level has also been confirmed by the γ-branching observed in the $^{208}\mathrm{Pb}(^6\mathrm{Li},\alpha 2n\gamma)$ reaction.[33]

The existence of two $\frac{17}{2}^+$ levels is experimentally supported by the strong excitation of each of these levels both in inelastic scattering experiments[4] and in the present $^{210}\mathrm{Bi}^m(d,t)$ measurement. Since only one $\frac{17}{2}^+$ state should be strongly populated in the present experiment via pickup from the $p_{1/2}$ orbital, the excitation of a second $\frac{17}{2}^+$ indicates admixture of the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|$ configuration with another configuration. Indeed, the calculations of Ref. 3 predict almost complete admixture of the $|^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}|_{17/2^+}$ and $|^{210}\mathrm{Bi}(8^-)\otimes p_{1/2}^{-1\nu}|_{17/2^+}$ configurations. In these calculations the microscopic 2p-1h structure of ^{209}Bi was derived for configurations involving the $g_{9/2}$, $h_{9/2}$, and $p_{1/2}$ orbitals by considering the individual two-body interactions between the various particles and holes. The theoretical energies and spectroscopic factors deduced from the calculated wave functions as expressed in the ^{210}Bi representation are compared with the experimental results for the 2.987, 3.154, and 3.212 MeV levels in Table III. In view of the restricted model space considered, the theoretical results provide a remarkable reproduction of the experimental energies and spectroscopic factors and support an interpretation of these levels in terms of their 2p-1h structure. Weak-coupling calculations have been performed by Arita and Horie[12] in which the levels in the energy region from 3.0 to 3.5 MeV in ^{209}Bi are interpreted as members of a multiplet built on the coupling of an $h_{9/2}$ proton to the 5^- state of ^{208}Pb. In marked contrast to the microscopic calculations, the weak-coupling calculations are not able to account for either the experimental energies or the fragmentation of the $\frac{17}{2}^+$ member of the multiplet. Arita and Horie also present a shell model analysis which more accurately accounts for the energies of the $\frac{19}{2}^+$ and lowest $\frac{17}{2}^+$ states but fails to predict the presence of a second $\frac{17}{2}^+$ state.

TABLE III. Comparison of theoretical and experimental results for $[^{210}\mathrm{Bi}(9^-)\otimes p_{1/2}^{-1\nu}]$ states in ^{209}Bi.

Experiment[a] Energy (MeV)	J^π	$S_{p_{1/2}}$	Theory[b] Energy (MeV)	$S_{p_{1/2}}$
2.987	$\frac{19}{2}^+$	0.98	2.892	1.053
3.154	$\frac{17}{2}^+$	0.61	3.171	0.495
3.212	$\frac{17}{2}^+$	0.48	3.264	0.452
		2.07		2.000

[a] From Table I.
[b] From Cleary *et al.*, Ref. 3.

VI. CONCLUSION

The $|^{210}\mathrm{Bi}(9^-)\otimes(l_j)^{-1\nu}|$ configurational structure of ^{209}Bi was examined by means of the $^{210}\mathrm{Bi}^m(d,t)$ reaction. Twenty-eight levels from 2.7 to 6.0 MeV excitation energy in ^{209}Bi are noted as having parentage in the 9^- state of ^{210}Bi. Based on the triton angular distributions and the unperturbed energies of the single-hole states derived from ^{207}Pb, the neutron hole structure for all of the strongly excited levels was suggested. These results are summarized in Table I. A comparison of the total spectroscopic strength and the energy centroids for the various hole state transitions for $^{210}\mathrm{Bi}^m(d,t)$ and $^{208}\mathrm{Pb}(d,t)$ reveals that most of the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ transition strengths have been identified. The existence of a total of 20 states is predicted from coupling the ^{210}Bi 9^- state to the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, and $f_{7/2}$ neutron hole orbitals. Since experimentally only 25 levels are associated with these neutron hole transitions and because the transitions to these levels account for approximately 70% of the expected hole strength, the fragmentation of strength caused by the presence of the extra-core neutron and proton is not large.

It is of course clear from Table II that ~60% of the $f_{7/2}$ and ~30% of the $f_{5/2}$ neutron hole strengths have not been observed. Some fraction of the $f_{7/2}$ strength could lie above the 6.0 MeV excitation energy which was the upper limit of this experiment. The intrinsically weaker cross section for the $l=3$ vs $l=1$ strength could result in some misassignment of strength through the presence of unresolved transitions and the existence of single transitions with mixed l transfers. Within the limits of the present data, some $l=3$ strength could be present in some of the angular distributions identified as $l=1$ transitions and thus be unaccounted for. While such situations would affect the total $l=3$ strength, it would have little effect on the assignment of $l=1$ strength. Since the energy centroids lie quite close to the unperturbed values, it is probable that the loss of strength through mixed or unresolved transitions is small. Finally, the missing strength could well be an indication of the breakdown of the simple description of the levels of ^{209}Bi in terms of the $|^{210}\text{Bi}(9^-) \otimes l_j^{-1\nu}|$ configuration. In this instance, the transition strength would be distributed over many more transitions than the 6 for the $f_{5/2}$ and the 8 for the $f_{7/2}$ transfers expected on the basis of angular momentum coupling. Considering the 3.0 μg/cm^2 target thickness, it is possible that such weak transitions would not be observed above the background in the present spectra. Indeed, in the light of the great density of levels in ^{209}Bi above an excitation energy of 3.0 MeV,[34] it is surprising that the description of ^{209}Bi in terms of the coupling of a neutron hole to the 9$^-$ state of ^{210}Bi works as well as it does in explaining the results from our measurements.

Transitions involving transfer of an $i_{13/2}$ neutron are not seen in the present experiment. This is consistent with the relatively weak cross section observed for this transition in the ^{208}Pb(d,t) reaction[28] and with the prediction that this small transition strength should be distributed over a minimum of 14 states arising from the $|^{210}\text{Bi}(9^-) \otimes i_{13/2}^{-1\nu}|$ configuration.

Finally, the excitations of the 2.987, 3.154, and 3.212 MeV levels in the present measurement by transfer of a $p_{1/2}$ neutron are consistent with the spin assignments of $\frac{19}{2}^+$, $\frac{17}{2}^+$, and $\frac{17}{2}^+$, respectively, given in Refs. 3 and 4, and in disagreement with the assignments of Refs. 13–15 in which a weak-coupling model was assumed in the spin determination. Indeed, a comparison of the spectroscopic factors and energies predicted by the microscopic shell model with the experimental results for these three levels strongly supports the 2p-1h description of the levels in this energy region.

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[1]N. Stein, in *Proceedings of the International Conference on Properties of Nuclear States, Montreal, 1969,* edited by M. Harvey, R. Y. Cusson, J. S. Geiger, and J. M. Pearson (Presses de l'Universite de Montreal, Montreal, 1969), p. 337.
[2]J. S. Lilley and N. Stein, Phys. Rev. Lett. 19, 709 (1967); B. H. Wildenthal, B. M. Preedom, E. Newman, and M. R. Cates, *ibid.* 17, 960 (1967); R. Woods, P. D. Barnes, E. R. Flynn, and G. J. Igo, *ibid.* 19, 453 (1967); J. Bardwick and R. Tickle, Phys. Rev. 171, 1305 (1968); C. Ellegaard and P. Vedelsby, Phys. Lett. 26B, 155 (1968); C. Ellegaard, B. Patnaik, and P. D. Barnes, Phys. Rev. C 2, 2450 (1970).
[3]T. P. Cleary, N. Stein, and P. R. Maurenzig, Nucl. Phys. A232, 287 (1974).
[4]T. P. Cleary, N. Stein, W. D. Callender, D. A. Bromley, J. P. Coffin, and A. Gallmann, Nucl. Phys. A232, 311 (1974).
[5]P. D. Barnes, E. Romberg, C. Ellegaard, R. F. Casten, O. Hansen, T. J. Mulligan, R. A. Broglia, and R. Liotta, Nucl. Phys. A195, 146 (1972).
[6]J. C. Hafele and R. Woods, Phys. Lett. 23, 579 (1966).
[7]J. W. Hertel, D. G. Fleming, J. P. Schiffer, and H. E. Gove, Phys. Rev. Lett. 23, 488 (1969).
[8]R. A. Broglia, J. S. Lilley, R. Perazzo, and W. R. Phillips, Phys. Rev. C 1, 1508 (1970).
[9]J. P. Coffin, N. Stein, T. P. Cleary, C. H. King, and D. A. Bromley, Nucl. Phys. A181, 337 (1972).
[10]B. R. Mottelson, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, 1967,* edited by J. Sanada, J. Phys. Soc. Japan, Suppl. 24, 87 (1968).
[11]I. Hamamoto, Phys. Rep. 10, No. 2, 63 (1974).
[12]K. Arita and H. Horie, Nucl. Phys. A173, 97 (1971).
[13]G. Francillon, Y. Terrien, and G. Vallois, Phys. Lett. 33B, 216 (1970).
[14]J. Ungrin, R. M. Diamond, P. O. Tjøm, and B. Elbek, Mat. Fys. Medd. Dan. Vid. Selsk. 38, No. 1 (1971).
[15]W. T. Wagner, G. M. Crawley, and G. R. Hammerstein, Phys. Rev. C 11, 486 (1975).
[16]M. B. Lewis, C. D. Goodman, and D. C. Hensley, Phys. Rev. C 3, 2027 (1971).
[17]T. P. Cleary, W. D. Callender, N. Stein, C. H. King, D. A. Bromley, J. P. Coffin, and A. Gallmann, Phys. Rev. Lett. 28, 699 (1972).
[18]R. Leonard, R. L. Ponting, and R. K. Sheline, Nucl. Instrum. Methods 100, 459 (1972).
[19]Y. E. Kim and J. O. Rasmussen, Nucl. Phys. 47, 184 (1963).
[20]J. Vary and J. N. Ginocchio, Nucl. Phys. A166, 479 (1971).
[21]G. H. Herling and T. T. S. Kuo, Nucl. Phys. A181, 113 (1971).
[22]J. R. Erskine, W. W. Buechner, and H. A. Enge, Phys. Rev. 128, 720 (1962).

[23] J. J. Kolata and W. W. Daehnick, Phys. Rev. C 5, 568 (1972).
[24] C. H. Cline, W. P. Alford, H. E. Gove, and R. Tickle, Nucl. Phys. A186, 273 (1972).
[25] H. T. Motz, E. T. Jurney, E. B. Shera, and R. K. Sheline, Phys. Rev. Lett. 26, 854 (1971).
[26] T. R. Canada, R. A. Eisenstein, C. Ellegaard, P. D. Barnes, and J. Miller, Nucl. Phys. A205, 145 (1972).
[27] D. Proetel, F. Riess, E. Grosse, R. Ley, M. R. Maier, and P. von Brentano, Phys. Rev. C 7, 2137 (1973).
[28] R. A. Moyer, B. L. Cohen, and R. C. Diehl, Phys. Rev. C 2, 1898 (1970).
[29] D. G. Kovar, C. K. Bockelman, W. D. Callender, L. J. McVay, C. F. Maguire, and W. D. Metz, Wright Nuclear Structure Laboratory Internal Report No. 49, 1970 (unpublished).
[30] G. Muehllehner, A. S. Poltorak, W. C. Parkinson, and R. H. Bassel, Phys. Rev. 159, 1039 (1967).
[31] P. D. Kunz, computer code DWUCK, University of Colorado, 1969 (unpublished).
[32] V. Gillet, A. M. Green, and E. A. Sanderson, Nucl. Phys. 88, 321 (1966).
[33] J. R. Beene, O. Häusser, T. K. Alexander, and A. B. McDonald, Phys. Rev. C 17, 1359 (1978).
[34] M. J. Martin, Nucl. Data Sheets 22, 545 (1977).