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Direct population of $j_p + j_n = J_{max}$ two-particle states in $^{206,208,210}Bi$†

W. W. Daehnick, M. J. Spisak, R. M. DelVecchio, and W. Oelert
Nuclear Physics Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania 15260
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Closely related high spin states in ^{206}Bi, ^{208}Bi, and ^{210}Bi are preferentially excited in the $^{204,206,208}Pb(\alpha,d)$ reaction at 48 MeV. The character of these states can be understood from the selectivity of the (α,d) transfer mechanism and experimental systematics. Microscopic distorted-wave Born approximation predictions are consistent with new J^π assignments for 14 strongly excited states with $9 \leq J \leq 14$. The accuracy of standard distorted-wave Born approximation predictions for $Pb(\alpha,d)$ at 48 MeV changes systematically with increasing L transfer from good ($L \leq 5$) to poor ($L \geq 11$). This shortcoming is not overcome by full finite range calculations. The strong population of 10^-, 11^+, 12^+, and 14^- states involves the largest L transfers in direct reactions observed to date.

[NUCLEAR REACTIONS $^{204,206,208}Pb(\alpha, d)$, E_α=48 MeV, measured $\sigma(E_d, \theta)$, resolution 25 keV. DWBA analysis, deduced l, π, J of J_{max} states.]

I. INTRODUCTION

The $^{204,206,208}Pb(\alpha, d)$ reactions lead to low-lying states in the $^{206,208,210}Bi$ isotopes which differ considerably in Q value and structure.[1-3] Hence it is noteworthy to observe a pattern of *higher*-lying states in these isotopes that bear a striking resemblance to each other. We wish to point out this unexpectedly close similarity (see Fig. 1), and propose to use it as the basis for understanding the nature of some special, presumably simple, higher-lying states in ^{206}Bi, ^{208}Bi, and ^{210}Bi. For the Q values of interest little is known about ^{206}Bi and ^{208}Bi. However, a number of ^{210}Bi states are known from (d,p) reactions. They are well described by shell model calculations in terms of relatively pure two-particle configurations.[1,4-6] All low-lying ^{210}Bi $p+n$ multiplets are of considerable interest for the study of n-p residual interactions; however, states where the proton or proton *and* neutron are in excited orbits are difficult to observe and have remained largely unknown. The experiment reported here should add considerably to the knowledge of such configurations.

Our interpretation of the $Pb(\alpha, d)Bi$ experiments will use the known selectivity of direct (α, d) transfer reactions, particularly the preferential excitation of high spin and $j_p+j_n=J_{max}$ states for energetic α projectiles.[7] Hence we should recall that the lowest three open Bi proton orbits—$1h_{9/2}$, $2f_{7/2}$, and $1i_{13/2}$—and the lowest three unfilled neutron orbits—$2g_{9/2}$, $1i_{11/2}$, and $1j_{15/2}$—have the highest single-particle spins of the major shell beginning with $^{208}_{82}Pb_{126}$. The centroids of the nine resulting $p+n$ multiplets are predicted to lie below 3 MeV excitation in ^{210}Bi; and the maximum spins for these multiplets, J_{max}, range from $J=8$ to 14. For the $Pb(\alpha, d)Bi$ reaction at $E_\alpha \approx 48$ MeV one-step transfers of $6 \leq L \leq 10$ are dynamically favored. $j_p+j_n=J_{max}$ selectivity is further enhanced by coupling rules for two-particle transfer reactions.[8] This has been shown convincingly for j^2 configurations with p and n in the same shell.[7] The enhancement is particularly strong (>5) for $\sigma(J_{max})$ compared to $\sigma(J_{max}-1)$. Detailed microscopic distorted-wave Born approximation (DWBA) $^{208}Pb(\alpha, d)$ calculations[9,10] predict that even favorable transitions with $L<6$ should be much weaker than the strongly excited J_{max} states, and that within each of the nine multiplets of interest the J_{max} state (even the 14^- state) should be dominant over all other members by at least a factor of 3.

II. EXPERIMENTAL RESULTS

In spite of the predicted selectivity of the experiment, good resolution remains a prime requirement in any study of the odd-odd Bi isotopes. Self-supporting $^{204,206,208}Pb$ targets of 100–300 $\mu g/cm^2$ thickness and isotopic purity in excess of 99% were used. In all runs reaction products were detected in the focal plane of a high resolution quadrupole-dipole-dipole-dipole (QDDD) spectrograph. A 60 cm position-sensitive proportional counter was used in a two-dimensional, computer-aided mode, which afforded excellent particle-type separation.[11] A 48 MeV α beam from the Princeton cyclotron produced the data reported here. Characteristic $^{206,208,210}Bi$ spectra obtained are shown in Fig. 1. Experimental resolution was 25 keV. Angular distributions were taken over the range $10° \leq \theta_{lab} \leq 40°$ in 5° steps. Each angle required three mag-

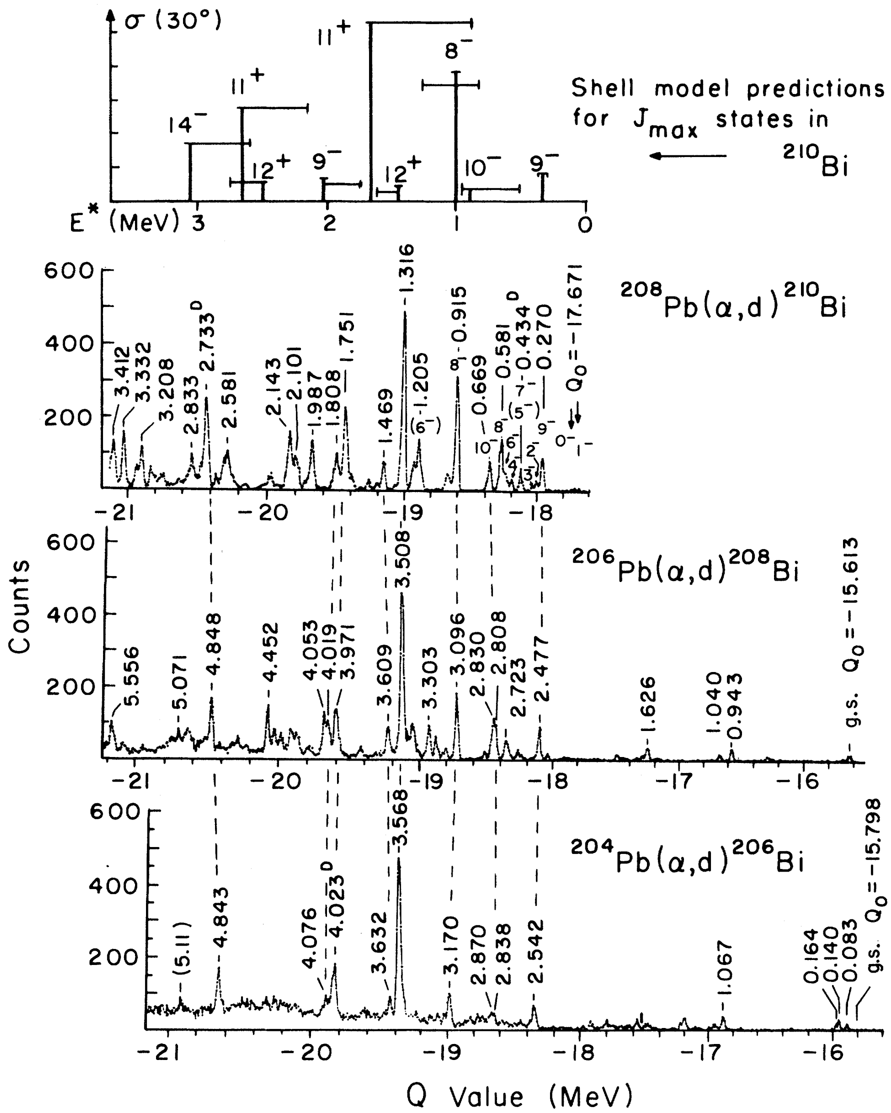

FIG. 1. Comparison of $^{204,206,208}Pb(\alpha, d)^{206,208,210}Bi$ spectra for $\theta_{lab} \approx 30°$ taken at $E_\alpha = 48.2$ MeV with a QDDD spectrograph. Note the correlation of many strong ^{210}Bi two-particle states to states at nearly identical Q values in the lighter Bi isotopes. [These spectra differ from our typical raw data in that for $\theta = 30°$ increased run time led to better statistics at slightly inferior resolution. A properly normalized sum of 25° and 35° spectra was substituted for regions near $Q = -18$ and -19.8 MeV which at 30° were obscured by broad $^{12}C(\alpha, d)$ and $^{16}O(\alpha, d)$ impurity peaks.] Excitation energies are given in MeV. Microscopic zero-range DWBA predictions for $j_p + j_n = J_{max}$ states and wave functions of Ref. 1 are shown to scale at the top of Fig. 1. Horizontal bars indicate ranges in E^* predictions in Refs. 1–3.

netic field settings for the QDDD to cover the range $-21 \le Q \le -15.5$ MeV with reasonable spectrum overlaps. Excitation energies listed for resolved states are uncertain to ±0.2%. Cross section uncertainties are primarily due to errors in separating poorly resolved levels. Absolute scale errors are below 20%.

The strongest peaks in the three Bi isotopes show remarkably consistent behavior. The dominant peak in all three spectra lies at $Q = -19.2 \pm 0.2$ MeV. When the peaks are lined up as in Fig. 1, other correspondences become clear. The known J_{max} states in ^{210}Bi at 0.270 MeV (9^-), 0.669 MeV (10^-), and 0.915 MeV (8^-) (Refs. 4–6) have counterparts in ^{208}Bi and ^{206}Bi separated from the dominant peak by very similar energy intervals. This was previously noted in experiments at lower energies.[12,13] In fact, in ^{206}Bi only these "J_{max}" states stand out significantly over hundreds of weak and unresolved levels per MeV expected at

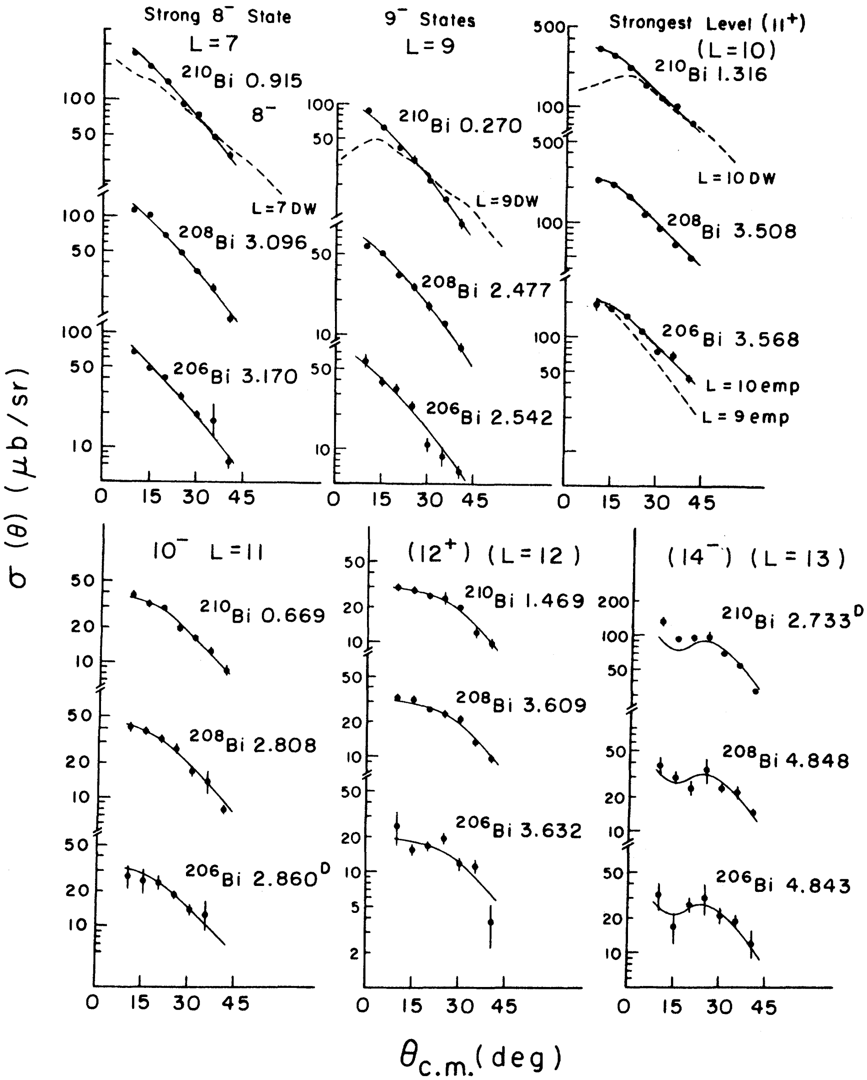

FIG. 2. Comparison of six sets of ^{208}Pb(α, d)^{210}Bi, ^{206}Pb(α, d)^{208}Bi, and ^{204}Pb(α, d)^{206}Bi transitions which show a very simple correlation in reaction Q value and cross section. Excitation energies marked by D refer to peaks for which the contribution of a second not fully resolved level was appreciable. Comments and L assignments refer to the dominant level only. Empirical shapes (solid lines) do not differentiate between L =7 and 9 and between L =10 and 11 for the angular range observed, but L =9, 10, 12, and 13 shapes are easily distinguished. Finite range DWBA curves (dotted) are shown for a few known transitions.

3 MeV excitation. In addition, the angular distributions of the states which are correlated in Fig. 1 have remarkably similar shapes, as evidenced in Fig. 2. We use these observations to argue that the higher-lying strong states in ^{206}Bi at E^* = 3.568, 3.632, 4.023^D, 4.076, and 4.843 MeV must be the very states that should be preferentially excited in this (α, d) experiment because of their (core + n + p) and high-spin (J > 5) nature. (D indicates poorly resolved doublets.) Their survival in ^{206}Bi as states with strengths comparable to those in ^{210}Bi indicates that they are high-spin J_{max} states for which there are still very few core-excited states in ^{206}Bi with which they can mix.

III. DWBA CALCULATION AND CONCLUSIONS

Finite range DWBA predictions as well as experimental results indicate that angular distribution shapes for Pb(α, d) at 48 MeV change systematically with angular momentum transfer L and very slowly with target mass and excitation energy. Good *correspondence* of observed and predicted cross sections for J_{max} states was found (see top of Fig. 1), particularly at the larger angles and with respect to the total (integrated) cross sections. However, details of $\sigma(\theta)$ are not well reproduced. A large number of calculations was performed in order to investigate effects of configuration mixing (negligible), full finite range treatment, and DWBA dependence on optical model parameters. Figure 3 shows a comparison of empirical cross sections for ^{208}Pb(α, d) with DWBA curves. The j_p, j_n configurations and Q values were chosen to match the most probable assignments for the empirical curves shown on the left of Fig. 3. It is seen that, for (α, d), improvements obtained with finite range fall short of bridging the gap between DWBA and experiment. Optical model parameters used are shown in Table I. The effect of small variations in the optical parameters was negligible; however, a switch to a shallower α parameter family ($110 < V_0 < 150$ MeV, at $E_a = 48$ MeV) as favored in high energy elastic scattering[14] resulted in DWBA curves that had no resemblance to the data.[15] (The deep Maryland α potentials[14] produced DWBA curves very similar to those shown in Fig. 3.) It is likely that higher order transfer processes have to be computed before a detailed numerical comparison of DWBA theory and experiment becomes meaningful.[16] At this time it seems safer to base our arguments on empirical systematics and predictions of shell model calculations.[1] The use of the wave functions of Ref. 2, which gives almost pure configurations for J_{max} states, would not visibly alter the predicted intensities shown at the top of Fig. 1. Reference 3 predicts significantly more mixing, particularly for the 11^+ states, but not for the 8^- states where the need is most apparent experimentally. The predicted J_{max} energies scatter by 150 to 300 keV.[1-3]

In suggesting the assignments of Table II we use the following arguments which we believe are justified by the strong direct population of these levels: (a) Correlated $[j_p, j_n]_{J_{max}}$ states must have identical angular distributions. (b) Correlated states have nearly identical (α, d) Q values which vary only little and systematically from ^{210}Bi to ^{208}Bi and ^{206}Bi. (c) The absolute differential cross sections for correlated states must not change strongly from isotope to isotope. Any significant change must be a decrease in σ_{tot} as we move away from ^{210}Bi because of the increasing likelihood of mixing with core excited states. (d) If conditions a, b, and c are fulfilled we expect that states strongly excited in all three isotopes are closely related, i.e., they are simple, fairly pure two-particle states in ^{210}Bi, two-particle–two-hole states in ^{208}Bi, and two-particle–four-hole states in ^{206}Bi.

Comparison with theoretical predictions[1,2] (top of Fig. 1) would suggest 11^+ for the 3.568 MeV

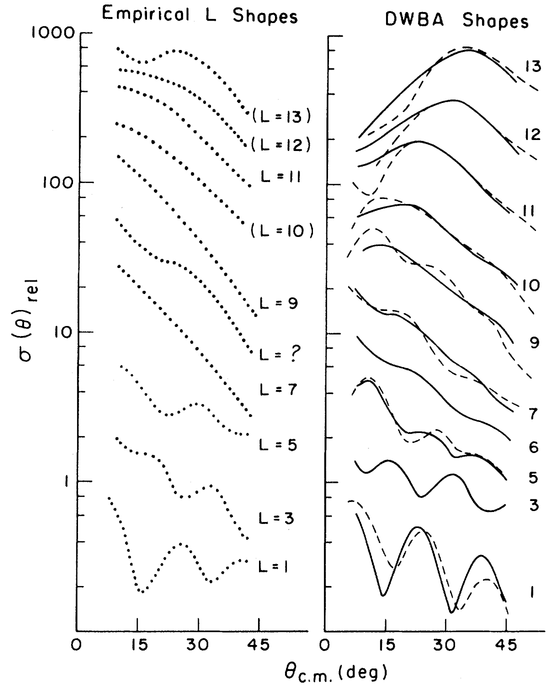

FIG. 3. Comparison of empirical cross sections for ^{208}Pb(α, d) with DWBA curves. Solid lines refer to full finite range (α, d) transfer calculations (Ref. 10); dashed lines are the corresponding microscope zero-range calculations (Ref. 9).

TABLE I. Optical model parameters used for the DWBA calculations shown.

	V (MeV)	r_0 (fm)	a (fm)	$4W_D$ (MeV)	W_v (MeV)	r_I (fm)	a_I (fm)	V_{so}
α + Pb [a]	182.8	1.20	0.75	0	24.2	1.40	0.60	
d + Pb [b]	89.35	1.20	0.75	54.0	0.552	1.31	0.89	
Bound p	c	1.25	0.75					$\lambda = 25$
Bound n	c	1.25	0.75					$\lambda = 25$

[a] ZR calculations use the nonlocality correction parameter $\beta_\alpha = 0.2$
[b] ZR calculations use the nonlocality correction parameter $\beta_d = 0.54$.
[c] Well depth adjusted by code to fit nucleon separation energy.

TABLE II. Correlated states in ^{206}Bi, ^{208}Bi, and ^{210}Bi. (Energies and Q values are given in MeV. D indicates poorly resolved doublets.)

Known or suggested dominant p-n configuration p	n	L	J^π	^{210}Bi Q	E^*	^{208}Bi Q	E^*	^{206}Bi Q	E^*
$h_{9/2}$	$g_{9/2}$	9	9^-	−17.941	0.270	−18.090	2.477	−18.340	2.542
$h_{9/2}$	$i_{11/2}$	11	10^-	−18.340	0.669	−18.42	2.81^D	−18.66	(2.86^D)
$f_{7/2}$	$g_{9/2}$	7	8^-	−18.586	0.915	−18.709	3.096	−18.968	3.170
$(i_{13/2}$	$g_{9/2})$	10	11^+	−18.987	1.316	−19.121	3.508	−19.366	3.568
$(h_{9/2}$	$j_{15/2})$	(12)	(12^+)	−19.140	1.469	−19.222	3.609	−19.430	3.632
$(i_{13/2}$	$j_{15/2})$	(13)	(14^-)	−20.404	2.733^D	−20.461	4.848	−20.641	4.843

level in ^{206}Bi, 12^+ for the 3.632 MeV level, and 14^- for the state at 4.843 MeV, and similarly for their correspondents in ^{208}Bi and ^{210}Bi. Substantial support for such assignments is obtained from the differential cross section systematics shown in Fig. 2. Empirical $L=7$, 9, and 11 angular distributions are taken from the known 8^-, 9^-, and 10^- states in ^{210}Bi. Proposed $L=10$, 12, and 13 empirical distributions fit easily into the empirical and DWBA systematics (decreasing slope for increasing L transfer).

Six of the nine J_{max} states searched for are listed in Table II. The location of the three remaining J_{max} levels is still uncertain. The $(f_{7/2}i_{11/2})_{9^-}$ and $(i_{13/2}i_{11/2})_{12^+}$ levels are expected to be two of the weaker J_{max} levels at fairly high excitation, and are probably to be found among the strong levels with $2.3 \le E^* \le 1.7$ MeV in ^{210}Bi. Unfortunately, their correspondents in ^{206}Bi are not adequately resolved. Our failure to identify the higher lying strong $(f_{7/2}j_{15/2})_{11^+}$ state may be related to the *enhancement* of the 1.316 MeV 11^+ state.[17] There are four two-particle type 11^+ states between 1.3 and 2.8 MeV excitation in ^{210}Bi and the levels may not be as pure as predicted in Ref. 1. A similar shell model failure, to correctly predict the $(f_{7/2}g_{9/2})$ admixture in the lowest 8^- state (0.581 MeV), has been well documented. ^{209}Bi(d,p) studies[4,5] have measured an 18% $(h_{9/2}g_{9/2})_{8^-}$ admixture in the 0.915 MeV $(f_{7/2}g_{9/2})_{8^-}$ state. Reference 3 predicts a 3% admixture, whereas Refs. 1 and 2 predict only a 1% admixture. On the basis of the ^{209}Bi(d,p) spectroscopic factors (which determine only some of the admixtures) the ratio $R=\sigma(0.915/\sigma(0.581)$ for ^{208}Pb(α,d) should be $R=4 \to 5$, compared to $R_{th}=20$ for the wave functions of Ref. 1. The ratio actually seen is $R=2$. It is difficult to say at this time to what extent higher order processes in the (α,d) reaction are responsible for the remaining discrepancy.

In conclusion we wish to emphasize the most interesting results of this experiment: $j_p+j_n=J_{max}$ states are the most strongly excited states in Pb(α,d)Bi at 48 MeV, even though n and p occupy different major shells. More remarkably, these two-particle + core states seem to survive with little change in structure and Q value in ^{208}Bi and ^{206}Bi, where they occur at excitations of 2.5 to 5 MeV. Assuming our suggested J^π assignments for the 11^+, 12^+, and 14^- states are correct, we see the largest L transfers in direct transfer reactions reported to date— some with cross sections that are large for two-nucleon transfers.

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