Levels and transitions in ^{204}Pb and the four valence neutron-hole configurations

J. M. Hanly, S. E. Hicks, and M. T. McEllistrem
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506

S. W. Yates
Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506
(Received 13 November 1987)

Levels of the nucleus ^{204}Pb have been investigated using the (n,n'γ) reaction, and γ rays from low-spin excited levels have been observed. Forty-three low-spin levels connected by 78 γ rays are found below 2.9 MeV, whereas only about 28 levels had previously been known. The levels below 2 MeV excitation energy are expected to be dominated by the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ valence neutron hole excitations, and 0^+ levels at 0, 1730, and 2433.1 keV are associated primarily with these configurations. These states are at almost the same excitation energies as parent 0^+ excitations in ^{206}Pb. Approximately six unnatural-parity levels are identified; this is close to the number predicted in six orbit valence-space shell model calculations. The number of natural-parity levels found, however, is almost twice that calculated with the shell model. Levels and transitions below 2 MeV excitation energy are consistent with expectations basing ^{204}Pb states on correlated two-hole excitations dominant in ^{206}Pb.

I. INTRODUCTION

Neutron scattering from ^{204}Pb is being studied as part of a larger study of the evolution of collective strengths in scattering as one proceeds from doubly magic ^{208}Pb toward the collective nuclei of the Os-Pt region. Since collective excitation effects in neutron scattering from the Os-Pt nuclei are clear and striking,[1,2] it seemed feasible to observe the expected weaker collective effects in scattering to the heavy Pb nuclei just below ^{208}Pb. To gain the maximum insight into the origin of the anticipated weak collective effects, it is important to have as much knowledge as possible about the character of the nuclear levels in ^{204}Pb and ^{206}Pb. The present study reports on an (n,n'γ) study of the levels of ^{204}Pb.

The levels of ^{206}Pb, particularly the natural-parity levels, are generally well characterized experimentally[3] up to an excitation energy of about 2.5 MeV. Most of these known levels are well represented in the several extant shell model calculations based on two valence neutron-holes occupying states in the six active neutron orbits[4,5] just below the neutron number $N=126$. Knowledge of level and decay schemes for ^{204}Pb, in contrast, are quite meager. It was the purpose of this project to make a substantial increase in the knowledge of the levels and γ-ray decays in ^{204}Pb. An additional and major reason for measuring the (n,n'γ) production cross sections is to infer from them the inelastic neutron scattering (INS) cross sections. These cross sections serve both as a test of those measured in separate, ongoing neutron detection experiments[6] and, more importantly, to resolve contributions for the many closely spaced levels which cannot be separated in the neutron detection experiments. Energy spreads in neutron detection experiments are typically about 40–60 keV, while with γ-ray detection an energy spread of about 2 keV was achieved.

An important aspect of these structure studies for our purposes is that the degree of collectivity shown, for example, by neutron scattering to levels of these Pb nuclei would be just that of the coherence between the valence neutron configurations; the collectivity of ^{204}Pb would be closely related to that of ^{206}Pb.

A. Background knowledge from previous studies

Levels of ^{204}Pb have been studied extensively in a series of (p,t) experiments at different incident energies; the most detailed of these was the study of Lanford.[7] Later studies, particularly that of Takahashi *et al.*,[8] added to the knowledge of natural-parity states and, particularly, the relationship between ^{204}Pb and ^{206}Pb levels. The experimental information about ^{204}Pb levels was summarized and interpreted in an extensive set of shell model calculations by Liotta and Pomar.[9] The main result of these calculations was that most of the then known levels of ^{204}Pb could be represented through their parentage in terms of the two-hole states of ^{206}Pb. This neutron-hole pair basis for ^{204}Pb was first advanced by Ko *et al.*[5] in a modest basis, weak coupling form of the shell model; Liotta and Pomar developed a much more complete shell model calculation using ^{206}Pb excitations as basis states and provided a level scheme quite similar to that known from the several experiments cited. The various shell model calculations, including another extensive six-orbit calculation by McGrory and Kuo,[10] all yielded about 22 or 23 natural-parity levels below 2.9 MeV excitation energy. Liotta and Pomar[9] concluded that the model spectrum they produced was essentially complete; that is, nearly all levels known at that time were within their model space. They also calculated the two-nucleon spectroscopic factors as determined in the (p,t) studies with ^{206}Pb targets.

One prior study of the ^{204}Pb(n,n$'\gamma$) reactions was performed[11] to search for levels not excited in the (p,t) studies.[7,8,12] Five new levels were found below 2.5 MeV. [But one of those, reported at 2276 keV, cannot be confirmed in the present (n,n$'\gamma$) study. We find a new level at 2269 keV, which could possibly be the one they found at 2276 keV, except for the large energy discrepancy.] Since Dawson *et al.*[11] used a very small scattering sample in a geometry which does not well separate backgrounds from the neutron source, their sensitivity only permitted them to see about 20 levels below 2.5 MeV excitation energy. Some of the five newly found levels were proposed as unnatural-parity levels, since they had not been seen in (p,t) two-neutron transfer reactions. Statistical uncertainties precluded definite spin assignments in the earlier (n,n$'\gamma$) study, however. The six-orbit shell model calculations of McGrory and Kuo[10] had included unnatural-parity states as well as natural-parity ones; their calculated spectrum was presented in the (n,n$'\gamma$) study.[11] Against this background of experiments and calculations, Liotta and Pomar, in their shell model study,[9] could report that their calculated spectrum for ^{204}Pb included all known levels below 2.9 MeV excitation energy; the projected unnatural-parity levels of Ref. 11 had not actually been assigned, and thus they were ignored by Liotta and Pomar. The comparison of measured levels and shell model calculations for ^{204}Pb seemed quite satisfactory, except that little experimental information existed to test predictions of the unnatural-parity levels.

Experiments completed prior to the present study, then, led to the conclusions that about 22 or 23 natural-parity levels existed in ^{204}Pb up to an excitation energy of 2.9 MeV, with perhaps also a few unnatural-parity levels. The natural-parity level energies could be interpreted rather well in calculations based on neutron-hole excitations in which those pairs corresponding to ^{206}Pb levels provided a good expansion basis for the four valence nucleon states of ^{204}Pb. These pair excitation models arose naturally because the two-neutron transfer experiments had given detailed spectroscopic factors for levels of both Pb isotopes. The spectroscopic factors were well described in the shell model. Rather little information had been extracted from γ-ray decays, either in support of these pictures for the Pb isotopes or in opposition to them.

B. Review of results from the present (n,n$'\gamma$) experiment

Completion of the present (n,n$'\gamma$) study results in substantial additions to the level and decay schemes previously known for this nucleus and alters our notions about the completeness of models which find ^{204}Pb levels to be associated with the subset of ^{206}Pb excitations as basis states.

We now find 43 low-spin levels, with $J<6$, below 2.9 MeV excitation energy, rather than the previously known 23 levels, and have tentatively identified ten unnatural-parity levels below 2.5 MeV. The total number of known levels,[13] including those with $J\leq 9$, had been 34. Excluding the odd-parity levels with $J\geq 6$, which arise from $i_{13/2}$ neutron-hole admixtures, ten unnatural-parity levels are found below 2.5 MeV and about 30 natural-parity, low-spin levels are observed. The number of unnatural-parity levels is just about the number projected in the six-orbit shell model calculations[10] of McGrory and Kuo. The number of natural-parity levels, however, is much larger than previously known or calculated in any of the shell model calculations. Many of these levels must be outside the valence neutron hole space used in these calculations.

Most of the new or newly assigned levels in the present experiment, in which twenty-one new levels are reported and thirteen new definite spin and parity assignments are made, are for levels above 2 MeV excitation energy. Thus the picture advanced earlier by Ko *et al.*[5] and expanded upon so thoroughly by Liotta and Pomar[9] may apply well to most of the natural-parity levels below 2 MeV excitation energy, in spite of the expanded number of levels now known. In fact, by examining γ-ray decays, we find the excitations of ^{204}Pb are almost as simply related to parent configurations in ^{206}Pb as earlier proposed, if attention is restricted to natural-parity levels below 2 MeV. The few changes we have found for levels at very low excitation energy may imply that the levels of ^{204}Pb are to be treated with even simpler configurations than those advanced in the cited shell model calculations.

II. EXPERIMENTAL METHODS

An extensive program of measurements of γ-ray production cross sections, angular distributions of γ rays, and inference of level and decay schemes has been developed in this laboratory. The methods have been described in several previous publications,[14–16] some of which provide more detailed descriptions of physical arrangements and procedures. The γ rays from levels excited in INS were detected in a large, high-purity Ge detector, with a detection efficiency of 20%, according to standard definition, and an energy resolution of 1.9 keV at 1332 keV. The Ge detector was mounted in closed geometry shielding on a rotatable carriage to permit detection at angles from 30° to 155°. The detector shield and collimator consist of a 1100 kg copper collimator followed by a large, borated polyethylene shield which actually houses the Ge detector. The massive shield and collimator have the consequence that the detector must be more than 1 m from the scattering sample, and detection was limited to the angular range indicated. A pulsed neutron flux, with a burst width of 6 ns and 2 MHz repetition rate, was produced by a pulsed proton beam entering a ^{3}H gas cell (T cell), and neutrons were produced via the ^{3}H(p,n)^{3}He reaction. The scattering sample was a 93-g cylindrical metal sample, 1.6 cm in diameter by 4.2 cm in length, enriched to 71.4% in ^{204}Pb. It was mounted 6.5 cm from the end of the 3.1-cm long T cell, with its axis perpendicular to the scattering plane.

Time-of-flight (TOF) spectra of radiation detected in the Ge detector were obtained by timing events with respect to the beam pulses. Time gating enabled separation of prompt γ rays from INS from events caused by neutrons scattering in the Ge detector or surrounding materials, and from time-uncorrelated events. Methods, procedures, and many spectra illustrating these are detailed in a separate report.[6] The very clean energy spectra obtained allowed us to find transitions from weakly excited levels. A small portion of an energy spectrum from the ^{204}Pb sample is shown in the top panel of Fig. 1.

Shown also in Fig. 1 is a spectrum of γ rays produced in scattering from a radiolead sample of about the same dimensions as the ^{204}Pb sample. Radiolead is enriched to 88% in ^{206}Pb; the compositions of both scattering samples are given in Table I. The spectra of these samples permitted easy identification of ^{206,207}Pb γ rays in the ^{204}Pb sample spectra, and thus clean identification of ^{204}Pb transitions. Sample-out spectra were also taken to identify all background transitions not associated with any sample. The primary difference between this and the earlier (n,n$'\gamma$) experiment[11] was that by settling for a lower isotopic enrichment in our scattering sample, 71.4% vs their 99.7%, we were able to work with a sample having 10 times the mass. Since we had the radiolead sample data to aid with isotopic identifications, the lower enrichment was not a serious impediment to obtaining accurate knowledge of transitions and cross sections.

Data-taking procedures were designed to produce information to probe two classes of questions about ^{204}Pb structure. γ-ray yields were acquired both as a function of incident neutron energy at fixed γ-ray angle, and, separately, as a function of detection angle at fixed incident neutron energy. Neutron energy dependence excitation functions were measured by accumulating spectra similar to that of Fig. 1 at a detection angle of 125° and for incident neutron energies from 1.4 to 3.0 MeV. The angle 125° was chosen because the incident neutron energy dependence of yields at that angle approximate best that of the angle-integrated production cross sections. These excitation functions enabled us to determine γ-ray thresholds, and thus to place γ rays confidently in the level scheme. They also allowed us to obtain accurate production cross sections, from which neutron scattering cross sections could be inferred.

TABLE I. Sample assays.

	Percent of sample			
Sample	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb
^{204}Pb	71.4	12.5	6.3	9.8
^{206}Pb	0.0	88.6	8.5	2.9

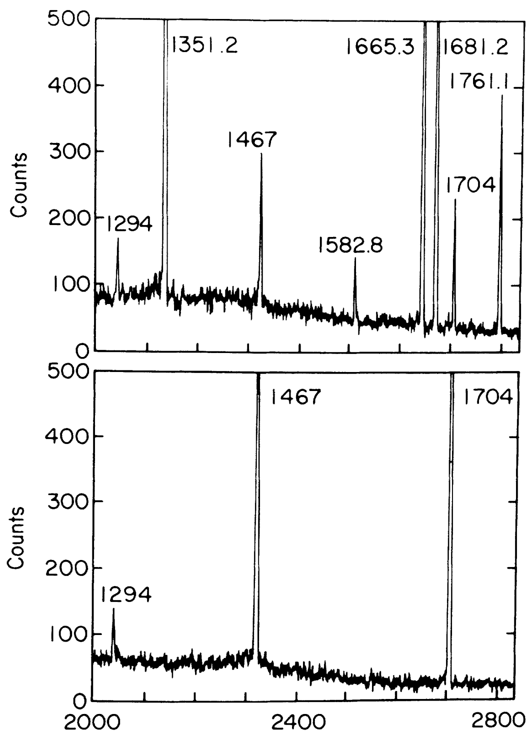

FIG. 1. Energy spectra from the enriched ^{204}Pb sample and radiolead sample are shown in the upper and lower panels, respectively; only a small energy region is shown. Both spectra were measured at a scattering angle of 125° and an incident neutron energy of 2 MeV. A background peak at 1294 keV, and two ^{206}Pb peaks, 1467 and 1704 keV, are easily identified by the corresponding peaks in the radiolead spectrum. The 1582.8-keV ground state decay is also evident in the ^{204}Pb spectrum.

The yields measured as a function of angle at fixed incident energy, i.e., the angular distributions, provided valuable information for deducing the angular momentum transferred in a transition and often enabled us to make unique spin and spin-parity determinations. Angular distributions were measured at two incident neutron energies, 2 and 3 MeV. Spectra were also taken at several incident neutron energies from a ^{nat}Fe sample, so that the results of the Pb samples could be normalized to the well known[17,18] γ-ray production cross sections for the 847-keV γ ray of ^{56}Fe.

The γ-ray yields had to be corrected for detection geometry, for neutron multiple scattering in the sample, and for γ-ray attenuation in the sample. These corrections and uncertainties in them have been well described previously.[14]

III. RESULTS

We are able to report levels at 1712, 1948, 2202, 2304, and 2316 keV, along with 16 levels above 2.4 MeV for the first time, together with a serious question about whether we find a new level near 1582.8 keV. The thresholds for exciting these levels are determined with an energy uncertainty of ±30 keV for strong transitions, but less accurately for weak lines. Even for weak lines, however, thresholds were not more uncertain than ±60 keV. Since most transitions are to the sparsely distributed levels below 2 MeV excitation energy, and most levels have multiple decay paths, the thresholds and transition energies are quite adequate to fix the decay scheme with complete confidence. The transition energies are measured to within ±0.1 keV, and, with thresholds, determine level energies to within an uncertainty of ±0.2 keV. Typical 125° excitation functions are shown in Figs. 2 and 3. The level and decay schemes based on these excitation functions are presented in Figs. 4 and 5, which show all known low-spin levels below 2.9 MeV. We find thus 43 levels below the indicated energy; this means that the various shell model[9,10] level schemes, which provide

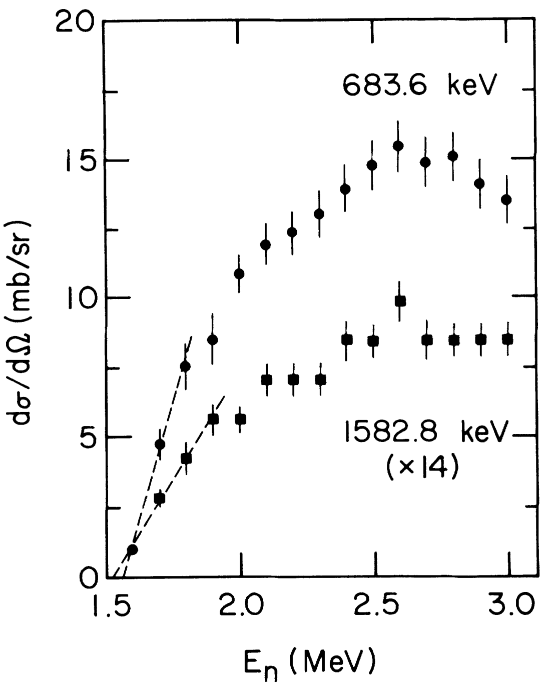

FIG. 2. The excitation function of two γ rays decaying from the 2^+ level of ^{204}Pb at 1582.8 keV. The 683.6-keV γ ray is given in mb/sr, while the scale for the comparatively weak 1582.8-keV ground state transition has been multiplied by 14.

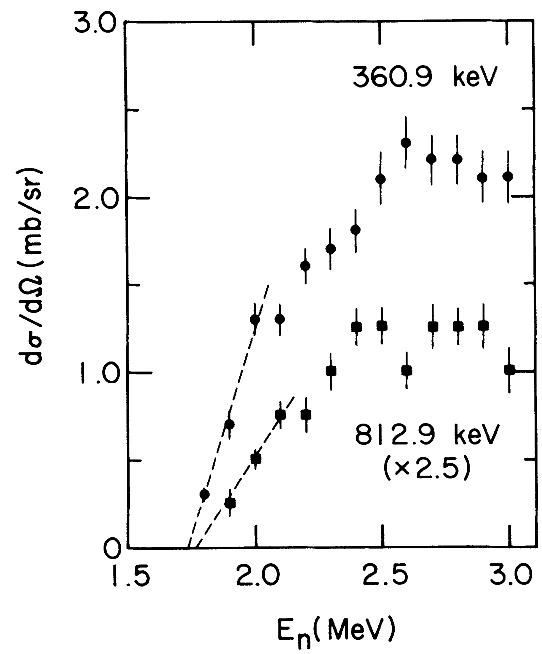

FIG. 3. The excitation function of two γ rays decaying from the 1712.3-keV level of ^{204}Pb. The 361.1-keV transition is given in mb/sr, while the magnitude of the 813.1-keV transition has been multiplied by 2.5. The threshold is clearly above 1.7 MeV.

22–23 natural parity levels below 2.9 MeV excitation energy, are far from complete.

Angular distributions of γ rays are least-squares-fitted to an expansion of the form

$$W(\theta)=A_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)] ,$$

where the P_j's are Legendre polynomials. These angular distributions may then be analyzed using statistical model calculations to calculate the excited-state alignments produced in INS. The alignments and the spins of the initial and final states of the subsequent γ-ray transitions, together with the multipole order of the γ-ray transitions,[19,20] determine the angular distributions. It has been known for many years that excited-state alignments produced in scattering are quite insensitive to scattering mechanisms and, further, that statistical model distributions dominate at low neutron energies.[18,20] Thus the multipole mixing ratios are determined accurately, even though undetermined competition may exist between different scattering mechanisms. In practice, the only mixed γ-ray transitions are those for $M1$ and $E2$ amplitudes. The mixing ratio, δ, is defined as: $\delta\equiv\langle E2\rangle/\langle M1\rangle$. The a_2 and a_4 coefficients from the least squares fit, the mixing ratios, and the γ-ray branching ratios are listed in Table II with the γ-ray transition energies and the levels from which the transitions originate. The γ-ray angular distributions are often powerful tools for providing unique spin assignments, as well as fixing multipole mixing ratios. Where the γ-ray angular distributions have been used to make particular spin assignments, or where they can be used to determine unique values for mixing ratios, the angular distributions are shown. For other cases, the distributions are represented by their expansion coefficients in Table II.

A. 0^+ excitations

There are, as noted in the Introduction, six valence orbits usually included in shell model calculations.[9,10] Three of these, the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ configurations, are nearest the Fermi surface and dominate the low-lying levels. Thus we should expect three 0^+ levels at low excitation energies, with substantial two-nucleon transfer strengths in (p,t) reactions. Three such 0^+ levels are known in ^{206}Pb, at 0, 1167, and 2314 keV, and corresponding levels are to be expected in ^{204}Pb. Several experiments[7,8,21] have indicated that there are three 0^+ levels in ^{204}Pb at excitation energies below 1.8 MeV, with substantially lower level spacings than in ^{206}Pb.

The natural-parity structure of ^{204}Pb for excitation energies below 2 MeV is well described in a shell model space in which the states of ^{206}Pb are used as basis states. Moreover, the overlap between single ^{204}Pb and low-lying ^{206}Pb states is very strong.[9] Thus we would expect strong similarities between levels and decay patterns in the two nuclei. The compressed spectrum of three 0^+ levels in ^{204}Pb below 1.8 MeV seems supported by some shell model calculations.[5,10] Experimentally, the three 0^+ levels had been reported[13] at 0, 1582.7, and 1730 keV. The 0^+ assignment for a level near 1583 keV had originally been made[21] through observation of a conversion electron line

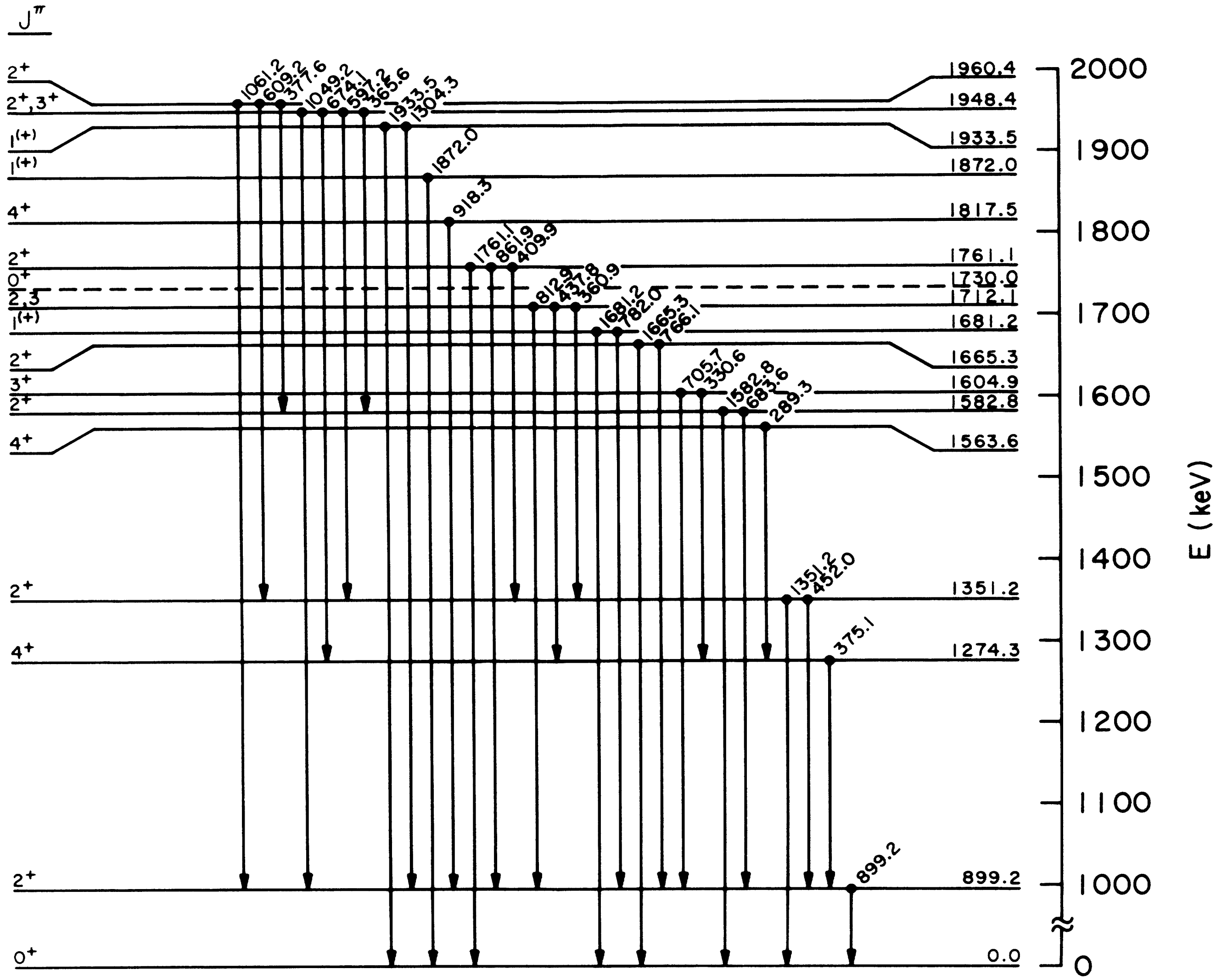

FIG. 4. Low lying level diagram for ^{204}Pb deduced from ^{204}Pb(n,n'γ) up to 2 MeV excitation energy. Level and γ-ray energies are in keV and tentative spin assignments are in parentheses. The 0^+ level indicated at 1730 eV was not observed in this work.

of that energy which was too intense to be anything other than $E0$ multipolarity. It has been confirmed[22] in a new conversion electron study which provides improved energy resolution and definition. However, the 0^+ assignment to that level is now in question for reasons detailed below.

We report a new, definite ground state transition from a level at 1582.8 keV; its threshold is apparent in Fig. 2, where the common threshold of this γ ray and of the 683.6-keV cascade decay is evident. Our transition energies, measured to within ± 0.1 keV, show that the cascade energies sum to the level energy to better than ± 0.1 keV. Careful examination of spectra taken with radiolead and natural isotopic abundance samples shows that these transitions are not in any other naturally occurring isotope of Pb. Morever, no reaction channel other than INS contributes significantly at low neutron energies. The observed ground-state transition means that there is certainly a non-zero-spin level at that energy in ^{204}Pb.

We have searched for a second transition from the reported[21,22] 0^+ level at 1582.7 keV to the 899.2-keV 2_1^+ first excited level, near the energy of the 683.6-keV cascade from the 1582.8-keV level. We find, since our resolution is 1.9 keV, that if the 0^+ level is 0.25 keV or more separated from the 1582.8-keV level, its cascade intensity to the 899.2-keV level must be less than 8% that of the 683.6-keV line. The energy scales for the two experiments agree to about 0.1 keV, as is evident from comparing energies for transitions common to the two experiments. Thus there is no evidence for two levels near 1583 keV in this experiment. The absence of two apparent γ-ray decays is not conclusive, however, since the reported 0^+ energy is only 0.1 keV away from our energy. Furthermore, neither of the known 0^+ levels at 1167 keV in ^{206}Pb or at 1730 keV in ^{204}Pb decay by photon emission; both decay entirely by $E0$ transitions. We cannot rule out the possibility of two levels within 0.1 keV of each other, especially if one of them does not decay by photon emission. We note, however, that the two well-known 0^+ levels cited above in the two Pb isotopes are strongly ex-

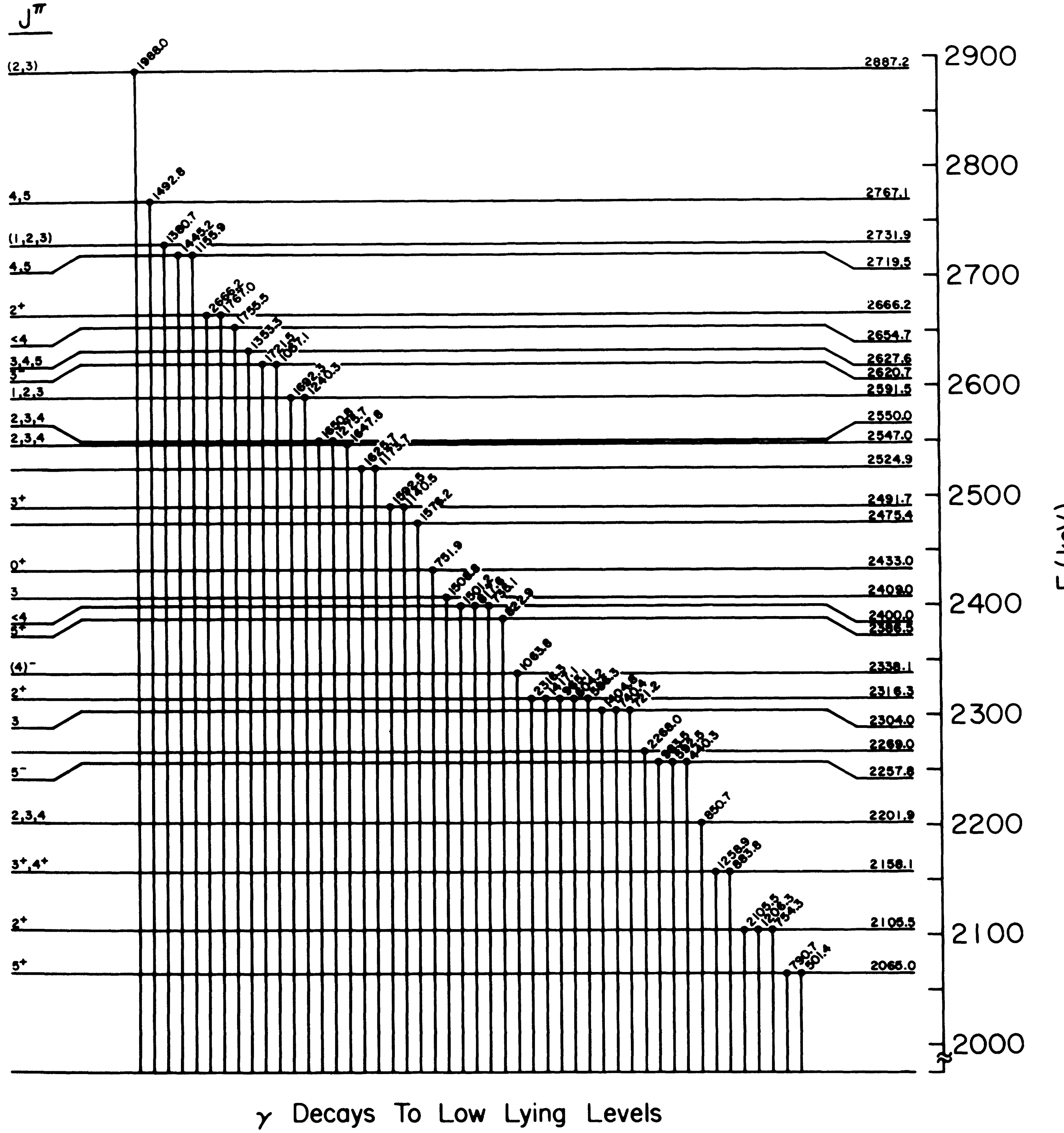

FIG. 5. Level diagram for ^{204}Pb deduced from ^{204}Pb(n,n'γ) between 2 and 3 MeV excitation energy. Level and γ-ray energies are in keV and tentative spin assignments are in parentheses.

cited in $L=0$ transitions by (p,t) (Refs. 7 and 8) and (t,p) reactions.[23] The proposed[22] 1582.7-keV 0^+ level of ^{204}Pb is not excited in any of the two-neutron transfer studies.

This remarkable conclusion of two energy-coincident levels could be avoided if the earlier 0^+ assignment were incorrect. As noted, the conversion electron spectra were just remeasured,[22] confirming a 1582.7-keV line and a 684-keV $E2$ cascade electron line. Combining the electron line intensities with our γ-ray intensities for the 683.6- and 1582.8-keV γ rays enables us to calculate the conversion coefficient of the 1582.8-keV decay in terms of that for the 683.6-keV decay, assuming there is only one level near 1583 keV. This would lead to a conversion coefficient for a 1582.8-keV $E2$ transition 2 orders of magnitude too large for a normal $E2$ or, alternatively, a conversion coefficient 2 orders of magnitude too small for either an $M1$ or $E2$ 683.6-keV cascade transition. Thus it is impossible to escape the conclusion of two levels unless

TABLE II. ^{204}Pb energy levels and transitions. Energy levels, spins and parities, γ-ray transition energies, spin and parity of final state, mixing ratio δ, Legendre polynomial coefficients and branching ratios. Energies are in keV's. Transition energies are measured to within ± 0.1 keV, while level energies are determined with ± 0.2 keV. Levels discovered in this work are indicated by an asterisk. The coefficients a_2 and a_4 were determined from the angular distributions at 2 MeV incident neutron energy for transitions from levels below 1900 keV excitation energy, and at 3 MeV incident neutron energy for transitions from levels above 1900 keV excitation energy.

E (level) (keV)	J^π	E_γ (keV)	J_f^π	δ	a_2	a_4	Branching ratio
899.2	2^+	899.2	0_1^+	$E2$	0.14 ± 0.01	-0.04 ± 0.01	100
1274.3	4^+	375.1	2_1^+	$E2$	0.29 ± 0.07	-0.14 ± 0.10	100
1351.2	2^+	452.0	2_1^+	0.8/3.4	-0.17 ± 0.02		22
		1351.2	0_1^+	$E2$	0.23 ± 0.01	-0.09 ± 0.02	78
1563.6	4^+	289.3	4_1^+	0.09	0.31 ± 0.02		100
1582.8*	2^+	683.6	2_1^+	$-1.7/-0.2$	0.31 ± 0.01		97
		1582.8	0_1^+	$E2$	0.37 ± 0.07		3
1604.9	3^+	330.6	4_1^+	0.1/23	-0.12 ± 0.02	-0.04 ± 0.03	59
		705.7	2_1^+	0.2	-0.45 ± 0.03		41
1665.3	2^+	766.1	2_1^+	0.1/3.0	0.17 ± 0.03		51
		1665.3	0_1^+	$E2$	0.36 ± 0.03	-0.12 ± 0.04	49
1681.2	$1^{(+)}$	782.0	2_1^+	0.1/3.7	0.0		48
		1681.2	0_1^+	$M1$	-0.18 ± 0.02	-0.04 ± 0.04	52
1712.3*	2,3	361.1	2_2^+		-0.28 ± 0.1		72
		438.0	4_1^+		0.0		15
		813.1	2_1^+		-0.46 ± 0.17		12
1730.0	0^+						
1761.1	2^+	409.9	2_2^+				7
		861.9	2_1^+	1.4	-0.30 ± 0.03		52
		1761.1	0_1^+	$E2$	0.33 ± 0.04	-0.14 ± 0.06	41
1817.4	4^+	918.2	2_1^+	$E2$	0.39 ± 0.04	-0.16 ± 0.05	100
1872.1	$1^{(+)}$	1872.1	0_1^+	$M1$	-0.09 ± 0.02	-0.04 ± 0.03	100
1933.3	$1^{(+)}$	1034.1	2_1^+		-0.26 ± 0.10	-0.29 ± 0.17	11
		1933.3	0_1^+	$M1$	-0.09 ± 0.03		89
1948.4*	$2^+,3^+$	365.5	2_3^+		-0.34 ± 0.08		22
		597.2	2_2^+		0.39 ± 0.12		31
		674.1	4_1^+		0.17 ± 0.06		18
		1049.2	2_1^+		0.30 ± 0.06	0.12 ± 0.08	29
1960.4	2^+	377.6	2_3^+	$-0.1/-1.8$	0.18 ± 0.08		23
		609.2	2_2^+		0.74 ± 0.40		21
		1061.2	2_1^+	$-0.2/1.6$	0.27 ± 0.03		56
2065.0	5^+	501.4	4_2^+	0.1	-0.41 ± 0.11		25
		790.7	4_1^+	-0.9	0.65 ± 0.07	0.18 ± 0.10	75
2105.5	2^+	754.3	2_2^+		0.10 ± 0.07	-0.14 ± 0.01	31
		1206.3	2_1^+				24
		2105.5	0_1^+	$E2$	0.28 ± 0.05		45
2158.1	$4^+,3^+$	883.8	4_1^+		0.38 ± 0.14	-0.35 ± 0.19	25
		1258.9	2_1^+		0.27 ± 0.08	-0.13 ± 0.10	75
2201.9*	2,3,4	850.7	2_2^+		0.28 ± 0.08	-0.18 ± 0.11	100
2257.8	5^-	440.4	4_3^+				7
		592.5	2_4^+				3
		983.5	4_1^+	0.0	-0.22 ± 0.01		90
2269.0		2269.0	0_1^+				100
2304.0*	3	721.2	2_3^+		-0.11 ± 0.08		41
		740.4	4_2^+	$-0.3/-15$	-0.34 ± 0.08		41
		1404.8	2_1^+		0.32 ± 0.16	0.23 ± 0.20	18
2316.3*	2^+	586.3	0^+	$E2$	0.21 ± 0.14	-0.28 ± 0.22	25
		604.0	(3^+)	$-0.3/-7$	-0.15 ± 0.06	0.23 ± 0.09	32
		965.1	2_2^+	1.0/2.5	-0.22 ± 0.08		18
		1417.1	2_1^+				18
		2316.3	0_1^+	$E2$	0.33 ± 0.15		10
2338.1	$(4)^-$	1063.8	4_1^+	0.2	0.21 ± 0.04		100
2386.5	5^+	822.9	4_2^+	2.0	-0.80 ± 0.06	0.24 ± 0.09	100
2400.4*	1,2,3	735.1	2_4^+		0.19 ± 0.15		12

TABLE II. (*Continued*).

E (level) (keV)	J^π	E_γ (keV)	J_f^π	δ	a_2	a_4	Branching ratio
		817.6	2_3^+				9
		1501.1	2_1^+		−0.09±0.04	−0.12±0.05	79
2409.0*	3	1509.8	2_1^+	0.07	−0.36±0.06		100
2433.0	0^+	751.8	1_1^+				100
2475.4*		1576.2	2_1^+				100
2491.7*	3^+	1140.5	2_2^+	−0.5	0.35±0.06		65
		1592.5	2_1^+	−1.0	0.66±0.12		35
2524.9*		1173.7	2_2^+				37
		1625.7	2_1^+		0.20±0.07		63
2547.0*	2,3,4	1647.8	2_1^+		0.22±0.10		100
2550.0*	2,3,4	1275.6	4_1^+		−0.07±0.05		83
		1650.6	2_1^+		−0.16±0.05	−0.17±0.07	17
2591.5*	1,2,3	1240.3	2_2^+				21
		1692.3	2_1^+		−0.15±0.09		79
2620.7	3^-	1057.1	4_2^+		−0.13±0.11		9
		1721.5	2_1^+	0.04	−0.33±0.02		91
2627.6*	3,4,5	1353.3	4_1^+		−0.35±0.14		100
2654.7*	<4	1755.5	2_1^+		−0.23±0.16		100
2666.2*	2^+	1767.0	2_1^+				23
		2666.2	0_1^+	*E*2	0.48±0.09		77
2719.5*	4,5	1155.9	4_2^+		0.0±0.05		30
		1445.2	4_1^+		0.35±0.11		70
2731.9*	1,2,3	1380.8	2_2^+		−0.12±0.07		100
2767.1*	(4,5)	1492.8	4_1^+		0.55±0.10		100
2887.2*	2,3	1988.0	2_1^+		−0.31±0.07		100

there is a possibility that the 1582.7-keV electron line could be in a different nucleus. A 1584-keV transition had been reported[7] in ^{202}Pb, which could have been excited in the (p,2n) reactions on natural *Tl* targets as well as the ^{204}Pb lines, for example. However, both conversion electron studies took special care[22] to assure that the electron yields were arising from properly identified nuclei.

The reported 1582.7-keV 0^+ level cannot be one of the 0^+ excitations identified with the valence neutron-hole spectrum, since it is not excited in the (p,t) transfer studies, whereas it should have been strongly excited in that reaction were it dominated by one of the low-lying configurations. The three parent 0^+ excitations in ^{206}Pb are all strongly excited in (p,t) reactions, as is the known 0^+ level at 1730 keV in ^{204}Pb.

A new 0^+ level had been discovered recently at 2433.1 keV through identification of *E*0 transitions,[22] but was thought to be an intruder state, outside the valence neutron-hole space.[22] There are several reasons for concluding now that this level does belong to the space spanned by the valence neutron-hole orbits, and is not an intruder. We have identified a 751.8-keV γ ray with an excitation threshold of 2450±50 keV, which we identify as a transition from the 2433.1-keV level. This transition is, to within 0.1 keV, a cascade transition from the 2433.1-keV level to the 1^+ level at 1681.2 keV. The angular distribution of the 751.8-keV line is isotropic, consistent with the 0^+ assignment to the 2433.1-keV level. Thus the 2433.1-keV level decays to a 1^+ level which almost certainly belongs to the four neutron-hole valence space. Were the 2433.1-keV level a two-particle, two-hole core excitation, strong decays to valence space levels would be extremely unlikely. However, a 0^+ level of the valence space could very easily decay by an *M*1 transition to the 1681.2-keV 1^+ level.

There are three definitely confirmed 0^+ levels in ^{204}Pb, at 0, 1730, and 2433.1 keV. The 1730-keV level has two-nucleon transfer strengths and decays just like those of the 1167-keV level of ^{206}Pb, and the 2433.1-keV level decays just as expected for a valence-space level. The fact that these low-lying 0^+ levels and the 2_1^+ levels are well represented as valence neutron-hole configurations leads directly to strong excitation in two-nucleon transfer reactions and, correspondingly, forbiddeness of γ-ray decays of the 0_2^+ levels. That is, at least in ^{206}Pb, the 0_2^+ level is a configuration admixture almost orthogonal to that of the ground state; the configurations lead to two pairs of approximately canceling *E*2 amplitudes[8] in γ decay to the 2_1^+ level, which may account for its being seen only in *E*0 decay. The 1730-keV level of ^{204}Pb has very similar excitation and decay properties; it also is seen only in *E*0 decay.

It seems natural to associate the cited 0^+ levels of the two nuclei, including the 0-, 1730-, and 2433-keV levels of ^{204}Pb corresponding to the 0-, 1167-, and 2314-keV levels of ^{206}Pb. The major problem with this association is that the shell model, which describes so well much of what we see, including the decay patterns of low-lying natural-parity levels and the right number of unnatural-parity levels, also predicts that the 0^+ level spectrum of

^{204}Pb should be more compressed in energy than that of ^{206}Pb.

An early shell model calculation for ^{204}Pb had been made[24] based on the parametrization developed by True and Ford[25] for ^{206}Pb. The True and Ford parameters were used without modification to calculate the expected spectrum of ^{204}Pb. This calculation produced quite reasonable results, especially for the few levels known at that time. These authors calculated excited 0^+ levels spaced 650 keV apart, comparable to the spacing of the 1730- and 2433.1-keV levels. They also point out that the 0^+ level energies are particularly sensitive to the monopole component of the residual nucleon-nucleon force used, while levels of other spins are most sensitive to other components.[24] Thus, it is quite feasible that more recent shell model calculations[9,10] could give a good description for most nonzero spin levels without locating the 0^+ levels correctly.

B. Natural-parity levels below 2 MeV excitation energy

Despite the fact that we now find 43 low-spin levels below 2.9 MeV, rather than the 22–23 natural-parity levels predicted, there are some surprising simplicities amongst the lowest few levels, and good correspondence exists between excitations in ^{206}Pb and ^{204}Pb.

1. 1351.2-keV level 2^+

The 1351.2-keV 2_2^+ level of ^{204}Pb decays via transitions to the 0_1^+ and 2_1^+ levels. These decays are consistent with shell model calculations, in which the $p_{1/2}f_{5/2}$ component in the 2_2^+ wave function can decay to the $(p_{1/2})^2$ and $(f_{5/2})^2$ components in the 0_1^+ state by $E2$ decay, and the $p_{1/2}p_{3/2}$ configuration undergoes $M1$ decay to the $(p_{3/2})^2$ configuration in the 2_1^+ state. Thus, as expected, that state decays to both lower-energy levels. The angular distributions of the 1351.2-keV γ ray, shown in Fig. 6 at both 2 and 3 MeV neutron energies, are only consistent with an assignment of 2^+ to that level, in agreement with an earlier assignment.[11] The 452-keV cascade transition is of mixed $E2$-$M1$ character, which is also consistent with the expected configurations. The spectroscopic amplitudes for this level are such that its (p,t) two-nucleon strength is weak; this is also consistent with shell model expectations.[8]

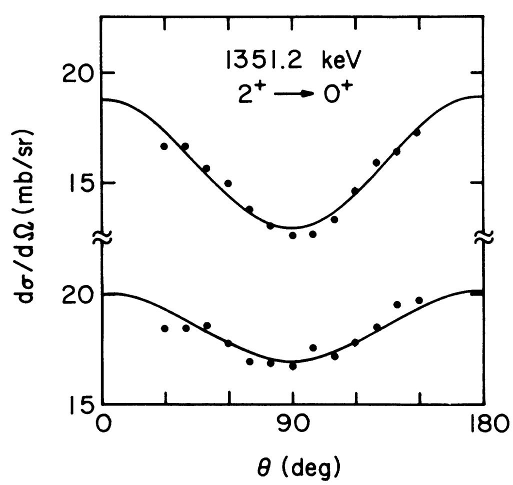

FIG. 6. Angular distributions from the 1351.2-keV $2_1^+ \rightarrow 0^+$ γ ray. The data in the upper and lower panels were measured at 2 and 3 MeV incident neutron energies, respectively.

2. 1563.6-keV level 4^+

The second 4^+ level at 1563.6 keV has as its main parent configuration the 4_2^+ level of ^{206}Pb. Since the lower levels of ^{204}Pb have the 0_1^+, 2_1^+, and 4_1^+ levels of ^{206}Pb as parents, the decay of the 1563.6-keV level to them should be quite weak, as are the corresponding decays in ^{206}Pb. No decay from the 1563.6-keV level to the lower levels is observed, except for the transition connecting the two 4^+ levels. The two levels can connect through an $M1$ transition, via the $p_{3/2}f_{7/2}$ and $p_{3/2}f_{5/2}$ configurations. Thus, that $M1$ transition should be allowed; it is, in fact, the only decay from the 1563.6-keV level. The mixing ratio we determine for this transition, $\delta = 0.09 \pm 0.02$, is quite consistent with the multipole mixing determined from ^{204}Bi decay.[26]

3. 1582.8-keV level 2^+

The 1582.8-keV ground state and the 683.6-keV cascade angular distributions are shown for an incident neutron energy of 2.0 MeV in Fig. 7. Only a 2^+ level can provide this ground-state angular distribution; the level is firmly assigned as 2^+. The combined analyses of the 683.6-keV angular distributions show at both 2 and 3

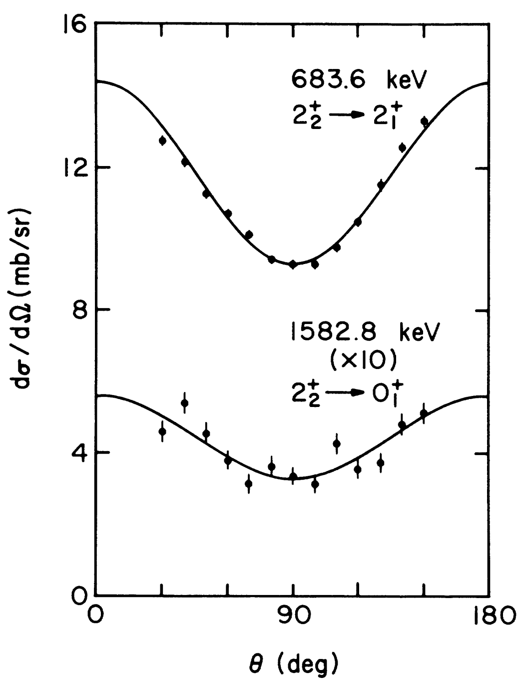

FIG. 7. Two angular distributions of γ rays decaying from the 2_3^+ level at 1582.8 keV are shown. The 683.6 keV angular distribution is given in mb/sr, while the 1582.8 keV angular distribution has been multiplied by 10.

MeV incident neutron energies that this transition, which dominates the decay of the level, probably has strong $E2$ and $M1$ amplitudes. The 1582.8-keV $E2$ transition is only a 3% branch. These decay properties are completely consistent with the suggestion that this is the 2_3^+ level of the shell model calculations.[8,10] That level would be dominated by a configuration which contained a $(p_{3/2})^2$ neutron-hole component.[8,23] This component would easily decay by an $M1$ transition to a similar $(p_{3/2}p_{1/2})$ component[8] of the 2_1^+ level, and by an $E2$ amplitude to the $(p_{3/2}f_{5/2})$ component. The most likely decay amplitudes for the 683.6-keV transition are mixed $E2$ and $M1$, dominated by $E2$; but a pure $M1$ decay cannot be ruled out. The 2_3^+ level would have only weak $E2$ decays to the ground state, through small components like $(p_{3/2})^2(f_{7/2})^2$ in the ground state wave function.[23] This weak decay to the ground state, only 3% of the total decay intensity of the level, provides the reason that this level had been missed in previous studies. There is a problem with considering the newly assigned 1582.8-keV level as the 2_3^+ level, however. If its configuration has a dominant $(p_{3/2})^2$ component, it should be strongly excited in the ^{206}Pb(p,t)^{204}Pb reaction, and its quite weak excitation[7] is another reason it has been previously missed. Thus its γ decay is just as expected from the shell model, but not its (p,t) transfer strength.

4. 1665.3-keV level 2^+

This level is strongly excited by $L=2$ transfer in (p,t) experiments.[7,8] This is just what would be expected of the 2_3^+ shell model level dominated by the $(p_{3/2})^2$ configuration. However, it decays both to the ground state and 2_1^+ level; this is not at all characteristic of the expected configuration. Thus, in some sense, the 1582.8-keV and 1665.3-keV levels seem to share the properties of the $(p_{3/2})^2$ configuration, in that the lower one has γ-ray decays like that configuration, but it is the upper one which displays the large (p,t) transfer strength.

5. 1761.1-keV level 2^+

This level had also been found in the earlier (n,n'γ) experiment,[11] but was not assigned there. Speculation led to a projected[13] 1^+ assignment. However, the ground-state angular distribution of Fig. 8 clearly fixes this as a 2^+ level. The 861.9-keV cascade to the 2_1^+ level, also shown in Fig. 8, requires a mixing ratio $\delta=1.4\pm0.4$. Since such large $M2$-$E1$ admixtures are not observed, the decay must be mixed $E2$-$M1$, and the parity of the level is positive.

6. 1817.4-keV level 4^+

This level is strongly excited in (p,t) transfer[8] as an $L=4$ transition, and the stretched $E2$ cascade to the 2_1^+ level, with an $a_2>0$ and $a_4<0$, requires also the 4^+ assignment. The level has only a single decay path.

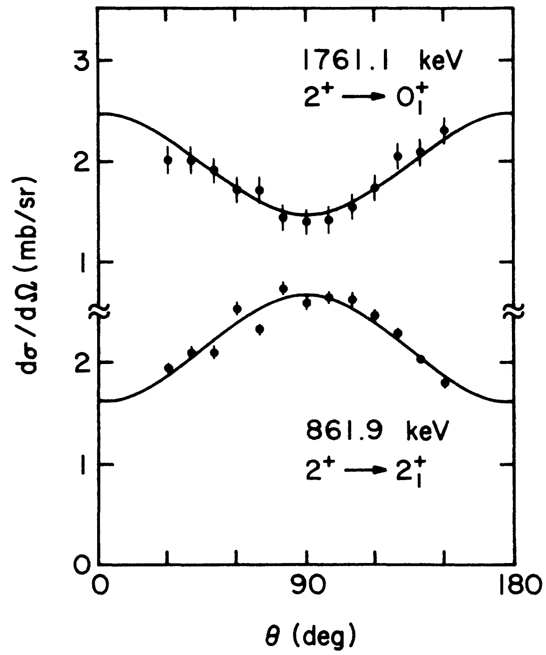

FIG. 8. Angular distributions of two γ-ray decays from the 1761.1-keV 2^+ level are shown.

7. 1960.4-keV level 2^+

This level decays to the 1582.8-, 1351.2-, and 899.2-keV levels. The angular distributions to the 1582.8- and 899.2-keV levels have anisotropies much too small to correspond to stretched $E2$'s from a $J=4$ level. That possibility is ruled out, but the several angular distributions would not permit us to distinguish between possible J assignments of 2 and 3. This level, however, is strongly excited with an $L=2$ amplitude in the (p,t) reaction from ^{206}Pb. Hence, it is firmly assigned as $J^\pi=2^+$. The 1061.2-keV $2^+\rightarrow2_1^+$ transition appears to be an $M1$ transition, but would admit also an assignment of 70% $E2$ intensity, with only a 30% $M1$ admixture.

C. Unnatural-parity levels below 2 MeV excitation energy

The other major new element in this study for levels below 2 MeV excitation energy is the identification and tentative assignment of six unnatural-parity levels. That number is expected[10,11] on the basis of shell model calculations in the four neutron-hole space.

1. 1604.9-keV level 3^+

This 3^+ level is the only unnatural-parity level which was previously well established.[27–29] The 330.6-keV cascade transition to the 1274.3-keV 4_1^+ level could be almost pure $M1$, although an almost pure $E2$ decay cannot be ruled out, from our analysis of this angular distribution. The 705.7-keV cascade to the 2_1^+ level has $\delta=0.2\pm0.1$. This finding is consistent with the results from ^{204}Bi decay, which gave $\delta<1$. We find that these two γ-ray intensities are approximately equal, rather than the two to one intensity ratio of a recent compilation.[13] The dominance of $M1$ decays is quite consistent with the mixed shell configurations associated with the valence neutron-hole models. That is, unnatural-parity levels of the four neutron-hole valence space will easily decay by fast $M1$ transitions to natural-parity levels of the same model space. The 3^+ assignment for this level is definitively confirmed through analysis of the angular distributions of Fig. 9.

2. 1681.2-keV level $1^{(+)}$

The 1681.2-keV level had been discovered[11] in the earlier (n,n′γ) experiment and is here definitely assigned as $J=1$ through observation of the dipole decay directly to the ground state. The negative a_2 coefficient in the 1681.2-keV angular distribution admits no other spin assignment. This transition allows only a $J=1$ assignment; only a 1 to 0 transition can lead to a negative a_2 coefficient in the angular distribution of a ground state transition. Since no multipole mixing can occur, we cannot use that to fix the parity; however, since electric dipole excitations are not expected this low in excitation energy,[30] it is probably positive parity. The $M1$ to the ground state is consistent with an unnatural-parity level of the valence configurations. The nearly isotropic 782-keV cascade to the 2_1^+ level does not permit a determination of δ.

3. 1712.3-keV level 2,3

This level, which is discovered in this work, is firmly identified through three cascade decays to 2^+ levels at 899.2 and 1351.2 keV, and to the 1274.3-keV level. With decays to these three levels, the spin of the 1712.3-keV level must be between 2 and 4. The large negative a_2's for the 361.1- and 813.1-keV cascade decays to 2^+ levels rules out 4 as a possible assignment, since 4 to 2 transitions would be stretched $E2$'s, with large positive a_2's. That leaves $J=2$ or 3 as possibilities. The assignment $J=3$ would admit multipole mixing ratios δ approximately 0 or 5 for both the 361.1- and 813.1-keV decays.

One observed discrepancy helps explain why this level has not been observed before. Its decay intensities sum to only $\frac{1}{5}$ of that expected for a $J=3$ level; all observed decays are very weak. The level may decay also to levels within 200 keV of it, in which case we would have missed those transitions. Alternatively, one or more of its decays may be highly converted. To confirm that we were not deceiving ourselves about the origin of the γ rays, we note the clearly defined thresholds below 1.8 MeV but above 1.7 MeV in Fig. 3. Furthermore, the three decay-path energy sums agree to within 0.2 keV on the level energy of 1712.3 keV.

4. 1872.1-keV level $1^{(+)}$

This is one of the rare cases in which a level is observed to decay with only one transition, direct to the ground state, shown in Fig. 10. This transition allows only a $J=1$ assignment. Following the arguments given for the 1681.2-keV level, the parity is assumed to be positive.

5. 1933.3-keV level $1^{(+)}$

This is another level, one of a triplet of closely spaced levels near 1.95 MeV, which decays dominantly to the ground state. Again, the 1933.3-MeV transition has $a_2<0$, and the level is definitely assigned as $J=1$. The 1034.1-keV $J=1$ to 2^+ cascade, which is 9 times less intense than the ground state transition, has an angular distribution insensitive to δ. Hence, the parity remains undetermined, but is probably also positive.

6. 1948.4-keV level $2^+,3^+$

This level is newly discovered and its spin is limited to two possible values in this work. It decays to three

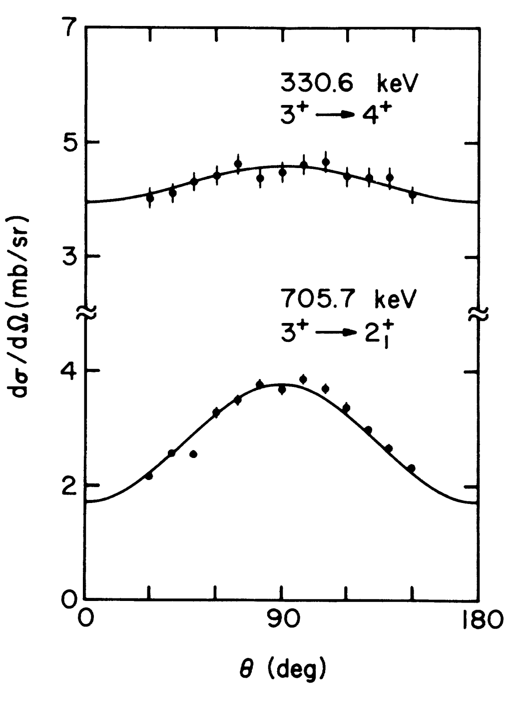

FIG. 9. Two angular distributions of the 330.6- and 705.7-keV γ rays decaying from the 1604.9-keV 3^+ level are shown.

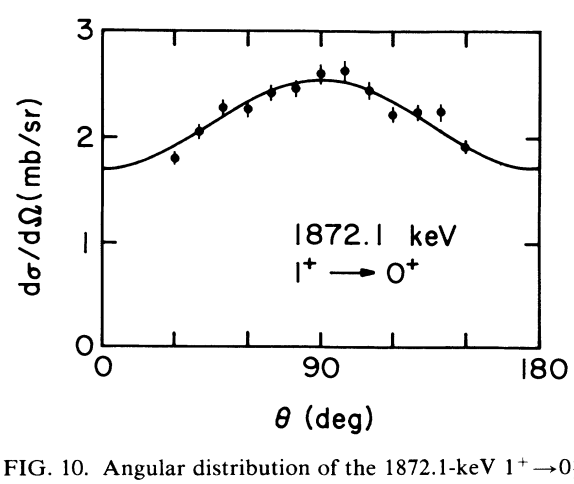

FIG. 10. Angular distribution of the 1872.1-keV $1^+ \rightarrow 0_1^+$ decay.

different 2^+ levels and one 4^+ level, but all four decays are consistent with spin $J=2$ or 3. The decay to the newly discovered 1582.8-keV, 2^+ level has $a_2<0$, which rules out $J>3$. If the level has $J=3$, then all of the decays to natural-parity levels are dominated by $M1$ amplitudes. The several $M1$ decays to natural-parity levels would again be consistent with the presumption that this is a 3^+ level. Two of the decays would have mixed $E2$-$M1$ multipole order with $|\delta|\sim0.3$ for either a $J=2$ or 3 assignment, so the parity is clearly positive.

D. Levels above 2 MeV excitation energy

Twenty-seven levels were identified between 2.0 and 3.0 MeV excitation energy and 11 of these states have absolute spin assignments. A brief discussion of each level above 2.0 MeV excitation energy, which was observed in this study, is given below.

1. 2065.0 keV 5^+

Both of the previously reported[31] γ-ray decays from this level were observed in this work. The decay to the 4_1^+ was reported[31] to be a mixed $M1$-$E2$ transition with $\delta=1.0$ while the decay to the 4_2^+ was reported as pure $M1$, but the spin assignment was tentative. We find $\delta=0.1\pm0.1$ for the decay to the 4_2^+ level and $\delta=-0.9\pm0.5$ for the 4_1^+ decay using the convention of Ref. 31; thus we disagree on the sign of the mixing ratio for the 790.7-keV γ ray. More importantly, since $a_2<0$ for the 501.4-keV line but $a_2>0$ for the 790.7-keV decay, we have a unique spin and parity assignment of 5^+. The assignment is no longer tentative. A $J=6^+$ level would have stretched $E2$ decays to both 4^+ levels, and a $4^+\rightarrow4^+$ transition cannot provide $a_2>0.4$.

2. 2105.5 keV 2^+

This state probably corresponds to the 2103 keV 2^+ state reported from a (p,t) study.[7] Three γ-ray decays were observed in this work to the ground state, the 2_1^+, and the 2_2^+ states. The angular distribution for the ground state transition enables a definite spin assignment of 2^+ to be made for this level. No mixing ratio information was obtained from the cascade decays.

3. 2158.1 keV 3^+,4^+

A state was reported[7] at 2156±2 keV which probably corresponds to this state. No spin assignment was suggested in that report. Two γ-ray decays were observed from this level; the sensitivity allows us to reject $J=2$, but either a 3^+ or 4^+ assignment could be made.

4. 2201.9 keV 2,3,4

This is a newly discovered level. One γ-ray decay to the 2_2^+ is observed from this state. This decay limits J between 2 and 4.

5. 2257.8 keV 5^-

Both of the previously reported[31] γ-ray decays from this level were observed in this work along with a new decay to the 2_4^+ state. The transition to the 4_1^+ is consistent with pure $E1$; the 440.4-keV transition to the 1817.4-keV 4^+ level was observed, but was too weak to determine the multipolarity.

6. 2269.0 keV

A very weak γ ray was observed with an energy of 2269 keV. It was initially observed at 2.5 MeV neutron energy, and hence could only be a ground state transition. The intensity of this γ ray was too weak for angular distribution measurements, so a spin assignment could not be made. This state may correspond to a 2270-keV level reported[31] from an (α,α') study.

7. 2304.0 keV 3

This is a newly discovered level. Three γ-ray transitions were observed from this level to the 2_1^+ state, the 4_2^+ state at 1563.6 keV and the 2_3^+ state at 1582.8 keV. γ-ray decays to levels of spin 2 and 4 occur only from a state of spin 2, 3, or 4. The angular distribution of the decay to the 4_2^+ state enabled spin assignments of 2 and 4 to be eliminated, and thus a spin assignment of 3 is given to this state. The mixing ratio $|\delta|\geq0.3$ for the cascade to the 4_2^+ level; hence, the parity is positive.

8. 2316.3 keV 2^+

This level is first reported and assigned in this work. Five γ-ray decays were observed from this level to the ground state, the 2_1^+ and 2_2^+ states, the 0^+ state at 1728 keV, and the 1712-keV 3^+ state. The excitation function of the 2316.3-keV γ ray led to an unambiguous placement of this level; the other γ rays were placed as decays from this level based on their excitation functions and energies. The angular distribution for the ground state transition enables a definite spin assignment of 2 to be made. Several mixing and branching ratios have been determined.

9. 2338.1 keV $(4)^-$

Two γ-ray decays were previously reported[31] from this level to the 4_1^+ state (1064.1 keV) and to the 5^- state at 2257.8 keV (80.3 keV). The 80.3-keV γ ray was too low in energy to be observed in the present work but the 1063.8-keV γ ray was observed. The 1063.8-keV γ ray was reported to be a pure $E1$ transition, but was determined in this work to be a mixed $E1$-$M2$ transition with a $\delta=0.2$ for a spin 4 state or $\delta=0.3$ for a spin 5 state. A mixed $E1$-$M2$ transition with $|\delta|\geq0.2$ is rare, usually occurring only in deformed nuclei. It is extremely unlikely that a $5^-\rightarrow4^+$ transition has $\delta=0.3$; thus J is probably 4. In any case the $M2$-$E1$ mixing is unusually large.

10. 2386.5 keV 5^+

This previously reported level was observed in this work via the decay to the 1563.5-keV 4_2^+ state. It had been tentatively assigned $J=5$, with no parity determination. The other reported decay from this level, to the 5^+ state of 2065.0 keV, was not observed in this work. A definite spin assignment of 5 can be made for this level based on the large value of a_2. Indeed, this line shows one of the largest γ-ray anisotropies ever observed in a nucleon induced scattering experiment. Shown in Fig. 11 is a plot of the calculated angular distribution for a $5 \rightarrow 4$ transition along with the data. The large mixing ratio, $\delta = 2$, denotes an $M1$-$E2$ mixture, so the parity must be positive. The assignment is now definite.

11. 2400.4 keV 1,2,3

This level is placed on the basis of the three γ-ray decays first reported here. The decays are to the 2_1^+ state, the 1582.8-keV 2_3^+ state, and the 1665.3-keV 2_4^+ state. The excitation function for the 1501.2 keV transition, not shown, enabled an unambiguous placement of this new level. Once this new level was placed, the other two γ rays were assigned as transitions from it because the γ-ray energies matched the transition energies. The spin is limited to $0 < J < 4$ by the negative a_2 for the transition to the 2_1^+ level.

12. 2409.0 keV 3

This level is also first reported in this experiment. One γ ray, $E_\gamma = 1509.8$ keV, was observed decaying from this state to the 899.2-keV 2_1^+ level. The excitation function enables an unambiguous placement of this level and the large negative value for a_2 can only arise from a 3 to 2 transition. The small mixing ratio, $\delta = 0.07$, would admit either positive or negative parity.

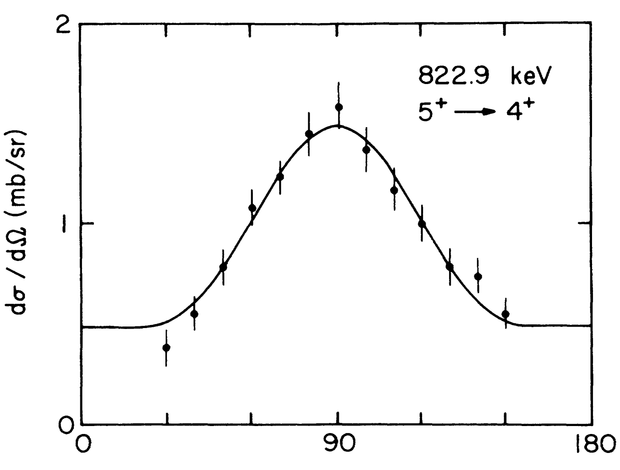

FIG. 11. Angular distribution of the 822.9-keV $5^+ \rightarrow 4^+$ decay.

13. 2433.0 keV 0^+

One γ-ray transition was observed from this level to the 1_1^+ state at 1681.2 keV. The angular distribution for this decay is isotropic, which is consistent with the 0^+ spin assignment from the electron conversion studies discussed earlier.[22]

14. 2475.4 keV

The identification of this new level was made by the observation of a γ-ray decay to the 2_1^+ state. No information on the spin of this level was obtained.

15. 2491.7 keV 3^+

This new level was identified from the observation of the γ-ray decays to the 2_1^+ and 2_2^+ states. Both γ rays were of mixed multipolarity and the angular distributions were consistent only with a spin of 3. A mixing ratio of $\delta \geq 0.3$ inevitably implies an $M1$-$E2$ admixture. Hence the parity is positive.

16. 2524.9 keV

This newly discovered level was identified by the γ-ray decays to the 2_1^+ and 2_2^+ states. A spin determination was not possible from the angular distributions. The excitation function of the decay to the 2_1^+ state would favor a low spin.

17. 2547.0 keV 2,3,4

The energy and the excitation function of the observed γ-ray decay to the 899.2-keV 2_1^+ state led to the placement of this new level. The spin is limited to $J = 2-4$.

18. 2550.0 keV 2,3,4

γ-ray decays were observed to the 899.2-keV 2_1^+ and 1274.3-keV 4_1^+ levels. No information was obtained on the spin of this new level except to say again that a state which decays to levels of spins 2 and 4 has a spin of 2, 3, or 4.

19. 2591.5 keV 1,2,3

The energy of this newly discovered level was determined from the excitation function for the γ-ray decay to the 2_1^+ level. A second weak γ ray was assigned to a transition from this level to the 2_2^+ because of the agreement in the energies. The small negative anisotropy limits the spin to $J=1$, 2, or 3.

20. 2620.7 keV 3^-

Two γ-ray decays were observed from this well-known state to the 2_1^+ and 4_2^+ states. The angular distribution coefficient determined from the decay to the 2_1^+ was consistent with the spin 3 assignment. The deduced neutron inelastic scattering cross section determined for this state is much larger than that determined for other nearby states and is a signature of the strong collective nature expected for this state.

21. 2627.6 keV 3,4,5

A single γ-ray transition was observed to the 4_1^+ state. This γ ray, of energy 1353.3 keV, formed a doublet with the very strong 1351.2-keV γ ray. The γ-ray anisotropy ($a_2 < -0.2$) requires $3 \leq J \leq 5$ for this newly discovered level.

22. 2654.7 keV <4

One γ-ray decay from this new level to the 2_1^+ state was observed with an isotropic angular distribution. This requires $J < 4$.

23. 2666.2 keV 2+

Two γ-ray decays of energies 1767.0 and 2666.2 keV were observed to the 2_1^+ state and the ground state. The angular distribution measurement for the ground state transition enabled an unambiguous spin assignment to be made for this new level.

24. 2719.5 keV 4,5

Two γ-ray decays are observed to the 4_1^+ and 4_2^+ states. The angular distribution measurements were consistent with a spin of 4 or 5 for this new level.

25. 2731.9 keV 1,2,3

This is a newly discovered level identified by the decay to the 2_2^+ level. The small negative anisotropy for the decay limits J from 1 to 3.

26. 2767.1 keV (4,5)

This new level was detected by observation of the γ-ray decay to the 4_1^+ state. There is also possibly a weak transition to the 1563-keV 4_2^+ state but the γ ray is located on the tail of a much larger peak making its identification uncertain.

27. 2887.2 keV 2,3

An unambiguous placement of this new level is possible from its energy and excitation function. The one observed γ-ray decay is to the 899.2-keV 2_1^+ state. The large negative a_2 determined for this γ-ray angular distribution allowed the possible spin assignments for the decaying state to be narrowed to 2 or 3.

IV. INTERPRETATION AND SUMMARY

The discovery of 21 new levels below 2.9 MeV excitation energy and definite spin assignments for six of these, plus definite assignments for seven previously known but unassigned or only tentatively assigned levels, and the analyses of γ-ray decays, provides the additional information which allows us to clarify several aspects of the low-lying level scheme of ^{204}Pb.

There are three extensions of, and confirmations of, insight into the structure of ^{204}Pb which follow from this experiment and its interpretation. The clear and definite assignment of $J=1$ to the 1681.2-keV level helped with determination of the character of the 0^+ levels. The 751.8-keV decay of the 2433.1-keV 0^+ level to this $1^{(+)}$ level is characteristic of an $M1$ decay of a natural-parity valence-space level to an unnatural-parity one, and encourages us to propose including the 0^+ level as belonging to the four neutron-hole valence space. This inclusion is reinforced by a very recent systematic examination[32] of 2p-2h intruder 0^+ states in the Pb region. That examination finds that the lowest energy intruder state in ^{204}Pb should be above 3 MeV excitation energy. Thus the lowest valence-space 0^+ levels in ^{204}Pb are at 0, 1730, and 2433.1 keV. This would give three 0^+ levels with energy spacings in ^{204}Pb quite similar to those in ^{206}Pb, and the two of them lowest in energy have appreciable two-neutron transfer strengths, as would be expected for these 0^+ levels.

Recent shell model calculations[8,10] predict smaller level spacings, with two excited 0^+ levels predicted below 2 MeV excitation energy; this is a direct consequence of having three major, active orbits with high occupancy, the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ orbits. However, we attribute only one excited 0^+ level to the model space, the 1730-keV level. The next 0^+ level is expected to appear at about 2.3 MeV excitation energy, and indeed one is found[22] at 2433.1 keV. It may be that the reason that the 0^+ levels are more widely spaced in ^{204}Pb than calculated[8,10] is that in ^{204}Pb the $p_{1/2}$ orbit is less active, or remains more nearly empty, than is implied in recent model calculations. That would leave the $f_{5/2}$ and $p_{3/2}$ orbits as most active at low energy. An older model calculation,[24] a parameter-free calculation based on the successful model[25] for ^{206}Pb, had found 0^+ spacings more characteristic of the present experimental results.

There is, nonetheless, a severe problem with the fact that this experiment finds a 2^+ level only 0.1 keV from a reported 0^+ level. Whether there are really two levels so closely spaced in energy should be resolved.

The second interesting finding relates to unnatural-parity levels. Approximately ten of these had been predicted in a full six-orbit shell model calculation.[10] This experiment finds about ten such levels below 2.5 MeV, with just the $M1$ decays one would expect to the natural-parity levels.

The third insight relates to low energy natural-parity levels, where we find good confirmation of shell model expectations,[9] particularly that these levels are well represented as constructed from the neutron-hole pair excitations which are the low-lying states of ^{206}Pb. This picture only seems to work well for levels below 2 MeV excitation; above that energy this experiment reveals twice the number of natural-parity levels as predicted by the shell model.

It is also interesting to review the decay properties of the low-lying 2^+ levels of this nucleus. According to the two-nucleon spectroscopic amplitudes for the (p,t) reactions leading to ^{204}Pb levels,[8] the 2_2^+ level is an admixture of the two dominant configurations, $f_{5/2}p_{1/2}$ and $(f_{5/2})^2$, almost exactly orthogonal to that of the 2_1^+ level. The result is that interconnecting $E2$ transition amplitudes tend to cancel. The next largest wave function amplitudes are $p_{1/2}p_{3/2}$ and $f_{5/2}p_{3/2}$. These also lead to interconnecting $E2$ amplitudes which cancel, although not as completely as do those for the dominant wave function amplitudes. The only reinforcing transition amplitudes from the mixed configuration wave functions are for $M1$ transitions, in which the $p_{1/2}p_{3/2}$ configuration can go to the $(p_{3/2})^2$ configuration without a corresponding canceling amplitude. On the other hand, the two 2^+ levels can both easily go to ground with fast $E2$ transitions. The decay of the 1351.2-keV level is dominantly directly to the ground state, with a weaker cascade transition to the 2_1^+ level, consistent with this picture.

As noted above in discussing the 1582.8-keV 2^+ level, the third 2^+ level of the model space is expected to be dominated by the $(p_{3/2})^2$ configuration. That configuration cannot decay directly to ground, so we should expect that this level decays quite weakly to ground, but strongly to the 2_1^+ level. This is exactly the decay pattern observed for the decay of the 1582.8-keV level. Its decay to the 2_1^+ level is primarily $M1$, and is more than thirty times as intense as the direct decay to the ground state.

There are several weaknesses associated with the picture we propose to reinforce, that of the natural-parity levels being states well described using the pair neutron-hole states of ^{206}Pb as the basis for the four-hole states of ^{204}Pb. First, and most obviously, this picture can be used only up to about 2 MeV excitation energy. A discrepancy is associated particularly with the newly identified 2^+ level at 1582.8 keV. This level has γ-ray decay properties nicely consistent with model expectations, but should also have been strongly excited in the (p,t) transfer experiment from ^{206}Pb as an $L=2$ transition; this is not the case. Instead, the strong (p,t) transfer occurs for the next higher 2^+ level at 1665 keV, as though the two levels were sharing properties of the one model level. On the whole, however, the picture gives us a good basis for explaining collective strengths in neutron scattering to low-lying levels. These collective scattering strengths are the subject of another experiment.

ACKNOWLEDGMENTS

The authors would like to thank Dr. J. L. Weil for carefully proofreading this document. The support of the National Science Foundation for this project through Grant PHY-8403278 is gratefully acknowledged.

---

[1] M. C. Mirzaa, J. P. Delaroche, J. L. Weil, J. Hanly, and M. T. McEllistrem, Phys. Rev. C **32**, 1488 (1985); S. E. Hicks, J. P. Delaroche, M. C. Mirzaa, J. Hanly, and M. T. McEllistrem, *ibid.* **36**, 73 (1987).

[2] Steven E. Hicks, Ph.D. dissertation, University of Kentucky, 1987 (unpublished).

[3] J. K. Dickens, Phys. Rev. C **28**, 916 (1983).

[4] William A. True, Phys. Rev. **168**, 1388 (1968).

[5] C. M. Ko, T. T. S. Kuo, and J. B. McGrory, Phys. Rev. C **8**, 2379 (1973).

[6] John M. Hanly, Ph.D. dissertation, University of Kentucky, 1987 (unpublished).

[7] W. A. Lanford, Phys. Rev. C **16**, 988 (1977).

[8] M. Takahashi, T. Murakami, S. Morita, H. Orihara, Y. Ishizaki, and H. Yamaguchi, Phys. Rev. C **27**, 1454 (1983).

[9] R. J. Liotta and C. Pomar, Nucl. Phys. **A362**, 137 (1981).

[10] J. B. McGrory and T. T. S. Kuo, Nucl. Phys. **A247**, 283 (1975).

[11] W. K. Dawson, P. W. Green, H. R. Hooper, G. C. Neilson, D. M. Sheppard, H. E. Siefken, D. L. Smith, and J. M. Davidson, Phys. Rev. C **22**, 928 (1980).

[12] R. C. Weiss, R. E. Anderson, J. J. Kraushaar, R. A. Ristinen, E. Rost, and S. Shastry, Nucl. Phys. **A355**, 45 (1981).

[13] M. R. Schmorak, Nucl. Data Sheets **50**, 791 (1987).

[14] G. P. Glasgow, F. D. McDaniel, J. L. Weil, J. D. Brandenburger, and M. T. McEllistrem, Phys. Rev. C **18**, 2520 (1978).

[15] A. J. Filo, S. W. Yates, D. F. Coope, J. L. Weil, and M. T. McEllistrem, Phys. Rev. C **23**, 1938 (1981).

[16] E. W. Kleppinger, Ph.D. dissertation, University of Kentucky, 1984 (unpublished).

[17] M. T. McEllistrem, U.S. Energy Research and Development Administration Report CONF-760715-P1, 1976.

[18] F. D. McDaniel, G. P. Glasgow, M. T. McEllistrem, *Proceedings of the International Conference on Nuclear Cross Sections for Technology, Knoxville, Tennesse, 1979* (National Bureau of Standards, Washington, DC, 1980), p. 135.

[19] E. Sheldon and D. M. Van Patter, Rev. Mod. Phys. **38**, 143 (1966).

[20] B. D. Kern, M. T. McEllistrem, J. L. Weil, and S. W. Yates, in *Proceedings of the International Symposium on In-Beam Nuclear Spectroscopy, Debrecen, Hungary,* edited by Zs. Dombradi and T. Fényes (Akademiai Kiado, Budapest, 1985), p. 163.

[21] L. H. Goldman, B. L. Cohen, R. A. Moyer, and R. C. Diehl, Phys. Rev. C **1**, 1781 (1970).

[22] J. Kantele, M. Luontama, W. Trzaska, R. Julin, A. Passoja, and K. Heyde, Phys. Lett. B **171**, 151 (1986).

[23] E. R. Flynn, R. A. Broglia, R. Liotta, and B. S. Nilsson, Nucl. Phys. **A221**, 509 (1974).

[24] R. Arvieu and M. Veneroni, Phys. Lett. **5**, 142 (1963).

[25] W. W. True and K. W. Ford, Phys. Rev. **109**, 1675 (1958).

[26] V. Hnatowicz, J. Kristak, and R. D. Conner, Nucl. Phys. **A185**, 601 (1972).

[27] R. Tickle and J. Bardwick, Phys. Rev. **166**, 1167 (1968).

[28] P. Richard, N. Stein, C. D. Kavaloski, and J. S. Lilley, Phys. Rev. **171**, 1308 (1968).

[29] J. C. Manthuruthil, D. C. Camp, A. V. Ramayya, J. H. Hamilton, J. J. Pinajian, and J. W. Doornebos, Phys. Rev. C **6**, 1870 (1972).

[30] D. F. Coope, S. N. Tripathi, M. C. Schell, J. L. Weil, and M. T. McEllistrem, Phys. Rev. C **16**, 2223 (1977).

[31] M. R. Schmorak, Nucl. Data Sheets **50**, 719 (1987).

[32] K. Heyde, J. Jolie, J. Moreau, J. Ryckebusch, M. Waroquier, P. Van Duppen, M. Huyse, and J. L. Wood, Nucl. Phys. **A466**, 189 (1987).