Gamma-ray transitions in ^{206}Pb studied in the ^{205}Pb(n,γ) reaction

S. Raman and J. B. McGrory*
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

E. T. Jurney and J. W. Starner
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
(Received 26 January 1996)

A study of the γ-ray spectrum following thermal-neutron capture by ^{205}Pb has revealed 54 γ rays, which have been incorporated into a level scheme consisting of 22 excited states in ^{206}Pb. This study was carried out with an ~9 mg lead sample enriched to 78.9% in radioactive ^{205}Pb. The neutron binding energy of ^{206}Pb was determined to be 8086.67±0.06 keV, and the thermal-neutron-capture cross section for ^{206}Pb to be 4.5±0.2 b. The low-lying portion of the level scheme of ^{206}Pb and the γ-ray branchings of positive-parity states have been compared with shell-model predictions. The overall agreement is excellent for the former and reasonably good for the latter. [S0556-2813(96)04706-1]

PACS number(s): 25.40.Lw, 21.60.Cs, 27.80.+w

I. INTRODUCTION

The domain of applicability of the spherical shell model is restricted to those nuclei with proton and/or neutron numbers that lie close to the magic numbers; that is, to nuclei close in mass to ^{4}He, ^{16}O, ^{40}Ca, ^{56}Ni, ^{88}Sr, and ^{208}Pb. Of these, the best closed-shell core nucleus is probably ^{208}Pb. Thus, the lead region is perhaps the best mass region to investigate questions about the effective one- and two-body interactions. Not surprisingly, there have been several shell-model investigations of the structure of nuclei near ^{208}Pb. So-called realistic effective two-body shell-model residual interactions have been constructed for this mass region by Kuo and Herling [1]. Based on the experimental data available at that time, it was concluded in Ref. [2] that the structure of low-lying states in $^{204-207}$Pb was well described in terms of the spherical shell model with the Kuo-Herling interaction. Subsequent shell-model studies in this region [3,4] using a variety of interactions (surface-δ, modified surface-δ, Schiffer-True, Gogny, etc.) have led to similar conclusions. The available data used in Ref. [2] include level energies, spectroscopic factors for one-neutron transfer reactions, and cross sections for two-neutron transfer reactions. The comparison with experiment of electromagnetic observables provides a more stringent test of the wave functions, and while there were some data available at that time on $M1$ and $E2$ transitions in the Pb isotopes, they were not of high precision.

Over the years there has been considerable interest in the effective one-body operators for $M1$ and $E2$ observables and in the information these operators provide on questions of ground-state correlation, effects of the Δ resonance, core polarization, etc. The most direct experimental information on the effective one-body operators comes from data on moments and transitions in the one-particle and one-hole systems. There is a moderate amount of information on the one-neutron hole operators from data on ^{207}Pb. Given the rather precise agreement between shell-model theory and experiment, as summarized below for the energy levels in ^{206}Pb, it is of interest to extend this comparison to the $M1/E2$ branching ratios using as much information (from experiments) as possible on the one-body operators. This comparison gives partial answers to questions such as is there any clear evidence of renormalization of these operators in the two-particle system, and does the branching ratio data provide information on those effective one-body operators that cannot be deduced directly from the ^{207}Pb information?

The energy levels in ^{206}Pb have been studied by a variety of techniques [5]. The currently adopted γ-ray branching ratios [5] are mainly from a study of the ^{206}Pb$(n,n'\gamma)$ reaction [6] supplemented by data from a study of ^{206}Bi electron-capture (ϵ) decay [7]. In this work we have made a detailed study of the ^{205}Pb(n,γ) reaction and obtained more precise branching ratios for several low-lying levels in ^{206}Pb.

II. EXPERIMENT

A. Sample preparation

To our best knowledge, the first attempt [8] to produce macroscopic amounts of ^{205}Pb ($T_{1/2}=1.52\times10^{7}$ y) was made by J. M. Wampler, J. B. Siberts, and R. W. Fink of the Georgia Institute of Technology with the assistance of P. L. Gray of Savannah River Laboratory. These authors irradiated ~1 mg of 99.8% enriched ^{204}Pb for over a year as part of the Savannah River High Flux Demonstration [9]. They produced not only ~18.6 μg of ^{205}Pb (as expected) from single-neutron capture but also ~1.5 μg of ^{206}Pb (which was totally unexpected) from double-neutron capture. The inference was made that the cross section for the ^{205}Pb (n,γ) reaction was about eight times the cross section for the ^{204}Pb(n,γ) reaction. Based on the known value of 661±70 mb [10] for the latter, these results implied a cross section for the ^{205}Pb(n,γ) reaction of ~5 b, a value which was adopted by Holden [11]. These results remained unpublished because (i) the authors lacked a detailed knowledge of the reactor

*Current address: U.S. Department of Energy, ER-23 GTN, Washington, D.C. 20585.

TABLE I. Composition of the $PbCO_3$ sample.

Constituent	Cross section[a]	Amount (mg)
Boron	767 b	4.6×10^{-3}
Carbon	3.5 mb	0.54
Oxygen	0.19 mb	2.16
Sulfur	520 mb	0.08
Chlorine	33.1 b	10.7×10^{-3}
Calcium	430 mb	0.25
Nickel	4.49 b	2.9×10^{-3}
Titanium	6.09 b	0.04
Iron	2.56 b	0.14
Cadmium	2520 b	0.6×10^{-3}
Samarium	5670 b	0.5×10^{-3}
Gadolinium	48890 b	0.8×10^{-6}
^{204}Pb	661 mb	1.23
^{205}Pb	~5 b	7.13
^{206}Pb	30.6 mb	0.42
^{207}Pb	712 mb	0.11
^{208}Pb	0.49 mb	0.14
	Total	12.25

[a]All values are from Ref. [15] except that for ^{205}Pb which is from Ref. [11]. All values are thermal (n,γ) cross sections except those for boron and cadmium which are absorption cross sections.

neutron spectrum and (ii) the epithermal contribution (resonance integral) of the ^{204}Pb(n,γ) reaction was unknown.

The current sample was prepared more than two decades ago. An $\sim$10 g sample of PbO enriched to 70.9% in ^{204}Pb was irradiated over a three-year period with a flux of $\sim 8\times10^{14}$ n/cm^2 s at the Oak Ridge High Flux Isotope Reactor. Upon removal from the reactor, the sample was taken to a hot cell and chemically purified. Most of the radioactive impurities were removed during the process of (i) dissolution in nitric acid and (ii) precipitation of lead as sulfate and oxalate. The latter compound was then ignited to oxide. The sample could then be removed and handled outside the hot cell. At this stage, the isotopic abundance of ^{205}Pb in the sample was 2.7%. The sample was then enriched to 78.9% in ^{205}Pb by passing it through a calutron. This procedure was accomplished by inserting the lead oxide into the vacuum system of the separator in a graphite charge bottle. Carbon tetrachloride was passed over the heated lead oxide to produce lead chloride vapor. This vapor was ionized and passed through a magnetic field to separate the lead isotopes. The enriched ^{205}Pb was collected in a water-cooled copper pocket. This material was dissolved off the copper with nitric acid, and the solution was boiled down and filtered. The lead was electrolyzed onto a platinum anode from $\sim 2M$ nitric acid solution, dissolved off the anode with nitric oxide and hydrogen peroxide, and precipitated as lead carbonate by means of ammonium carbonate. The precipitate was centrifuged and dried at 110 °C. The total yield of ^{205}Pb was $\sim$17 mg. About 40% of this material was available for the current study.

The 12.25-mg $PbCO_3$ sample that we used was analyzed for isotopic composition, but the usual analysis (spark-source spectrography) for chemical impurities was not performed. A preliminary (n,γ) measurement showed the presence of several impurities (Table I) that could potentially interfere with the ^{205}Pb(n,γ) measurements. At about the same time, we had built up a detailed library of γ-ray energies and intensities resulting from thermal-neutron capture for a large number of elements including those listed in Table I. Because the cross section for the ^{205}Pb(n,γ) is quite large, we decided that the degree of interference was not serious enough to warrant further chemical separations. Another series of measurements followed, and the final results are presented in this paper.

B. Measurements

The neutron capture γ-ray spectrum from the 12.25-mg $PbCO_3$ target and a 100.0-mg CH_2 standard was measured at the internal target facility located at the Los Alamos Omega West reactor. The experimental arrangement has been described in Refs. [12] and [13]. Briefly, the target was placed in a graphite holder which was inside an evacuated bismuth channel. The target position was 1.5 m from the edge of the reactor core, and at this position the thermal neutron flux was nominally 6×10^{11} n/cm^2 s. The γ rays were studied with a 30-cm^3 coaxial Ge(Li) detector positioned inside a 20-cm-diam $\times$ 30-cm-long NaI(Tl) annulus. This detector was located 6.3 m from the target and was

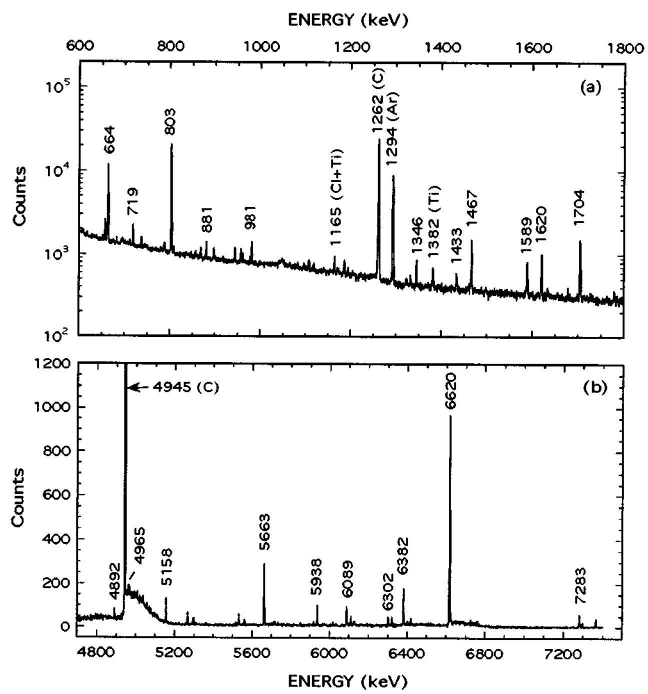

FIG. 1. Selected portions of γ-ray spectra from thermal-neutron capture by ^{205}Pb. The Ge(Li) detector was operated either in the Compton-suppression mode (a) or in the pair-spectrometer mode (b). All energies are in keV. A detailed list of γ rays observed in ^{206}Pb is given in Table II. The prominent 1262- and 4945-keV peaks arise mainly from the graphite holder which contained the ^{205}Pb sample. The 1294-keV peak is caused by argon present as an ambient background. See also Table I.

TABLE II. Energies (E_γ) and intensities (I_γ) of γ rays observed in the ^{205}Pb(thermal n, γ)^{206}Pb reaction.

E_γ^a (keV)	I_γ^b (mb)	Placement[c]	E_γ^a (keV)	I_γ^b (mb)	Placement[c]
126.42 *6*	53 *5*	1466.8 → 1340.5	1704.45 *3*	521 *11*	1704.4 → 0.0
313.67 *10*	39 *4*	1997.6 → 1684.0	1764.2 *7*	14 *5*	4000.7 → 2236.5
317.52 *14*	32 *4*	1784.1 → 1466.8	1822.1 *3*	53 *7*	3606.3 → 1784.1
343.55 *14*	37 *5*	1684.0 → 1340.5	1843.9 *6*	25 *6*	2646.9 → 803.0
537.48 *4*	793 *9*	1340.5 → 803.0	2319.32 *17*	58 *6*	3122.3 → 803.0
617.6 *4*	15 *4*	1784.1 → 1166.5	2391.0 *4*	17 *4*	3194.3 → 803.0
639.0 *4*	15 *4*	2423.4 → 1784.1	2650.3 *7*	15 *4*	3453.4 → 803.0
657.20 *4*	170 *5*	1997.6 → 1340.5	2682.0 *4*	28 *5*	3484.8 → 803.0
663.75 *3*	1413 *15*	1466.8 → 803.0	3194.6 *5*	26 *5*	3194.3 → 0.0
682.29 *19*	28 *4*	2148.9 → 1466.8	4115.9 *6*	27 *7*	4116.0 → 0.0
718.92 *5*	148 *6*	2423.4 → 1704.4	4480.2 *4*	87 *11*	C → 3606.3
803.04 *3*	3424 *33*	803.0 → 0.0	4568.1 *7*	23 *6*	C → 3518.5
808.58 *17*	28 *4*	2148.9 → 1340.5	4602.2 *9*	17 *6*	C → 3484.8
856.6 *6*	17 *5*	2197.3 → 1340.5	4892.3 *4*	71 *10*	C → 3194.3
880.92 *7*	105 *6*	1684.0 → 803.0	4964.6 *5*	85 *19*	C → 3122.3
956.56 *11*	63 *5*	2423.4 → 1466.8	5157.59 *19*	178 *14*	C → 2929.0
980.99 *5*	137 *6*	1784.1 → 803.0	5663.25 *7*	521 *17*	C → 2423.4
1082.7 *3*	26 *5*	2423.4 → 1340.5	5850.5 *5*	34 *5*	C → 2236.5
1194.3 *4*	23 *5*	1997.6 → 803.0	5888.1 *9*	11 *3*	C → 2197.3
1345.88 *7*	137 *7*	2148.9 → 803.0	5937.81 *14*	171 *10*	C → 2148.9
1393.8 *8*	15 *5*	2197.3 → 803.0	6089.09 *15*	199 *11*	C → 1997.6
1433.47 *13*	79 *6*	2236.5 → 803.0	6302.09 *21*	99 *8*	C → 1784.1
1466.78 *4*	429 *10*	1466.8 → 0.0	6382.06 *11*	351 *15*	C → 1704.4
1588.59 *8*	210 *8*	2929.0 → 1340.5	6402.3 *7*	28 *5*	C → 1684.0
1620.30 *6*	305 *11*	2423.4 → 803.0	6619.70 *5*	1885 *40*	C → 1466.8
1655.5 *6*	16 *4*	3122.3 → 1466.8	6746.0 *9*	22 *5*	C → 1340.5
1699.5 *9*	15 *4*	3484.8 → 1784.1	7283.4 *3*	122 *9*	C → 803.0

[a]In our notation, 126.42 *6* ≡ 126.42 ± 0.06, etc.
[b]Measured photon intensity. In our notation, 53 *5* ≡ 53 ± 5, etc. Multiply by 0.0224 to obtain photon intensity per 100 thermal-neutron captures.
[c]See also Table III. The symbol C denotes the capturing state at 8086.67 keV.

operated in either a Compton-suppression or pair spectrometer mode. The system resolution (full width at half maximum) in the latter mode was typically 2.5, 3.3, 4.0, and 4.7 keV, respectively, for γ-ray energies of 3, 5, 7, and 9 MeV. Measured spectra are shown in Fig. 1. The γ-ray energies quoted in this paper are based on the energy of the annihilation radiation (511.000 ± 0.002) keV and on the neutron separation energies (in keV) for ^{2}H, ^{13}C, and ^{3}T (2224.570 ± 0.004, 4946.312 ± 0.030, and 6257.246 ± 0.009, respectively) given in Ref. [14]. The capture cross sections are normalized to the recommended value of $\sigma_\gamma(2200\ \text{m/s}) = 332.6 \pm 0.7$ mb [15] for ^{1}H present in the CH_2 standard.

C. Results

The energies and intensities of 54 γ rays assigned to ^{206}Pb are given in Table II. All of these γ rays have been incorporated into the level scheme given in Table III. All levels listed in the latter are previously known, and the placements of transitions are consistent with both existing data and the results of new ^{206}Pb$(n,n'\gamma)$ measurements carried out at the University of Kentucky [16]. The level energies listed in Table III were obtained through an overall least-squares fit involving all transitions. Nuclear recoil was taken into account. Each measured photon intensity (I_γ) was converted to transition intensity (I_{tr}) by taking the corresponding internal conversion intensity into account. For this conversion, we used the multipolarities and mixing ratios given in Ref. [5]. The total transition intensity out of the capturing state is only (87 ± 2)% of the total intensity feeding the ground state. The missing 13% intensity is ascribed to weak and therefore unobserved primary transitions. This missing intensity is also reflected in the slight intensity imbalances for most levels (see Table III).

The neutron separation energy (S_n) of ^{206}Pb was determined as 8086.67 ± 0.06 keV where the uncertainty includes the uncertainty in the calibration energies. This value is significantly different from the S_n value of 8088.1 ± 0.4 keV

TABLE III. Level scheme of ^{206}Pb in tabular form and intensity balance in the ^{205}Pb(thermal n, γ) reaction.

E(level)[a] (keV)	Ref. [5] J^{π}	Deexciting transitions	$\sum I^{b}_{tr}$(in) (mb)	$\sum I^{b}_{tr}$(out) (mb)	$\sum I^{b}_{tr}$(in − out) (mb)
0.0	0^+		4464 *37*		4464 *37*
803.04 *3*	2^+	803.04	3428 *30*	3460 *33*	−32 *45*
1166.5 *4*	0^+	1166.5[c]	15 *4*	15 *4*	
1340.46 *4*	3^+	537.48	851 *34*	867 *10*	−16 *35*
1466.80 *3*	2^+	126.42, 663.75, 1466.78	2038 *41*	2237 *35*	−199 *54*
1683.98 *6*	4^+	343.55, 880.92	82 *8*	154 *10*	−72 *12*
1704.45 *3*	1^+	1704.45	506 *17*	521 *11*	−15 *20*
1784.09 *5*	2^+	317.52, 617.6, 980.99	183 *12*	199 *10*	−16 *16*
1997.65 *5*	4^+	313.67, 657.20, 1194.3	199 *11*	256 *10*	−57 *15*
2148.93 *6*	2^+	682.29, 808.58, 1345.88	171 *10*	196 *9*	−25 *14*
2197.3 *5*	(3^+)[d]	856.6, 1393.8	11 *3*	33 *7*	−22 *8*
2236.49 *13*	(1^+)[d]	1433.47	48 *7*	79 *6*	−31 *10*
2423.35 *4*	2^+	639.0, 718.92, 956.56, 1082.7, 1620.30	521 *17*	567 *16*	−46 *23*
2646.9 *6*	3^-	1843.9		25 *6*	−25 *6*
2929.05 *9*	4^+	1588.59	178 *14*	211 *8*	−33 *17*
3122.33 *16*	(3^+)	1655.5, 2319.32	85 *19*	74 *8*	11 *21*
3194.29 *25*	$1^{\pm}, 2^{+}$ [e]	2391.0, 3194.6	71 *10*	43 *7*	28 *12*
3453.4 *7*	4^{+} [f]	2650.3		15 *4*	−15 *4*
3484.8 *4*		1699.5, 2682.0	17 *6*	43 *7*	−26 *9*
3518.5 *7*	(4^+)		23 *6*		23 *6*
3606.28 *25*	2^+	1822.1	87 *11*	53 *7*	34 *13*
4000.7 *8*		1764.2		14 *5*	−14 *5*
4115.9 *6*	$1^{\pm}, 2^{+}$ [e]	4115.9		27 *7*	−27 *7*
...	..	...	..	..	..
...	..	...	..	..	..
8086.67[g] *5*	$2^- + 3^-$	4480.2, 4568.1, 4602.2, 4892.3, 4964.6, 5157.59, 5663.25, 5850.5, 5888.1, 5937.81, 6089.09, 6302.09, 6382.06, 6402.3, 6619.70, 6746.0, 7283.4		3904 *58*	−3904 *58*

[a]In our notation, 803.04 *3* ≡ 803.04 ± 0.03, etc.
[b]Total tansition intensity in and out of a particular level. In our notation, 4464 *37* ≡ 4464±37, 3460 *33* ≡ 3460±33, etc. Internal conversion is taken into account.
[c]Unobserved $E0$ transition whose intensity, 15±4 mb, is inferred from the intensity balance at the 1166.5-keV level. This level is known to decay nearly 100% to the ground state.
[d]Based partly on correspondence with the shell model. See Table IV. No J^{π} assignment given in Ref. [5].
[e]From the presence of a γ ray to the 0^+ ground state observed in this work.
[f]This assignment in inconsistent with recent ^{206}Pb($n,n'\gamma$) measurements [16] which suggest a definite $J=3$ assignment.
[g]Capturing state.

given in the 1993 Atomic Mass adjustment [18] based mainly on the measured value of $Q=-1831.2\pm0.5$ keV for the ^{206}Pb(d,t) reaction [17]. Our S_n(^{206}Pb) value implies $Q=-1829.42\pm0.07$ keV for this reaction. Our S_n(^{206}Pb) value and S_n(^{205}Pb)$=6731.57\pm0.15$ keV measured at Grenoble [19], both using the (n,γ) reaction, can be combined to predict a value of 4072.4±0.2 keV for the ^{206}Pb^{35}Cl−^{204}Pb^{37}Cl mass doublet. This value is in good agreement with the directly measured value of 4071.8±0.8 keV [20].

Because the level scheme is incomplete, the three quantities ΣI_{tr} (primary), $\Sigma E_{\gamma} I_{tr}/S_n$, and ΣI_{tr} (secondary to ground state) are not the same. The numerical values (in units of b) for these three quantities are 3.90±0.06, 4.03±0.05, and

TABLE IV. Observed and calculated energy levels in ^{206}Pb.

Experiment E(level) (keV)	Experiment J^π	Shell model E(level) (keV)	Shell model J^π	Comments
0	0^+	0	0_1^+	
803	2^+	818	2_1^+	
1166	0^+	1158	0_2^+	
1340	3^+	1332	3_1^+	
1467	2^+	1443	2_2^+	
1684	4^+	1718	4_1^+	
1704	1^+	1703	1_1^+	
1784	2^+	1788	2_3^+	
1998	4^+	1971	4_2^+	
2149	2^+	2157	2_4^+	
2197	(3^+)	2196	3_2^+	
2200	7^-	2198	7_1^-	
2236	(1^+)	2235	1_2^+	
2315	0^+	2327	0_3^+	
2384	6^-	2384	6_1^-	
2423	2^+	2409	2_5^+	
2647	3^-			Collective state
2658	9^-	2658	9_1^-	
2782	5^-	2777	5_1^-	
2826	$(4)^-$	2826	4_1^-	
2865	7^-	2868	7_2^-	
2929	4^+	2929	4_3^+	
2940	6^-	2941	6_2^-	
2960				Reported only in (p,p')
		2962	8_1^-	Experimental analog not known
2984	2^+			Reported in (p,p') and (p,t)
3016	5^-	3023	5_2^-	
3033				Reported only in (p,p')
		3096	0_4^+	Experimental analog not known
3122	(3^+)	3103	3_3^+	
3139				Reported only in (p,p')
3193	(5^-)			Reported in (p,p') and (p,t)
3194	$1^\pm,2^+$			
3225	$6^-,7^-$	3227	6_3^-	
		3254	7_3^-	Experimental analog not known
3244	4^-			Reported in ^{206}Bi decay
3260	6^+	3257	6_1^+	
3279	5^-			
		3286	8_2^-	Experimental analog not known
...	..	...	..	Approximately 23 levels here
3957	(10^+)	3958	10_1^+	
...	..	...	..	Approximately 9 levels here
4027	12^+	4027	12_1^+	
...	..	...	..	Approximately 210 levels below
...	..	...	..	the neutron separation energy

4.46 ± 0.04, respectively. We recommend a value of 4.5 ± 0.2 b for the thermal ^{205}Pb(n,γ) cross section where the generously assigned uncertainty takes into account the possibility that some weak secondary transitions feeding the ground state may have escaped detection.

III. SHELL-MODEL CALCULATIONS

There are currently 34 experimentally known excited states in ^{206}Pb (see Table IV) below 3.30 MeV, and 24 of these 34 states have firm spin and parity (J^π) assignments [5]. Sixteen of these 34 states are populated measurably in the ^{205}Pb(n,γ) reaction. The states at 2960, 3033, and 3139 keV have been reported only in the (p,p') reaction [21]. We found no evidence for these three levels in the current work. The 2984-keV, $J^\pi=2^+$ state, reported in the (p,p') [21] and (p,t) [22,23] reactions, is not populated measurably in the (thermal n,γ) reaction. Between 3.30 and 4.03 MeV, $\sim$34 levels are known, but only 13 of these have definite J^π assignments [5].

We have studied the structure of ^{206}Pb in terms of the spherical shell model in which we assume that the ^{208}Pb core is closed and neutron holes are ''occupied'' in the six lowest single-neutron-hole orbits ($2p_{1/2}$, $2p_{3/2}$, $1f_{5/2}$, $1f_{7/2}$, $0h_{9/2}$, and $0i_{13/2}$). In the calculations reported here, the neutron single-hole energies are the same as those used previously [2]. These energies are consistent with the observed spectrum of states in the single-hole nucleus ^{207}Pb. In our calculations, we used a variant of the one-parameter Kuo-Herling residual interaction [1]. We included the first two terms of this interaction; namely, the bare interaction and the core-polarization (or bubble) diagram. In addition, we multiplied the bubble diagram matrix elements by the single empirical constant 0.75. With this change, the calculated energies for 25 excited states below 3.30 MeV (see Table IV) are in virtually exact agreement with experiment, with the average deviation (absolute value) between theory and experiment being only 8 keV, and the root mean square deviation only 12 keV. An inspection of the wave functions for these states shows that there is large configuration mixing for the ground state and the first-excited $J^\pi=2^+$ state. Most of the rest of the even-parity states are rather pure, simple, single configuration, two-hole states.

We have also calculated the $M1$ and $E2$ branching ratios for the low-lying states in ^{206}Pb. In calculations of $E2$ observables, we used the single-particle wave functions of a harmonic oscillator with shell spacing given by $\hbar\omega = 41A^{-1/3}$ MeV. Further, we assumed a state-independent effective charge $e_n = 0.84e$ for all the neutron single-particle transition matrix elements—a parameter chosen so that the calculated lifetime of the first-excited $J^\pi=2^+$ state agreed with experiment. The $M1$ operator was specified by eight single-hole transition matrix elements. Five of these were determined from the three measured magnetic moments and two $M1$ transition rates in ^{207}Pb (see Table 2 of Ref. [2], except that we used the latest experimental values). Thus, there were three free parameters. We formed the $M1$ operator by using the experimental values for the five matrix elements, and we used the free nucleon magnetic-moment operator for the remaining three matrix elements.

TABLE V. Measured and calculated γ-ray branching ratios of positive-parity states in ^{206}Pb below 3.13 MeV.

				Photon branching[a]		
E_i(keV)	J^π	E_f(keV)	J^π	Previous[b]	Current	Theory
1467	2_2^+	0	0_1^+	22.6 *14*	22.6 *6*	48.3
		803	2_1^+	77.4 *18*	74.6 *9*	51.5
		1340	3_1^+		2.8 *3*	0.2
1684	4_1^+	803	2_1^+	73.8 *8*	74 *4*	77.2
		1340	3_1^+	26.2 *4*	26 *4*	22.8
1704	1_1^+	0	0_1^+	100	100	85.4
		803	2_1^+	< 4	< 2	7.4
		1166	0_2^+		< 2	6.3
		1467	2_2^+		< 2	0.9
1784	2_3^+	0	0_1^+	4 *1*	< 6	0.4
		803	2_1^+	73 *3*	74 *4*	59.0
		1166	0_2^+		8 *2*	5.5
		1340	3_1^+		< 7	2.5
		1467	2_2^+	24 *4*	17 *2*	32.2
1998	4_2^+	803	2_1^+	10.9 *6*	9.9 *22*	10.8
		1340	3_1^+	75.0 *12*	73.3 *22*	79.9
		1684	4_1^+	14.1 *4*	16.8 *17*	9.1
2149	2_4^+	0	0_1^+	< 3	< 5	0.7
		803	2_1^+	100	71.1 *36*	73.8
		1340	3_1^+		14.4 *21*	14.5
		1467	2_2^+		14.4 *21*	10.5
		1704	1_1^+			0.4
2197	3_2^+	803	2_1^+	44 *3*	47 *17*	33.5
		1340	3_1^+	56 *4*	53 *17*	52.3
		1467	2_2^+			7.6
		1684	4_1^+			5.1
		1998	4_2^+			1.3
2236	1_2^+	0	0_1^+			0.1
		803	2_1^+	100	100	95.7
		1340	3_1^+			0.3
		1467	2_2^+			3.6

				Photon branching[a]		
E_i(keV)	J^π	E_f(keV)	J^π	Previous[b]	Current	Theory
2315	0_3^+	803	2_1^+			1.5
		1467	2_2^+			1.7
		1704	1_1^+			96.8
2423	2_5^+	0	0_1^+	< 3	< 2	1.4
		803	2_1^+	64 *7*	54.8 *21*	26.2
		1166	0_2^+		< 3	0.1
		1340	3_1^+		4.7 *10*	0.7
		1467	2_2^+		11.3 *10*	15.2
		1704	1_1^+	36 *4*	26.6 *12*	51.8
		1784	2_3^+		2.7 *8*	4.2
		2149	2_4^+		< 2	0.4
2929	4_3^+	803	2_1^+		< 4	0.7
		1340	3_1^+	100	100	96.8
		1467	2_2^+		< 7	0.7
		1684	4_1^+		< 5	0.2
		1998	4_2^+		< 5	0.5
		2197	3_2^+		< 6	1.1
3096[c]	0_4^+	803	2_1^+			72.5
		1467	2_2^+			2.2
		1704	1_1^+			23.1
		1784	2_3^+			2.1
3122	3_3^+	803	2_1^+	100	78 *9*	78.9
		1340	3_1^+			4.2
		1467	2_2^+		22 *6*	13.7
		1684	4_1^+			0.5
		1704	1_1^+			0.8
		1784	2_3^+			1.0
		2149	2_4^+			0.5

[a]When setting the total photon intensity out of a particular level as 100, upper intensity limits for unobserved γ rays are ignored. In our notation, 22.6 *14* ≡ 22.6 ± 1.4, 22.6 *6* ≡ 22.6 ± 0.6, etc.

[b]Branchings of the 1467- and 1998-keV levels are from ^{206}Bi ε-decay studies [7]; all other branchings are from ^{206}Pb$(n,n'\gamma)$ studies [6].

[c]From theory (see Table IV). All other level energies are from experiment.

The calculated branching ratios are summarized in Table V, in which the measured values for the ratios are also shown. We give only those branchings that differ significantly from zero. Thus, the total branchings in this table do not always sum to 100%.

In general, the calculations and observations are in good agreement. The most significant discrepancies are for the decay of the second and fifth $J^{\pi}=2^{+}$ states. We have made a preliminary attempt to see if any simple modifications of the effective $M1$ operator can reduce these discrepancies. Because of the simple nature of many of the wave functions, the branching ratios in a number of cases should depend sensitively on only one or two of the effective operator matrix elements. We looked for such behavior by repeating the calculations a number of times while setting one of the effective $M1$ matrix elements to zero each time. The calculated branching ratios that are in most serious disagreement with the measurements were not found to be sensitive to any of the three bare matrix elements. Thus in spite of the simplicity of the wave functions, we have, to date, found no simple ''fix'' to settle these few discrepancies that do exist for the branching ratios.

IV. SUMMARY

Using $\sim$7 mg of radioactive ^{205}Pb, we have studied the ^{205}Pb(n,γ) reaction with thermal neutrons. This reaction was found to measurably populate 22 excited states in ^{206}Pb. For these states we have determined accurate level energies and, whenever possible, good branching ratios. We have calculated the energies and branching ratios of low-lying levels in ^{206}Pb within the framework of the conventional shell model with the Kuo-Herling residual interactions. Excellent agreement is obtained with the experimental level scheme. The branching ratios are in good agreement for most, but not all, low-lying positive-parity states in ^{206}Pb.

ACKNOWLEDGMENTS

We thank Professor Marcus McEllistrem, University of Kentucky, for sharing the new ^{206}Pb$(n,n'\gamma)$ results and Dr. Murray Martin for critically reading the manuscript. The current work was sponsored by the U.S. Department of Energy under Contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation (Oak Ridge) and W-7405-eng-36 with the University of California (Los Alamos).

[1] T. T. S. Kuo and G. Herling, U.S. Naval Research Laboratory Report No. 2258, 1971; G. Herling and T. T. S. Kuo, Nucl. Phys. **A181**, 113 (1972).
[2] J. B. McGrory and T. T. S. Kuo, Nucl. Phys. **A247**, 283 (1975).
[3] N. A. F. M. Poppelier and P. W. M. Glaudemans, Z. Phys. A **329**, 275 (1988).
[4] D. Wang and M. T. McEllistrem, Phys. Rev. C **42**, 252 (1990).
[5] See R. G. Helmer and M. A. Lee, Nucl. Data Sheets **61**, 93 (1990), and references contained therein.
[6] J. K. Dickens, Phys. Rev. C **28**, 916 (1983). See also Oak Ridge National Laboratory Report No. ORNL/TM-8137, 1982.
[7] M. Kanbe, M. Fujioka, and K. Hisatake, Nucl. Phys. **A192**, 151 (1972).
[8] J. M. Wampler (private communication).
[9] J. A. Smith, E. J. Henelly, C. H. Ice, and H. F. Allen, in ''The Savannah River High Flux Demonstration,'' edited by J. L. Crandall [E. I. Du Pont de Nemours and Co. Report No. D-999 (1965)].
[10] E. T. Jurney, H. T. Motz, and S. H. Vegors, Jr., Nucl. Phys. **A94**, 351 (1967).
[11] N. E. Holden, in *Handbook of Chemistry and Physics*, edited by D. R. Lide, Jr. (CRC Press, Boca Raton, 1994), pp. 11–119.
[12] S. Raman, R. F. Carlton, J. C. Wells, E. T. Jurney, and J. E. Lynn, Phys. Rev. C **32**, 18 (1985).
[13] T. A. Walkiewicz, S. Raman, E. T. Jurney, J. W. Starner, and J. E. Lynn, Phys. Rev. C **45**, 18 (1992).
[14] A. H. Wapstra, Nucl. Instrum. Methods, A **292**, 671 (1990). The values listed here are consistent with those given in the 1995 update to the atomic mass evaluation by G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[15] S. F. Mughabghab, M. Divadeenam, and N. E. Holden, *Neutron Cross-Sections* (Academic, New York, 1981), Vol. 1, Part A, p. 1–1.
[16] M. T. McEllistrem (private communication).
[17] H. Lindner, H. Trieb, T. von Egidy, H. Hiller, J. Klora, U. Mayerhofer, A. Walter, and A. H. Wapstra, Nucl. Instrum. Methods A **297**, 217 (1990). The measurement of this ground-state Q value is complicated by the fact that the first-excited state in ^{205}Pb lies only 2.3 keV above the ground state.
[18] G. Audi and A. H. Wapstra, Nucl. Phys. **A565**, 1 (1993).
[19] P. Hungerford, T. von Egidy, H. H. Schmidt, S. A. Kerr, H. G. Börner, and E. Monnand, Z. Phys. A **313**, 349 (1983).
[20] M. S. Sidky, J. G. Hykawy, G. R. Dyck, B. J. Hall, R. C. Barber, K. S. Sharma, C. A. Lander, and H. E. Duckworth, Nucl. Instrum. Methods, A **330**, 195 (1993).
[21] J. E. Finck, G. M. Crawley, J. A. Nolen, Jr., and R. T. Kouzes, Nucl. Phys. **A407**, 163 (1983).
[22] W. A. Lanford, Phys. Rev. C **16**, 988 (1977).
[23] H. Wienke, H. P. Blok, J. F. A. van Hienen, and J. Blok, Nucl. Phys. **A442**, 397 (1985).