Radiative Transitions in ^{207}Pb and ^{208}Pb Following Resonance Neutron Capture in ^{206}Pb and ^{207}Pb†

J. A. BIGGERSTAFF, J. R. BIRD,* J. H. GIBBONS, AND W. M. GOOD
Oak Ridge National Laboratory, Oak Ridge, Tennessee

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Measurements were made of the spectra of gamma rays that are emitted when neutrons of various energies below 100 keV are captured in ^{206}Pb and ^{207}Pb. Capture resonances were observed, and gamma-ray de-excitation takes place primarily to the $\frac{1}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$ levels in ^{207}Pb, and to the 0^+ and 3^- levels in ^{208}Pb. A few other weaker transitions are seen in ^{207}Pb to unidentified levels. It is possible to make plausible spin and parity assignments to the resonant states by combining these results with earlier measurements of total and capture cross sections. The measurements collectively indicate a predominance of negative-parity capturing states in ^{207}Pb and positive-parity capturing states in ^{208}Pb. The positive-parity resonances in ^{208}Pb decay predominantly through the 3^- state at 2.61 MeV, and the 1^- neutron resonance capture decays directly to ground.

I. INTRODUCTION

THE lead isotopes have been and continue to be prime tragets for theoretical and experimental investigations. The fact that these isotopes are nearly doubly magic means that there is hope, at least, of predicting properties of individual nuclear states without having to solve the many-body problem in detail. The relatively wide spacing of nuclear levels, also arising from the near-closed-shell configuration, is attractive to the experimentalist since this yields spectra which are easy to evaluate.

Knowledge of the energy level and angular momentum and parity structure of the lead nuclei has increased considerably in the last few years. Credit for this accomplishment goes to improved energy resolution of beams of particles with sufficient energy to "surmount" the potential barrier, together with greater efficiency for measuring reaction products with energy resolution adequate to resolve individual levels. The results of such measurements, especially by Mukherjee and Cohen,[1] and by Miller, Wegner, and Hall[2] have resulted, for example, in the identification of a number of new states in ^{207}Pb.

Some time ago we reported[3] new levels in ^{207}Pb using neutrons of up to 100 keV on radiogenic lead and the two-parameter neutron-flight-time versus gamma-ray-energy spectrometer described elsewhere.[4] In addition, our unpublished studies on resonance neutron capture on ^{207}Pb indicate at least one previously unobserved level in ^{208}Pb a few tens of keV above the neutron separation energy.

These results were instrumental in motivating detailed measurements on neutron total and capture cross sections for target nuclei of ^{206}Pb and ^{207}Pb. The results of these latter measurements have been published.[5] In this paper we present the results of measurements of the resonance neutron gamma-ray spectra on these same nuclei. The capture gamma-ray spectra results, when combined with information obtained in the capture and total cross-section measurements, have enabled us to obtain in some cases the absolute reduced partial radiative widths and also some evidence for previously unobserved *bound* states in ^{207}Pb. Finally, the spectra have helped identify the character of some of the virtual levels that are too weakly excited to be uniquely identified from total cross-section measurements.

II. EXPERIMENTAL ARRANGEMENT

We published the details of the gamma-ray detector (9 in.×12 in. NaI crystal) and pulsed-beam time-of-flight system in another paper.[4] The equipment and geometry described in that paper were essentially the same as those used for the lead measurements. Neutron flight paths of 15 to 69 cm were used, giving a neutron energy resolution of 150 to 40 nsec/m. The gamma-ray detector had a resolution of 5.5% full width at half maximum (FWHM) at 6.1 MeV. A schematic diagram of the experimental arrangement is given by Fig. 1.

Samples were metallic lead "pancakes." Radiogenic lead (88% ^{206}Pb), electromagnetically enriched ^{207}Pb (93% ^{207}Pb), and normal lead samples were used. The ^{207}Pb sample ($\sim$75 g total weight) was by far the smallest sample used; counting-rate considerations dictated the use of relatively poorer neutron resolution for this sample (150 nsec/m).

The data (counts versus gamma pulse height and neutron energy) were stored in a 16×128 or 8×256 channel two-parameter analyzer consisting of a 2048-channel RCL mated with an ORNL stacked-discriminator 20-channel analyzer. Inputs were arranged so that either the gamma pulse height or neutron flight time

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* Present address: Australian Atomic Energy Commission, Sutherland, N.S.W., Australia.

[1] P. Mukherjee and B. L. Cohen, Phys. Rev. **127**, 1284 (1963).
[2] D. W. Miller, H. E. Wegner, and W. S. Hall, Phys. Rev. **125**, 2054 (1962).
[3] J. R. Bird, J. H. Gibbons, and W. M. Good, Bull. Am. Phys. Soc. **7**, 552 (1962).
[4] J. R. Bird, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good, Phys. Rev. **138**, B20 (1965).
[5] R. L. Macklin, P. J. Pasma, and J. H. Gibbons, Phys. Rev. **136**, B695 (1964).

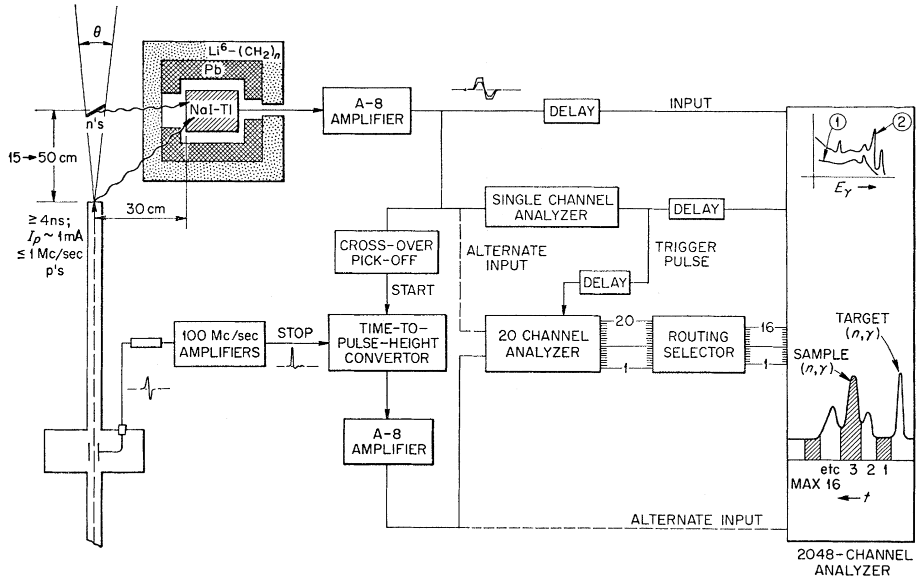


FIG. 1. Block diagram of experimental arrangement.

dimension could be fed into the 128-channel side. The normal operating mode was to allot the 128-channel dimension to gamma pulse height but the reverse was sometimes used for a detailed examination of neutron energy spectra. An example of results obtained under the usual conditions is shown in Fig. 2. The length of a run varied from 2 to 10 h, but was usually 4 to 6 h. The second, less frequently used, mode of acquisition gave results exemplified by Fig. 3. Finally, for the short-flight-path experiments using a sample of enriched ^{207}Pb only 8 channels of neutron energy were used and consequently 256 channels of gamma-ray data were available (Fig. 4).

III. CALIBRATIONS AND BACKGROUNDS

While several of the resonances in (^{207}Pb+n) referred to in this paper were originally discovered by our capture gamma-ray studies,[3] the resonance neutron energy has been much more accurately determined in transmission measurements.[5] Our results, though less accurate, are in good agreement with the transmission results. The NaI spectrometer was frequently calibrated for absolute gamma-ray energies by using ThC'' and other natural sources. We did not use automatic-gain-control techniques and as a consequence frequently could not inter-

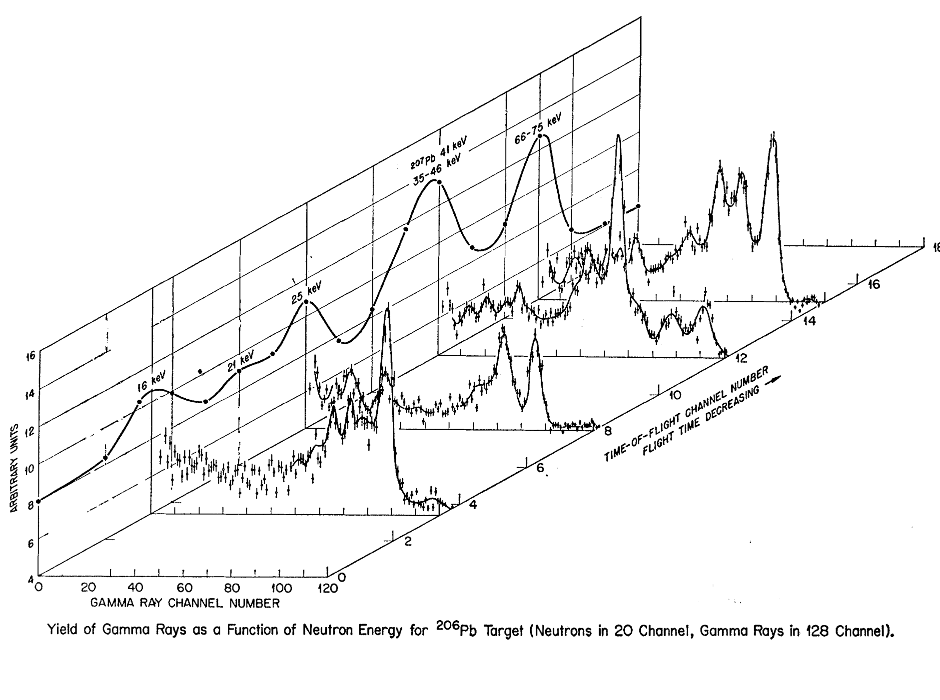
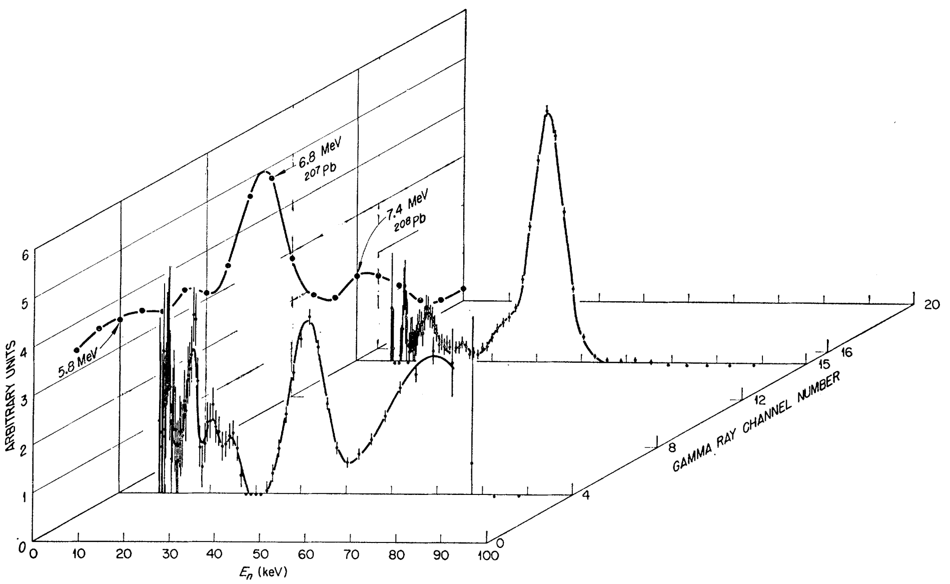


FIG. 2. Details of capture gamma-ray spectra taken simultaneously for several different values of neutron energy. The sample was radiogenic lead, and time-of-flight resolution over the 50-cm flight path was insufficient to always resolve the several resonances observed due to the two isotopes. Gamma energies are given in the text.



Yield of Gamma Rays as a Function of Neutron Energy for NATPb Target (Gamma Rays in 20 Channel, Neutrons in 128 Channel).

FIG. 3. Details of the time-of-flight capture rate in natural lead for two different values of capture gamma-ray energy. The curve corresponding to a gamma ray of 7.4 MeV can only be due to capture in ^{207}Pb.

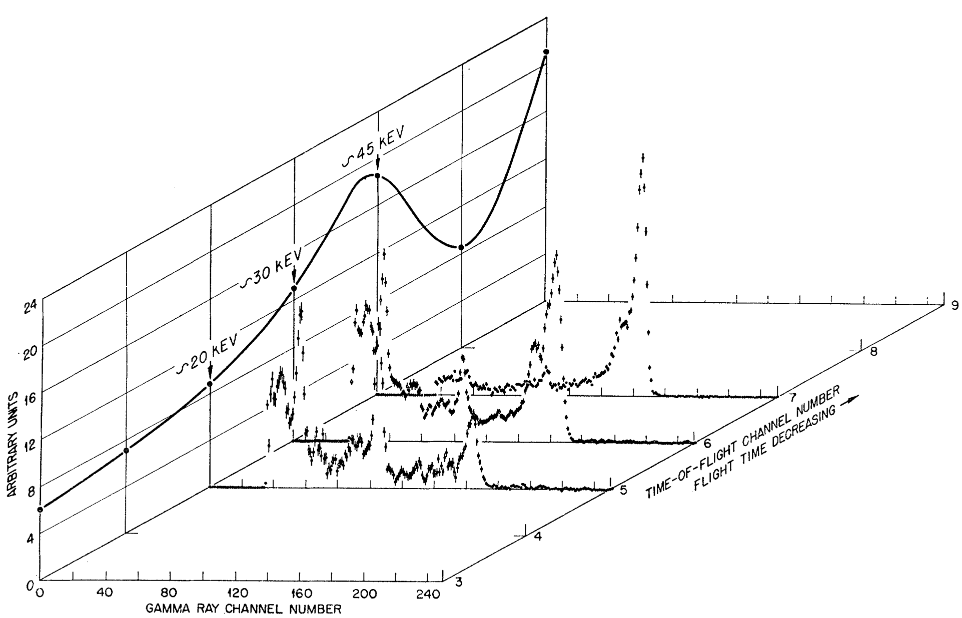
pret absolute gamma-ray energies to closer than about 1%.

The gamma-ray background had only a slight time dependence over a period of a few hundred nsec, largely due to radiation from epithermal neutron capture such as H(n,γ) in the shielding and crystal. Further, the time interval over which the background and data were taken was different and subject to drifts due to the use of the rather antiquated vacuum-tube 20-channel analyzer. As a consequence of these background effects, we assigned additional uncertainties to the accuracy of relative as well as absolute radiative widths.

IV. RESULTS

The experimental results can be presented and discussed in two different ways: (a) the relative cross section as a function of neutron energy for the production of a given capture gamma ray, and (b) the relative intensities of various capture gamma rays from a given neutron resonance.

The data presented in Fig. 3 (capture in natural lead) are illustrative of mode (a). Certain resonating gamma rays, such as the one at 7.4 MeV (ground-state transition from ^{207}Pb$+n$), give an unambiguous isotopic as-



Yield of Gamma Rays as a Function of Neutron Energy for 207Pb Target (Neutrons in 8 Channel, Gamma Rays in 256 Channel).

FIG. 4. Details of capture gamma-ray spectra taken simultaneously for several values of neutron energy. The sample was enriched to 93% ^{207}Pb. The flight path, only 15 cm, was insufficient to fully resolve individual resonances, but significant changes in the spectra were observed and interpreted with the aid of high-resolution capture and total cross sections. Gamma energies are given in the text.

TABLE I. Summary of individual gamma-ray relative intensities from neutron capture at various resonances in ^{206}Pb. The left column lists with each row the resonance energy, probable neutron angular momentum, and probable resonance spin and parity. The top row gives energy and J^π of final states to which transitions are observed.

E_{res} (keV)	g	Final state E_{ex} (MeV) J^π / J^π	3.55 or 3.21 $(\frac{3}{2}\pm)$	4.15 or 2.61 $(\frac{5}{2}+)$	0.87 $\frac{3}{2}-$	0.57 $\frac{5}{2}-$	Ground $\frac{1}{2}-$
16.5	1	$(\frac{1}{2}-)$	10±5	≤4	17±3	≤6	73±3
21	2	$(\frac{5}{2}+)$	36±12	10±5	19±8	34±8	≤4
25	2	$\frac{3}{2}-$	14±10	26±5	≤2	26±2	36±4
35 and 46	1	$(\frac{3}{2}-)$	15±8	15±3	47±3	15±3	8±2
66 and 72	···	$\frac{1}{2}+$	12±7	7±7	23±2	10±3	48±3

signment to the resonance. Resonances in (^{207}Pb+n) are evident at about 11 and 16 keV in addition to unresolved ones (later found by transmission studies) at 27 and 36 keV and the large resonance at 42 keV. In addition, the small peak near 23 keV is probably statistically significant. Additional resonances are seen for lower (≈5 MeV) gamma-ray pulse height, which corresponds to the more intense lines from (^{206}Pb+n). These were more difficult to assign isotopically from gamma-ray energy considerations alone, but were readily identified using isotopically enriched samples. Relative capture cross sections were obtained by comparison with the yield of capture gamma rays from a sample of cadmium, whose capture cross section is smoothly varying and reasonably well known.

We originally hoped to use ground-state gamma rays from the well-known 1^- level near 42 keV (^{207}Pb+n) to look for possible neutron energy-dependent interference effects between so-called direct and compound capture mechanisms.[6–10] If both types of phenomena occur appreciably in this reaction, the resonance shape, as determined from the ground-state gamma-ray yield, should show an asymmetry similar to that seen in neutron scattering. Our measurements indicated an asymmetry, but its shape seemed to imply an additional resonance rather than an interference effect. This turned out to be the case, as resonances at 27 and 36 keV were later found in transmission studies.[5] The presence of these resonances, especially the one at 36 keV, precludes for the present any further study of possible interference effects at the 42-keV resonance, mostly because of insufficient neutron energy resolution.

Transmission measurements, which can be performed with several times better resolution, have been performed[5] on ^{206}Pb and ^{207}Pb. Comparison of the 5-MeV gamma-ray yield corresponding to (^{206}Pb+n) capture in Fig. 3 with the total cross section shows that the resonances at 12, 16, 21, and 25 keV are resolved in the gamma-ray studies but that the gamma-ray peaks near 40 and 70 keV are each due to at least two resonances. Gamma spectra from these peaks are therefore much more difficult to interpret.

We present in Fig. 2 a sample of results obtained from mode (b), that is, capture spectra versus neutron energy using radiogenic lead (80% ^{206}Pb). Only representative data are shown; a total of 15 different spectra were obtained in this particular experiment but only 4 are shown. A summary of information obtained from these results is given in Table I. Individual line intensities were obtained by a "stripping" process based on known detector response to gamma rays of various energies. The intensities so obtained were then corrected for the detector total efficiency and for absorption in the LiH neutron shield. Probable spins and parities of the capturing state were assigned based on total cross-section results and upon the assumption that the observed radiation was dipole.

Results for (^{207}Pb+n) are given in Fig. 4. However, because of the small sample size the usable resolution was considerably poorer than for radiogenic lead. The data were sufficient to show that the (known) 42-keV (1^-) resonance decays almost exclusively by $E1$ emission to the ground state of ^{208}Pb and that the smaller resonances at lower energies decay primarily through the well known 3^- collective state at 2.61 MeV, indicating strongly that these capturing states probably are 2^+. Previous total-cross-section measurements[5] have indicated that these small scattering resonances are probably p wave.

The relative intensities of individual gamma rays from (^{206}Pb+n), summarized in Table I, when combined with results from capture and total cross-section measurements[5] yield the partial widths and reduced widths given in Table II. The reduced widths k were obtained from the partial widths $\Gamma_{\gamma\lambda}$ in the usual manner,[11] viz.,

$$k(E1)=\Gamma_\gamma(E1)[E_\gamma{}^3A^{2/3}D]^{-1}, \qquad (1)$$

$$k(M1)=\Gamma_\gamma(M1)[E_\gamma{}^3D]^{-1}, \qquad (2)$$

where Γ_γ is the observed partial radiative width in eV, D is the local spacing (in MeV) of resonances of a given spin and parity, and E_γ is the gamma energy in MeV.

[6] R. F. Christy, Nucl. Phys. 24, 89 (1961).
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[9] H. Moringa and C. Ishii, Progr. Theoret. Phys. (Kyoto) 23, 161 (1960).
[10] I. Lovas, Zh. Eksperim. i Teor. Fiz. 41, 1178 (1962) [English transl.: Soviet Phys.—JETP 14, 840 (1962)].

[11] G. A. Bartholomew, Natl. Acad. Sci.—Natl. Res. Council Publ. 974, 213 (1962).

TABLE II. Summary of information obtained on multipole character and radiation strength of various transitions observed in resonance neutron capture in ^{206}Pb. The left column lists with each row the resonance energy, probable spin and parity, probable statistical weight g, and radiative width. The top row gives excitation energy, and spin and parity of the final state. The entries in each position in the array are probable multipole type, partial radiation width (eV), and radiation strength as defined in Eqs. (1) and (2), using a level spacing D of 20 keV for p-wave resonances in (^{206}Pb+n). Parentheses imply uncertainity.

E_{res} (keV)	J^π	g	Γ_γ (eV) \ E_{exc} (MeV) / J^π	3.55 or 3.21 ($\frac{3}{2}^{+,-}$)	4.15 or 2.61 ($\frac{5}{2}^+$)	0.87 $\frac{3}{2}^-$	0.57 $\frac{5}{2}^-$	Ground $\frac{1}{2}^-$
16.5	($\frac{1}{2}^-$)	1	0.87	0.09	$\cdots$	(M1),0.15,3.6×10^{-2}	($E2$)$\cdots$	($M1$),0.63,10×10^{-2}
25	$\frac{3}{2}^-$	2	0.39	0.05	0.10	M1	$M1$,0.09,1.9×10^{-2}	$M1$,0.14 $2.3\times1,0^{-2}$
35 and 46	($\frac{3}{2}$)	2,2	0.43, 0.43	0.065	0.065	(M1),0.20,(5.0×10^{-2})	(M1),0.065,(1.4×10^{-2})	(M1),0.035,(0.57×10^{-2})

For (^{207}Pb+n), the corresponding results can be simply summarized: Assuming that all captures in the (1^-) resonance decay directly to the ground state, the $E1$ gamma ray reduced width is 41×10^{-3}; likewise transitions (assumed to be from 2^+ capturing states) through the 3^- level have an average $E1$ reduced width of about 7×10^{-3}.

V. DISCUSSION AND SUMMARY

Six high-energy capture gamma-ray lines were observed from (^{206}Pb+n). Three of these correspond to transitions to known states and the other lines correspond to levels, the possible locations of which are shown in Fig. 5. On the basis of energy measurement alone, the states could conceivably be identified, within the combined errors of measurement, as the 3.62- and 4.29-MeV levels observed in ^{206}Pb(d,p). However, these levels have been established to be $\frac{9}{2}^-$ and $15/2^-$, respectively.[1] Therefore, they could not be the states we observed in ^{206}Pb(n,γ) since they would require very high-order multipole radiation. Of course, the possibility of $\frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^\pm$ in close proximity to the $\frac{9}{2}^-$ and $15/2^-$ levels and not resolved in ^{206}Pb(d,p) measurements cannot be excluded. Experiments on ^{207}Pb(p,p') and (n,n') indicate a closely spaced pair of levels at about 2.62 MeV. The 4.62-MeV gammas observed in our (n,γ) studies are thus probably primary transitions to these states. The 3.2-MeV line, however, remains not accounted for. Possible level assignments are shown in Fig. 5.

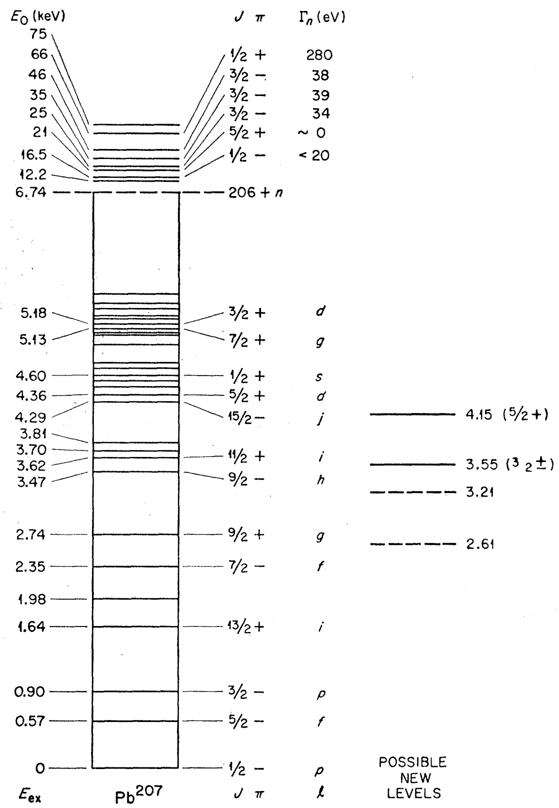

FIG. 5. Energy levels in ^{207}Pb. Levels observed up to 75 keV above the neutron separation energy are given with neutron widths and probable spin assignments. Two previously unobserved states between 2.61 and 4.1 MeV, discovered in the capture gamma-ray spectra, are shown on the right. Uncertainty as to the order of the transition makes it impossible to identify which of the two possible locations for each level is the correct one.

Resonances in the compound system were identified as to both probable spin and parity with the aid of total cross-section results. Clearly, p-wave, negative-parity states dominate the scene. From the point of view of the shell model it is possible to conceive of single-particle two-hole states of positive parity in the vicinity of excitation energies corresponding to neutron dissociation. However, it is not so easy to construct similar states of negative parity subject to the additional requirement that no change of orbit take place during the radiative act ($M1$ radiation). States based upon the $i_{13/2}\rightarrow i_{11/2}$ excitation for neutrons and the $h_{11/2}\rightarrow h_{9/2}$ excitation for protons are possibilities; however, the corresponding excitations in zero order are only 5.85 and 6 MeV, respectively.

The spectra observed for ^{207}Pb(n,γ) are strongly dominated by transitions to ground (0^+) and the 2.61-MeV state (3^-) (Fig. 6). All resonances observed, excepting the 1^- at 41 keV were assigned 2^+ since they appear to decay predominantly to this 3^- level, and since the neutron total cross-section results indicate $l=1$ (i.e., $J==0$, 1, 2^+). Pinkston and True[12] have discussed 2^+ states that can arise from a special class of 2-particle, 2-hole excitations, and for these they find a spacing of approximately 200 keV. Our results show a spacing of

[12] W. T. Pinkston and W. W. True, Can. J. Phys. 41, 1371 (1962).

about 15 keV, indicating that these levels, if they arise from 2-particle, 2-hole excitations, may represent a more general class than those studied by Pinkston and True. The $E1$ reduced widths for electromagnetic transitions to the 3^- collective state are normal for single-particle transitions.

The s-wave resonance at 42 keV has $J^\pi = 1^-$. This assignment can be made from the shape of the total cross section or from the fact that it decays direct to the ground state of ^{208}Pb. (The assignment 0^- would forbid a ground state gamma-ray emission.) This state decays, within experimental error, 100% of the time directly to ground. The radiative width for the level is about 6 eV. The integrated area is about 0.5 mb MeV compared with a value of about 24 mb MeV predicted if the state were a member of the giant dipole family.[13]

In summary, for compound ^{207}Pb almost all neutron resonances observed for $E_n < 70$ keV are p wave (negative parity) which decay primarily to ground and to a few states just above ground. Support is given for the existence of a state(s) near 2.62 MeV, and in addition an unassigned gamma is observed corresponding to a state near 3.2 or 3.5 MeV. The p-wave neutron widths are relatively small, as expected in this region from the optical model. The gamma-ray reduced widths are appropriate for single-particle transitions. In compound ^{208}Pb several p-wave (2^+) states are observed, and these seem to decay with single particle $E1$ speed to the 3^- collective state at 2.61 MeV. The s-wave (1^-) resonance at 42 keV was observed to have a relatively large electric dipole radiation width, but not sufficiently large to classify it as belonging to the giant dipole family.

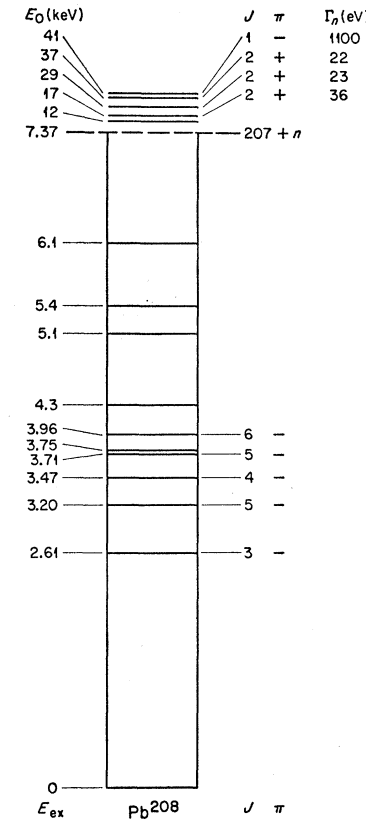

FIG. 6. Energy levels in ^{208}Pb. Resonances observed up to 41 keV above the neutron separation energy are given with neutron widths (previously determined) and probable spin and parity assignments.

[13] V. Balashov, V. G. Shevchenko, and N. P. Yudin, Zh. Eksperim. i Teor. Fiz. **41**, 1929 (1962) [English transl.: Soviet Phys.—JETP **14**, 1371 (1962)].