$^{204}Pb(n,n'\gamma)^{204}Pb$ reaction

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The excited states of ^{204}Pb were studied using the $^{204}Pb(n,n'\gamma)$ reaction. Gamma-ray excitation functions and angular distributions were recorded using a small-sample technique. Previously unreported ^{204}Pb levels were observed at 1605 ± 1, 1682 ± 1, 1762 ± 1, 1873 ± 1, and 2276 ± 3 keV excitation. The spins of the levels at 1682, 1762, 1873, and 2276 keV are $J = 1$, 2, or 3^-. The spin and parity of the 1605 keV level is limited to $J^\pi = 3^+$ or 4^+. Multipole mixing ratios were measured for several transitions where the initial and final state spins and parities were firmly established from previous work.

[NUCLEAR REACTION $^{204}Pb(n,n'\gamma)$, E=1.5–3.1 MeV; E_γ, $I(E)$, $I(E_\gamma, \theta_\gamma)$; ^{204}Pb deduced levels, J, δ. Enriched target. Ge(Li) detectors.]

Nuclei near the double magic nucleus ^{208}Pb are interesting from a nuclear structure point of view, because their low-lying states may be described by the interaction of only a few nucleons (or nucleon holes) lying outside the closed-shell core. Theoretical calculations based on the shell model[1,2] and weak-coupling model[3] have been reported for nuclei in this mass region. A major difficulty in the calculations involving neutron holes is that there are many low-lying orbitals which could be important in the structure of those nuclei. Often for reasons of economy, truncations of the model space have been made, with guidance to some extent, from any available experimental data. In the case of ^{204}Pb, however, experimental information is limited because of the difficulty of finding nuclear reactions that produce ^{204}Pb as the residual nucleus. The most extensive assignment of spins and parities for low-lying ^{204}Pb states has been made by Lanford[4] in a study of the $^{206}Pb(p,t)^{204}Pb$ reaction. Because the ^{206}Pb nucleus has $J^\pi = 0^+$, this reaction is expected to populate predominantly states of natural parity in the residual nucleus, and indeed many ^{204}Pb states of $J^\pi = 0^+$, 2^+, and 4^+ were identified below 2 MeV. Even though states of spin 1 and 3 are expected from shell model calculations[1,5] to occur in this region of excitation, no such states were identified by Lanford,[4] possibly because they are expected to have unnatural parity.[5]

We report a measurement of the $^{204}Pb(n,n'\gamma)^{204}Pb$ reaction. The essential features of the experimental setup and procedure have been described previously.[6,7] The neutrons were produced by bombarding a 3.27 mg/cm^2 erbium tritide target with a pulsed proton beam with a pulse width of 10 ns. The Pb scatterer (99.73% ^{204}Pb) was a cylinder of 0.17 cm thickness and 2.54 cm diameter, having a mass of 9.567 g.[8] Gamma-ray excitation functions were recorded for neutron energies from 1.5 to 3.1 MeV at intervals of approximately 0.2 MeV. The gamma-ray energies were determined by comparison with standard calibration sources; the uncertainties were typically 1 to 3 keV. Gamma-ray angular distributions were recorded at neutron energies of 2.0, 2.5, and 3.1 MeV. For each spectrum recorded with the ^{204}Pb scatterer in place, a "scatterer out" background spectrum was recorded with an equivalent integrated charge. Average proton beam currents were 0.5 μA and the total charge accumulated per angle ranged from 2 to 5 mC. A sample γ-ray spectrum for the $^{204}Pb(n,n'\gamma)^{204}Pb$ reaction is shown in Fig. 1.

The ^{204}Pb level and decay scheme is shown in Fig. 2. The levels at 1605, 1682, 1762, 1873, and 2276 keV excitation have not been reported previously; γ rays from the decays of some of these levels have been previously observed and listed as ^{204}Pb γ rays of unknown origin.[9] A γ ray of energy 1502 ± 1 keV observed in this work, and reported in Ref. 10, is shown by the excitation function data to arise from either a 2776 → 1274 keV ($J_f^\pi = 4^+$) or a 2853 → 1351 keV ($J_f^\pi = 2^+$) transition.

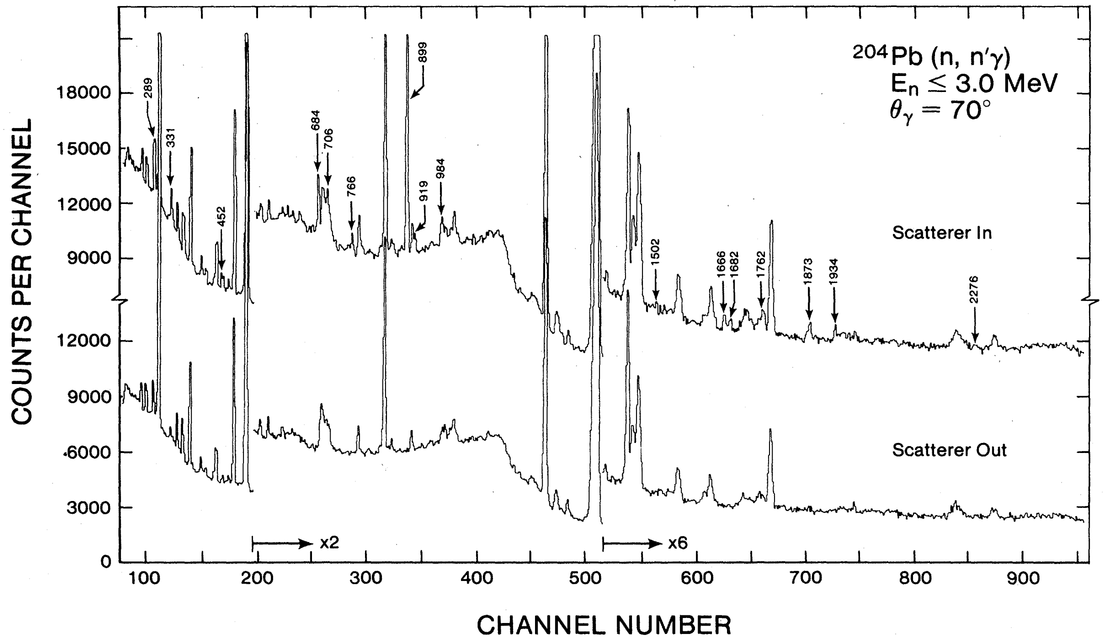

FIG. 1. Sample gamma-ray spectra are shown for scatterer in and scatterer out. ^{204}Pb gamma-ray energies are given in keV.

The γ-ray angular distributions were analyzed using a computer code[6] which applies corrections for finite beam spot and scatterer size to the theoretical angular distributions and compared to the data using a χ^2 test. A sample angular distribution and plots of χ^2 versus multipole mixing ratio δ are shown in Figs. 3 and 4, respectively.

Twenty excited states have now been reported in ^{204}Pb below 2.3 MeV excitation. The ^{204}Pb levels at 899, 1274, 1351, 1563, 1583, 1666, 1728, 1818, 1934, 1958, 2065, 2103, 2156, 2186, and 2258 keV excitation have been reported in previous works,[4,11] with spin assignments made as indicated in Fig. 2. The angular distribution data of the present work were consistent with these assignments for all cases where the deexcitation γ rays could be observed. For the ^{204}Pb levels at 2065 and 2186 keV excitation, the previously reported[12] deexcitation γ rays were not observed in this work. No evidence was seen for reported[4] levels at 1728, 1958, 2103, and 2156 keV excitation. In the cases of those γ-ray transitions where $E2/M1$ mixing was allowed, multipole mixing ratios were deduced and are listed in Table I.

Of the five new ^{204}Pb levels reported in this work, four (at 1682, 1762, 1873, and 2276 keV excitation) have strong γ-ray decay branches to the ground state. For these levels, the crude upper limit of 10 ns placed on the lifetime by the n-γ selection eliminates all spin possibilities except $J_i = 1$, 2, and 3^-.

The ^{204}Pb level at 1605 keV excitation is observed to have γ-ray decay branches to the 899 keV $(J_f^\pi = 2^+)$ and the 1274 keV $(J_f^\pi = 4^+)$ levels. This information, combined with the results of the conversion electron study[14] of Hnatowicz *et al.* in which the 331 keV γ ray from the 1605 → 1274 keV transition is found to be of a mixed $E2 + M1$ character, restricts the 1605 keV ^{204}Pb level to $J^\pi = 3^+$ or 4^+. From the present work, the angular distribution of the γ ray from the 1605 → 899 keV $(J_f^\pi \to 2^+)$ transition is consistent with either of these assignments. However, χ^2 for an assumed $J_i^\pi = 4^+$ is 8.1 for three degrees of freedom, corresponding to a confidence level of 3%. A 3^+ assignment would be supported by the fact that this level was not observed in the ^{206}Pb(p, t) reaction.[4]

The presence in the data of a 1502 keV γ ray with a threshold near $E_n = 3.0$ MeV establishes the existence of a sixth previously unreported ^{204}Pb level at either 2776 or 2853 keV excitation. This γ ray could not be placed unambiguously in the ^{204}Pb decay scheme.

In a shell model picture, the low-lying states of ^{204}Pb are formed by the coupling of four neutron holes to a ^{208}Pb core. From the neutron single-hole energies[2] at the major shell closure at $N = 126$ (listed in Table II), it can be inferred that these states should be dominated by configurations involving $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ holes. From these configurations there should arise a number of low-lying positive-parity states having spins $J = 0$ to 4.

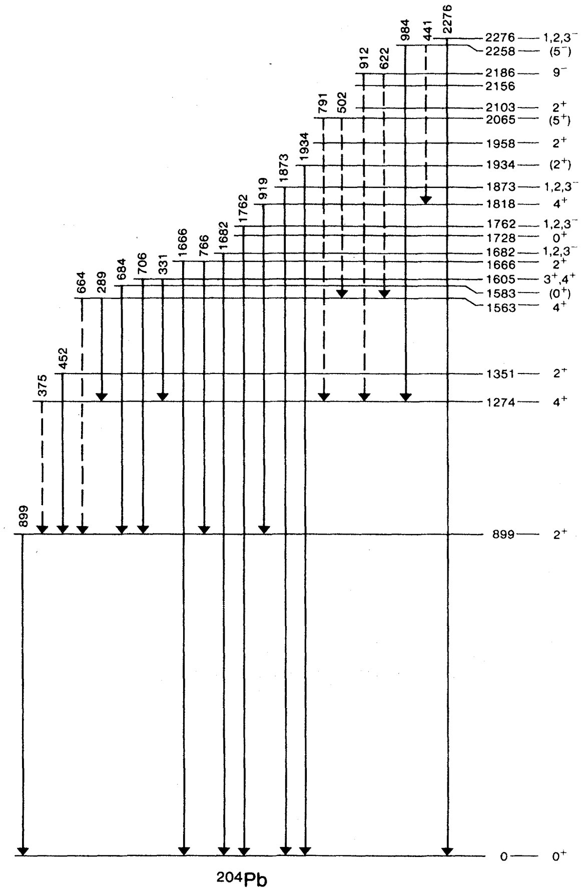

FIG. 2. The level and decay scheme of ^{204}Pb is shown. The energies are given keV. The gamma-ray energies are those of Refs. 4 and 9, except for the 2276 keV gamma ray, for which the energy is from the present work. The dashed lines refer to previously reported transitions which were not seen in this work. The level spins are from this and previous work.

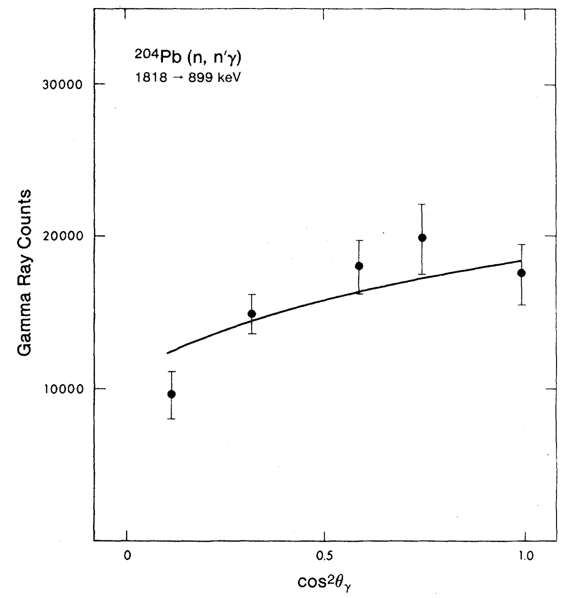

FIG. 3. A sample gamma-ray angular distribution and theoretical fit (Ref. 6) is shown for an initial state spin of 4; the final state is known (Ref. 4) to be 2^+.

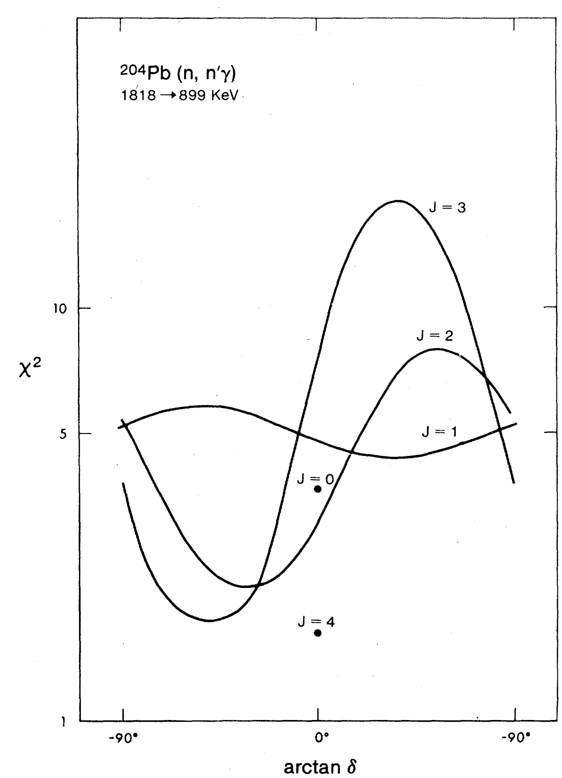

FIG. 4. Plots of χ^2 versus arctan δ are shown for the data of Fig. 3. A spin of $J=4^+$ was assigned by Lanford (Ref. 4) for the 1818 keV level.

This is consistent with the predictions of recent shell model calculations[1,5] and the known[4] properties of ^{204}Pb states below 2 MeV excitation (see Fig. 5). However, an examination of Fig. 5 shows that approximately 6 states of spin-parity $J^\pi = 1^+$ and 3^+, predicted by the shell-model calculations of McGrory[5] to occur near or below $E_x = 2$ MeV, do not appear in the experimental level scheme. This is not surprising because most of the existing experimental information on the levels of ^{204}Pb was obtained in a study[4] of the ^{206}Pb$(p,t)^{204}$Pb reaction.

The ^{204}Pb$(n,n'\gamma)^{204}$Pb reaction is well suited for a search for the 1^+ and 3^+ ^{204}Pb states. For low neutron energies, the population of states in the $(n,n'\gamma)$ reaction is expected to be statistical in nature and, therefore, relatively nonselective in the detailed structure of these states. Most states

TABLE I. Multipole mixing ratios in ^{204}Pb.

Initial state [a]	Final state [a]	J_i^π J_f^π	arctan δ [b]
1351	899	$2^+ \rightarrow 2^+$	57 ± 16
1666	899	$2^+ \rightarrow 2^+$	-32 ± 30
2258	1274	$5^- \rightarrow 4^+$	-3 ± 5 [c]

[a] The energies are in keV.
[b] The multipole mixing ratio is given in degrees. The phase convention of Rose and Brink is used (Ref. 13).
[c] Shown to be of $E1$ character in Ref. 12.

TABLE II. Experimental neutron single-hole orbitals (Ref. 2) near the major shell closure at $N=126$.

Neutron orbital	Single-hole energy (MeV)
$2p_{1/2}$	0.0
$1f_{5/2}$	0.570
$2p_{3/2}$	0.898
$0i_{13/2}$	1.633
$1f_{7/2}$	2.340
$0h_{9/2}$	3.409

of low spin will be populated with appreciable strength. Of the five previously unreported ^{204}Pb states observed in this work, only the one at $E_x = 1605$ keV can be assigned a spin with a reasonable level of confidence, probably $J^\pi = 3^+$ (although $J^\pi = 4^+$ is also possible at a 3% confidence level). The four ^{204}Pb levels observed in this work at 1682, 1762, 1873, and 2276 keV excitation are

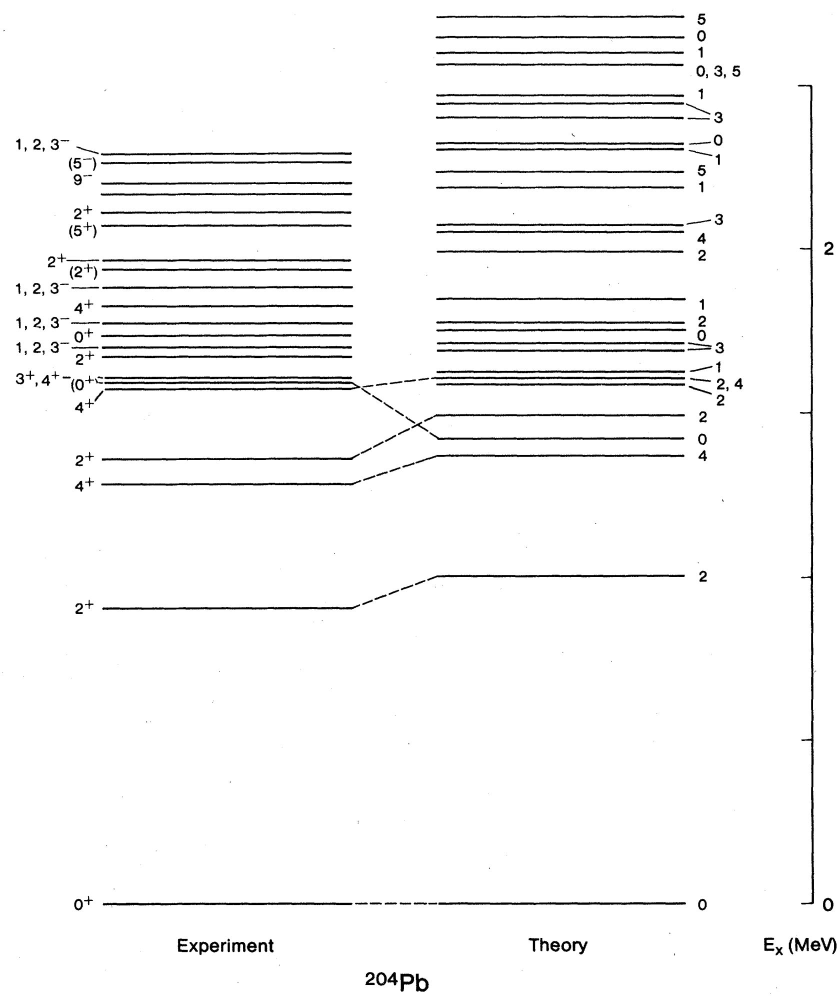

FIG. 5. A comparison of the experimental (Refs. 4,11) and theoretical (Refs. 1,5) ^{204}Pb level schemes is shown. Previously unreported levels at 1605 and at 1682, 1762, 1873, and 2276 keV excitation may be the states of $J^\pi = 1^+$ and 3^+ predicted by McGrory (Ref. 5).

limited to $J = 1$, 2, or 3^-. Although rigorous spin assignments are not made for any of these five states, some of these new ^{204}Pb levels may be identified with the states of $J^\pi = 1^+$ predicted by the shell model calculations of McGrory.[5]

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