PHYSICAL REVIEW C VOLUME 13, NUMBER 5 MAY 1976

J^{π} assignment to the 4.841 MeV level in ^{208}Pb†

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(Received 8 December 1975)

A study of γ rays in coincidence with inelastically scattered α particles shows the level at 4.841 ± 0.005 MeV in ^{208}Pb to possess a large probability for decay to the ground state. The directional correlation of these γ rays require that this level have $J^{\pi} = 1^-$.

[NUCLEAR REACTIONS ^{208}Pb$(\alpha, \alpha'\gamma)$, E_{α}=35 MeV; deduced J^{π} of 4.841 MeV level.]

In a previous comment[1] we showed that a level at 4.841 ± 0.005 MeV in ^{208}Pb exhibited a reasonable yield (~0.2 mb/sr) in the inelastic scattering of 35 MeV α particles and hence has natural parity. This conclusion is in apparent contradiction with the assignment[2] of $J^{\pi} = 1^+$ to a level at 4.843 MeV which has a radiative width of 5.1 ± 0.8 eV. The level certainly has $J = 1$ but there are considerable theoretical difficulties[1-4] presented for a 1^+ state with such a large radiative width at this low excitation energy. The 1^+ assignment was inferred from a measurement of the linear polarization of decay radiation to the ground state following excitation via bremstrahlung. As this technique is model independent and should be reliable, we felt that the (α, α') results should be reexamined. The simplest reconciliation of the two experimental results is that the (α, α') reaction excites a different level than the one studied in the linear polarization experiment. However, recent[5] high resolution inelastic proton scattering measurements show that if there is more than a single level in this region, they must be within 3 keV. Considering the local level density, the probability of two levels being within 3 keV is about 3%. In order to show that the level observed at 4.841 MeV in the (α, α') experiment is the same as the one discussed in Ref. 2, it must be established that it is $J^{\pi} = 1^-$. This will be done by first showing the level excited in (α, α') decays nearly 100% of the time directly to the ground state, which requires that it be 1^- or 2^+ and then showing the angular distribution of these γ rays is only consistent with a 1^- level.

A 35 MeV α particle beam from the Princeton University AVF cyclotron was scattered from a 0.1 mg/cm^2 ^{208}Pb foil (99.9%). The inelastically scattered α particles were detected in the Princeton University quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrometer which was set at 22.5° to the beam direction. A recently constructed beam dump allows the beam to be transported to a 15 cm hole in the concrete wall that is 122 cm deep. The spectrometer solid angle was 10 msr and the resolution 30 keV. The α particles are identified and their position in the focal plane determined with a resistive wire ionization chamber operated in coincidence with a scintillation detector. The decay γ rays are detected in a 10 cm $\times$ 12.5 cm NaI crystal which is positioned 9.5 cm from the target. A 1 cm thick Pb shield is placed in front of this detector to suppress low energy γ rays. The γ ray detector and the scintillator were operated in time coincidence. All delay times were easily fixed, using the ^{12}C$(\alpha, \alpha')^{12}$C* (4.43γ) reaction. For each event, the time to amplitude converter signal, the α particle position, and the γ ray energy were written on magnetic tape. The true to accidental coincidence rate was approximately 20 to 1.

Figure 1 shows the α particle singles spectrum and the α particle spectrum in coincidence with events from the γ ray detector placed out of the scattering plane (i.e., along $\vec{K}_{\alpha_0} \times \vec{K}_{\alpha'}$ scattering direction). The sequence of coincidence events are associated with γ ray energies greater than ~0.6 and $\simeq$3.0 MeV, respectively. The highest discriminator setting will only allow coincidence if there is a direct ground state transition. Only four levels are observed. They are at 4.085, 4.841, 5.291, and 5.502 MeV. The latter two are known[6] 1^- levels, while the 4.085 MeV level is[6,7] 2^+. As will be shown below, the γ decay of 1^- states is preferentially along $\vec{K}_{\alpha_0} \times \vec{K}_{\alpha'}$ and the γ ray yield in this direction is independent of the details of the reaction mechanism or the structure of the level.

The levels at 4.085, 5.291, and 5.502 MeV are known to preferentially decay[7-9] to the ground state. The relative coincidence ground state yield of the 4.841 MeV level to that of the 5.291 MeV levels shows $(\Gamma_0/\Gamma)_{4.841} = (1.25 \pm 0.29) \times (\Gamma_0/\Gamma)_{5.291}$.

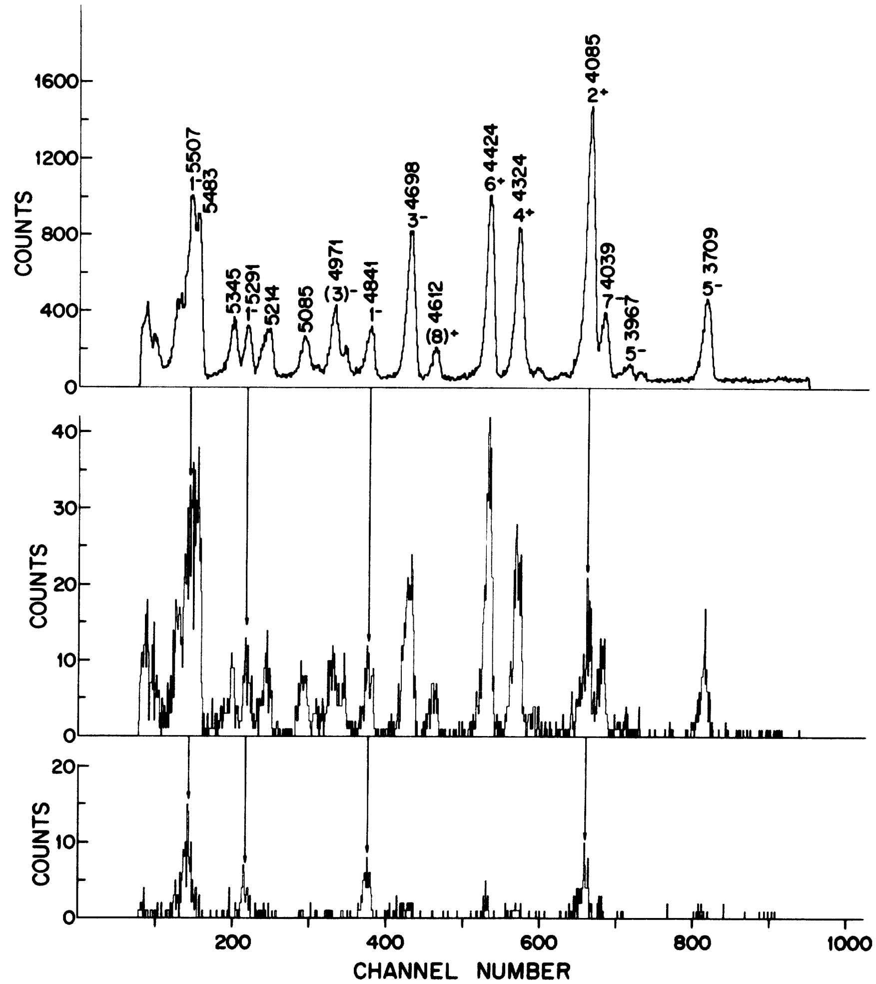

FIG. 1. ^{208}Pb$(\alpha,\alpha')^{208}$Pb spectra obtained with the QDDD spectrograph. The spectra, from top to bottom, show singles α particles, α particles in time coincidence with γ rays of energy > 0.6 MeV, and α particles in time coincidence with γ rays of energy > 3.0 MeV. The NaI γ detector was situated out of the reaction plane.

Figure 2 shows the coincidence spectra obtained with the γ ray counter in plane ($\theta\gamma = \frac{1}{2}\pi$, $\varphi\gamma = \frac{1}{2}\pi$) at two discriminator settings. The integrated beam current in this case is 0.38 that of the out of plane run. Only the peak corresponding to the 4.085 MeV level is readily evident in the coincidence spectrum associated with the highest energy γ ray cuts.

It is not widely appreciated but it is easy to show[10,11] employing the general formulation of Rybicki, Tamura, and Satchler[12] in conjuction with the Bohr[13] theorem, that unique model independent results can be obtained for the in-plane-out-of-plane γ ray asymmetry following excitation via inelastic α scattering. The magnetic substate populations are referred to a set of axis where $\hat{Z} = \hat{K}_{\alpha_0} \times \hat{K}_{\alpha'}$, and $\hat{X}$ is along the beam direction and $\hat{Y} = \hat{Z} \times \hat{X}$. In case of electric dipole radiation from a 1^- level, excited in an (α, α') reaction, which decays to a spin 0 final state, the angular correlation of the α particle and the γ ray can be written as

$$W(\theta_\alpha = \tfrac{1}{2}\pi, \varphi_\alpha, \theta_\gamma, \varphi_\gamma)$$

$$= \frac{3}{16\pi}\left[(1 + \cos^2\theta_\gamma) + 2a_1 a_{-1}\cos(b_1 - b_{-1} + 2\varphi_\gamma)\sin^2\theta_\gamma\right], \qquad (1)$$

where $\alpha_1 = a_1 e^{ib_1}$ specifies the population of the $m = 1$ substate and so forth. The Bohr theorem restricts the possible magnetic substates to be ± 1 in this case. The relative number of out of plane γ rays ($\theta_\gamma = 0$) is seen to be rather independent of any details of the reaction. In addition, the ratio of in plane to out of plane is bounded as the absolute magnitude of the coefficient of the $\sin^2\theta_\gamma$ term can not exceed 1. Hence one has

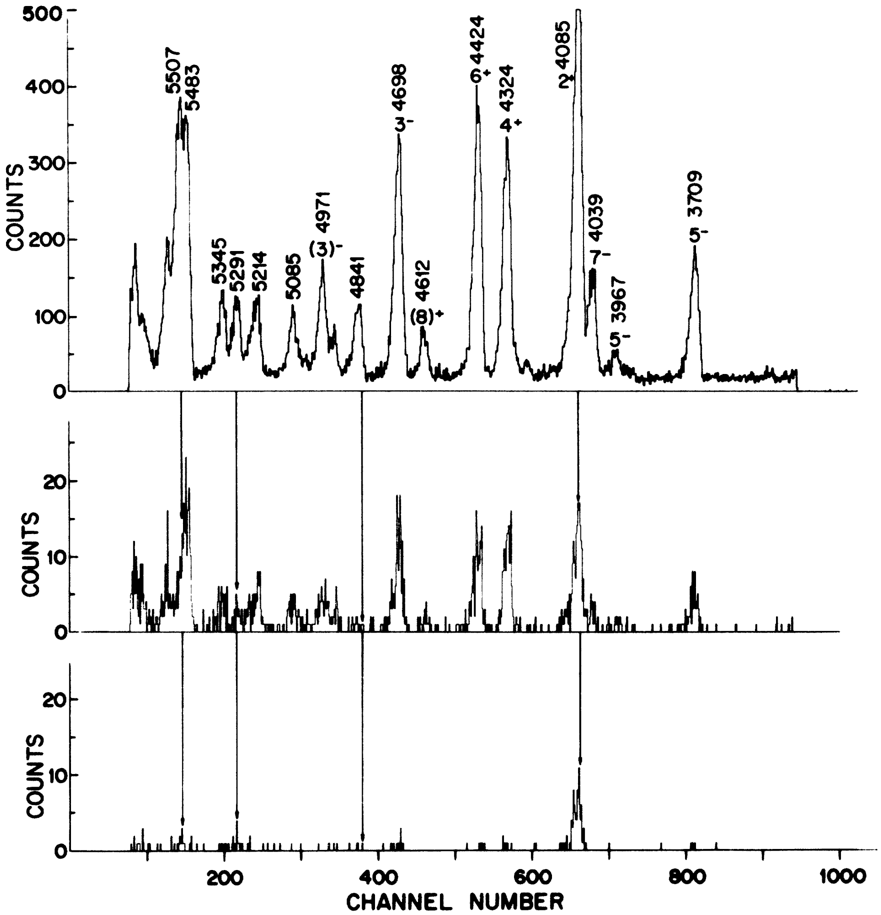

FIG. 2. ^{208}Pb(α,α')^{208}Pb spectra obtained with the QDDD spectrograph. The spectra, from top to bottom, show singles α particles, α particles in time coincidence with γ rays of energy > 0.6 MeV, and α particles in time coincidence with γ rays of energy > 3.0 MeV. The NaI γ detector was situated in the reaction plane.

$$0<\frac{W(\theta_\alpha=\frac{1}{2}\pi,\varphi_\alpha,\theta_\gamma=\frac{1}{2}\pi,\varphi_\gamma)}{W(\theta_\alpha=\frac{1}{2}\pi,\varphi_\alpha,\theta_\gamma=0,\varphi_\gamma)}<1 \quad (J^{\pi}=1^-)\,. \tag{2}$$

The third column of Table I shows this condition is satisfied by the 5.502, 5.291, and 4.841 MeV levels and grossly violated by the 4.085 state. For a 2^+ state, the Bohr theorem requires that only $m=\pm2$ or 0 states be populated. Thus only finite geometry effects can give a yield at $\theta_\gamma=0$ and we obtain

$$\frac{W(\theta_\alpha=\frac{1}{2}\pi,\varphi_\alpha,\theta_\gamma=\frac{1}{2}\pi,\varphi_\gamma)}{W(\theta_\alpha=\frac{1}{2}\pi,\varphi_\alpha,\theta_\gamma=0,\varphi_\gamma)}>1 \quad (J^{\pi}=2^+) \tag{3}$$

as is the case for the 4.085 MeV level.

Thus the level excited at 4.841 MeV in inelastic α scattering is seen to evidence a large relative

TABLE I. The first column lists the energy and spin parity (when known) of levels observed in this experiment which γ decay to the ground state. The second column gives the ratio of the relative number of in plane coincidence to out of plane coincidence. The third column lists the ratio of the yields of the three highest levels observed in the out-of-plane coincidence measurement while the last column lists the relative ground state $B(E1)$ values.

Level (MeV)	J^{π}	$\frac{W(\theta_\alpha=90°,\varphi_\alpha=22.5°,\theta_\gamma=90°,\varphi_\gamma=90°)}{W(\theta_\alpha=90°,\varphi_\alpha=22.5°,\theta_\gamma=0°)}$	$\left[\frac{d\sigma}{d\Omega}\left(\frac{\Gamma_0}{\Gamma}\right)\right]_E \Big/ \left[\frac{d\sigma}{d\Omega}\left(\frac{\Gamma_0}{\Gamma}\right)\right]_{4.841}$	$B(E1)_E/B(E1)_{4.841}$
4.085 ±0.005	2^+	2.93 ±0.44	...	...
4.841 ±0.005	?	0.16 ±0.09	1	1
5.291 ±0.005	1^-	0.70 ±0.22	0.71 ±0.16	0.61 ±0.15
5.502 ±0.005	1^-	0.29 ±0.08	2.2 ±0.4	1.6 ±0.4

branch for ground state decay which requires $J^\pi = 1^-$ or 2^+ and the in-plane–out-of-plane γ ray correlation is only consistent with $J^\pi = 1^-$. The relative yields in inelastic α particle scattering of the 4.841, 5.291, and 5.502 MeV levels should be related to their relative ground state $B(E1)$ values. This comparison is made in columns 4 and 5 of Table I. Column 4 lists the relative coincidence yield with the γ detector out of plane. This yield should be a direct measure of the inelastic scattering cross section from Eq. (1). The observed singles yield could not be employed because it is known[5] that there are other levels within a couple of keV of the 5.502 MeV state. The radiative width for the 4.841 MeV level was taken from Ref. 2, while the width of the 5.291 MeV level and the 5.502 MeV state were taken from Ref. 8. As the latter reference quotes no error for the radiative widths, we arbitrarily assigned it at 20%. The ratios also compare well with one another and hence it must be concluded that the level excited at 4.841 ± 0.005 in resonance flouorescence and inelastic α scattering are one in the same and that this level has $J^\pi = 1^-$.

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†Supported in part by the National Science Foundation under Grant No. MPS71-03445.

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