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Neutron decay from the giant resonance region in ^{208}Pb

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The neutron decay of the giant multipole resonance region from 9 to 15 MeV of excitation energy in ^{208}Pb has been studied. Neutron branching ratios for the decay to the ground state or to the low-lying excited states of ^{207}Pb were measured as a function of the excitation energy of ^{208}Pb and compared to Hauser-Feshbach calculations. While the neutron branching ratios from the isoscalar quadrupole resonance are reproduced by the calculations, the ratios from excitation energies above 12.5 MeV show a large excess with respect to the statistical predictions.

The study of the decay properties of the giant multipole resonances is a powerful tool for the investigation of the microscopic structure of these collective 1p-1h states.[1] The giant resonance states are located in general at excitation energies above the particle binding energies and therefore decay predominantly by particle emission (mostly neutron emission in heavy nuclei). The total width of a giant resonance consists mainly of two components, the escape width $\Gamma\uparrow$, which represents the coupling of the giant resonance to the continuum, and the spreading width $\Gamma\downarrow$, which represents the coupling to more complicated *n*p-*n*h states present in the vicinity of the resonance. Two-particle-two-hole states are usually referred to as doorway states because they represent the first step of the damping process of the resonance toward the compound nucleus. Particle decay can occur either directly from the initial 1p-1h resonance state, at any of the intermediate stages of the damping process, or from fully equilibrated compound states. The decay from fully damped states can be calculated with the Hauser-Feshbach statistical model. As a consequence, if the neutron decay to states in the daughter nucleus with varying nuclear structure is compared to predictions of the decay from the statistical model, insight can be obtained on both the microscopic structure and the damping process of the giant resonances.

In previous studies of neutron decay from giant resonances in ^{208}Pb,[2–5] comparison with statistical-model calculations indicated the presence of a small nonstatistical neutron branch in the isoscalar giant quadrupole (11 MeV) and isoscalar monopole (14 MeV) regions of excitation energy. However, a more recent analysis[6] of the data from Ref. 5 concluded that the neutron decay of the giant monopole resonance can be described without introducing a nonstatistical decay component. It appears that more detailed measurements are needed to draw more definitive conclusions on the amount of any direct or precompound contributions to the decay. Data on the fractional population via neutron decay to states in ^{207}Pb with known nuclear structure, as a function of excitation energy in ^{208}Pb, should provide more insight into the problem. Such data can be compared to absolute statistical model predictions and to microscopic calculations of the escape and precompound widths for particular final states. Detailed comparisons have not been possible with data from previous measurements because of limited statistics and energy resolution. We report in this Rapid Communication the first extensive experimental data on the neutron-decay branching ratios to low-lying states in ^{207}Pb as a function of ^{208}Pb excitation energy (9–15 MeV). Properties of the observed ^{207}Pb states are given in Table I.

In the present study giant resonances in ^{208}Pb were excited by inelastic scattering of 378-MeV ^{17}O ions from the Oak Ridge National Laboratory (ORNL) Holifield Facility coupled accelerators. Excitation by heavy ions provides a cross section for the quadrupole and monopole resonances large in comparison with the underlying continuum.[7] The inelastically scattered ^{17}O ions were detected in six cooled Si surface-barrier telescopes which were arranged symmetrically around the beam axis at an angle of 13° with each subtending $\Delta\theta = 3°$ and $\Delta\phi = 9°$; the to-

TABLE I. Levels in ^{207}Pb studied in this experiment.

E (MeV)	J^{π}	Configuration
0.0	$\frac{1}{2}^{-}$	$\nu p_{1/2}^{-1}$
0.570	$\frac{5}{2}^{-}$	$\nu f_{5/2}^{-1}$
0.898	$\frac{3}{2}^{-}$	$\nu p_{3/2}^{-1}$
1.633	$\frac{13}{2}^{+}$	$\nu i_{13/2}^{-1}$
2.339	$\frac{7}{2}^{-}$	$\nu_{7/2}^{-1}$
2.623	$\frac{5}{2}^{+}$	$3^{-} \otimes \nu p_{1/2}^{-1}$
2.662	$\frac{7}{2}^{+}$	
2.728	$\frac{9}{2}^{+}$	$\nu g_{9/2} \otimes gs\,(^{206}\mathrm{Pb})$

tal solid angle was 22.6 msr. Each telescope consisted of two elements, 500 and 1000 μm thick. The energy resolution was 800 keV and the mass resolution was sufficient to separate ^{17}O ions from other oxygen isotopes. Neutrons and gamma rays were detected in 70 elements of the ORNL spin spectrometer.[8] The spectrometer is a spherical shell of 17.8-cm-thick NaI crystals, divided into 72 independent detector elements surrounding the target chamber. The raw data obtained from the spectrometer consisted of the pulse heights for the individual NaI elements and the arrival times of these pulses relative to the pulse for the inelastically scattered ^{17}O with which they were in coincidence. Further experimental details may be found in Refs. 9 and 10. The total gamma-ray pulse height was obtained by summing all those pulses which occurred in a prompt time window. This window (which was a function of pulse height) was sufficiently narrow to eliminate most pulses resulting from detection of neutrons with energy less than 7 MeV. Because of the short flight path and the depth of the NaI detector, the energy resolution from neutron time of flight is insufficient to resolve decay to individual levels in ^{207}Pb. The residual excitation energy in ^{207}Pb following neutron emission is, however, accurately determined from the total gamma-ray energy in the spin spectrometer.

Events of interest for the present study were selected by the presence of neutrons (i.e., delayed pulses in the NaI), a total gamma energy deposited in the spin spectrometer equal to one of the ^{207}Pb level energies, and an ^{17}O kinetic energy corresponding to an excitation energy of ^{208}Pb above the neutron emission threshold (7.4 MeV). In order to discriminate against ^{208}Pb(^{17}O,^{18}O)^{207}Pb transfer followed by neutron decay of the ^{18}O in flight to the detectors, only those events in which a neutron was detected at an angle greater than 90° relative to the beam direction were used. This process is distinguished from inelastic excitation of ^{208}Pb by a tight correlation of the neutrons with the direction of emission of the ^{17}O ejectile. Transfer becomes significant above an apparent ^{208}Pb excitation energy of 13 MeV.[10] Another potential source of contamination is direct neutron knockout by the projectile, which should lead to neutrons peaked near the momentum transfer direction,[11] but no evidence was found for any significant yield from the process. A total gamma-ray energy spectrum is shown in Fig. 1, corresponding to an excitation energy of 12–13 MeV in ^{208}Pb. The spectrum was fitted with Gaussians whose centroids are either at the energy of known excited states in ^{207}Pb or at the energy difference of known states from 1.633 MeV, the energy corresponding to the isomeric $i_{13/2}$ state of ^{207}Pb. Since this isomer is sufficiently long lived ($T_{1/2}$=0.815 sec) that its decay does not contribute to the total gamma-ray energy measured by the spin spectrometer, it was treated in the analysis as, in effect, a second ground state for all cascades which pass through it.

The measured neutron-decay branching ratios are shown by the points in Fig. 2. The error bars indicate the statistical and peak fitting uncertainties. The neutron decay branching ratios were obtained using twice the angle-integrated $\theta > 90°$ yield to reflect the forward-backward symmetric portion of the total yield. The yields were corrected for gamma-ray and neutron detection efficiencies.

The solid lines in Fig. 2 were obtained from Hauser-Feshbach calculations using the known excited states of ^{207}Pb up to 4 MeV of excitation energy. Above 4 MeV an

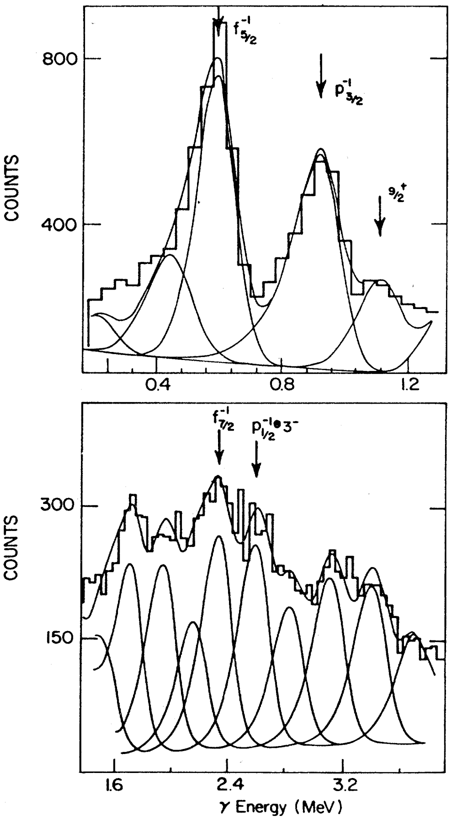

FIG. 1. Sum gamma energy spectrum for ^{208}Pb excitation energy of 12–13 MeV. The states indicated by the arrows are the ones having known decay branchings to the ground and isomeric states.

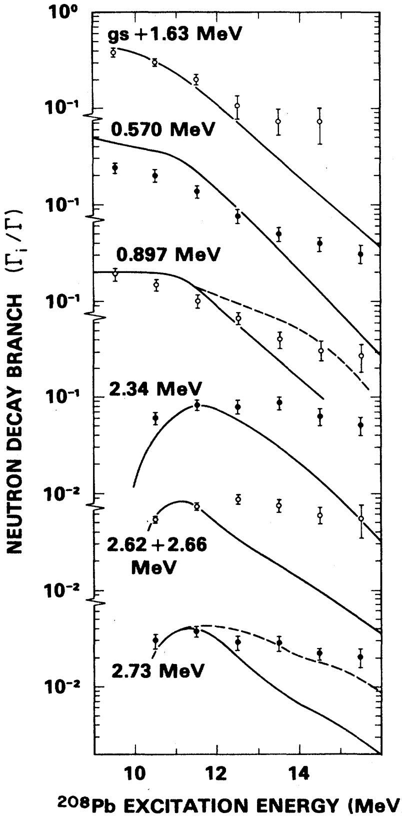

FIG. 2. The fraction of neutron decays which populate each of six states (or groups of states) as a function of excitation energy in ^{208}Pb. The solid lines are Hauser-Feshbach calculations, as discussed in the text. The dashed lines given for two of the final states are examples of the effect of a reduction of a factor of five in the ^{207}Pb level density.

empirical level density[12] formula was used. An alternative level density formula[13] produced almost identical results. Neutron transmission coefficients were calculated with the $^{207}\mathrm{Pb}+n$ optical potential of Ref. 14. The distribution of excited-state spins and pairities in ^{208}Pb was taken from the experimental strength distribution of Ref. 15, plus the $L=6$ strength reported in Ref. 16, converted to (^{17}O,^{17}O$'$) cross sections via distorted-wave Born approximation calculations. Consistency between the strength distribution of Ref. 15 and (^{17}O,^{17}O$'$) singles data acquired under conditions identical to those of the present experiment was demonstrated in Ref. 9. Relevant (^{17}O,^{17}O$'$) singles cross sections, at $\theta_{\mathrm{c.m.}}=14°$, determined in that analysis include $L=2$, $E=10.6$, $\Gamma=2.0$, 38 ± 5 mb/sr; $L=4$, $E=12.0$, $\Gamma=2.4$, 11 ± 5 mb/sr; and $L=0$, $E=13.9$, $\Gamma=2.9$, 14 ± 4 mb/sr (energies, E, and full widths, Γ, are given in MeV), corresponding to about 90%, 15%, and 100% of the respective energy-weighted sum rules. A smoothly varying background of ~6 mb/sr/MeV in the vicinity of the resonances was obtained from this analysis. Excitation of the $T=1$ giant dipole resonance makes a contribution less than ~1 mb/sr to the region ($E=13.9\pm1.5$ MeV) occupied by the $T=0$ monopole resonance. No attempt was made to adjust the ^{208}Pb excited-state strength distribution to improve agreement with the data; however, elimination of high spin ($L=4$ and 6) strength significantly worsens the agreement. Population of the $g_{9/2}$ state near threshold (10.1 MeV) is particularly sensitive to the presence of 4^+ strength. Below an excitation energy of 12 MeV in ^{208}Pb, the calculations fail completely to account for population of this state if the 4^+ strength is excluded. The population of the $i_{13/2}$ state at 1.633 MeV also depends on the presence of high spin (particularly 6^+) strength. We regard these data as strong corroboration of the presence of 4^+ and 6^+ strength as suggested in Refs. 4, 15, and 16. The distribution of neutron decay among the six ^{207}Pb levels studied is reproduced remarkably well by the calculation up to 12 MeV. Above this energy the statistical model predicts a more rapid falloff of population to these states than is observed. The yields to these individual states exceed the corresponding predictions by large factors at the highest energies. This illustrates the sensitivity obtained by concentrating on these low lying states. The bulk of the statistical decay populates states lying higher in excitation energy than those in Table I, so that the fraction of the total neutron yield represented by the yield in excess of predictions in Fig. 2 remains relatively modest. At 14 MeV (the peak of $T=0$, $L=0$ giant resonance) there is a combined yield to the states in Table I in excess of the statistical-model predictions corresponding to 15% to 19% of the total n yield. We emphasize that the comparison between calculation and data is absolute; there is no arbitrary normalization.

The branching ratio data below ~12 MeV of ^{208}Pb excitation energy, a region strongly dominated by the isoscalar giant quadrupole resonance (GQR) in our experiment, can be accounted for remarkably well by the Hauser-Feshbach calculations. There is no evidence for enhanced emission either to the hole states or the weak-coupling multiplet at 2.6 MeV. We conclude that the GQR is completely damped into compound states before any significant neutron emission occurs.

Pronounced disagreement is obvious between the calculations and the data above an excitation energy of 13 MeV, particularly for the three higher-lying ^{207}Pb states. One possible explanation is that the level-density formula for ^{207}Pb, which plays a significant role in the calculation above 12 MeV, overestimates the density of states available to neutron decay. The reduction in level density required is approximately a factor of five, leading to the dashed lines in Fig. 2, but such a drastic reduction does not seem plausible. A more natural and very interesting possibility is that the discrepancy reflects precompound emission from excited ^{208}Pb. The 15% nonequilibrium contribution deduced here is somewhat larger than the ~10% upper limit quoted in Ref. 2. One surprising observation is the similarity of the energy dependence and magnitude of the excess yields to the $g_{9/2}$ neutron state and the ~2.6 MeV weak-coupling states to those of the hole states. Naively, one expects the neutron hole states to be preferentially populated in precompound decays. These 1p-2h states can be populated by decays from particular 2p-2h states in the initial stage of the damping process, indicating that these states contribute to precompound decay in a manner and to an extent qualitatively similar to the coherent 1p-2h states.

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