Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

Low-lying levels in ^{148}Pm

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(Received 9 November 1987)

The ^{149}Sm(d,^{3}He) reaction has been used to populate levels in ^{148}Pm. Nineteen new excited states have been observed below 1 MeV excitation energy in ^{148}Pm. The possible astrophysical implications of these results are discussed.

The elements heavier than iron are believed to be synthesized via neutron-capture reactions that occur in stars. In their pioneering work on the origin of the elements, Burbidge, Burbidge, Fowler, and Hoyle[1] pointed out that two distinct neutron-capture processes were required to explain the observed solar-system elemental and isotopic abundances. In the *s* (slow) process, the neutron flux is so low that if a beta-unstable nucleus is produced, it almost always has time to decay before the next neutron capture occurs. In the *r* (rapid) process, on the other hand, the neutron flux is so high that many successive neutron captures can occur before a beta decay takes place. The site of the *s* process is generally believed to be the helium-burning zones of red-giant stars. A definite site for the *r* process has yet to be established.

While it is generally true that in the *s* process the neutron-capture rates are low compared to typical beta-decay rates, there are sites along the *s* process path where the half-lives are sufficiently long that neutron capture on these unstable nuclei competes favorably with beta decay. If one knows the relevant isotopic abundances, neutron-capture cross sections, and beta-decay half-lives, such "branch points" allow one to infer the neutron density during the *s* process.

Through recent measurements of the neutron-capture cross sections of ^{148,149,150}Sm, Winters *et al.*[2] have shown that such a branch in the *s* process path occurs at the odd-odd nucleus ^{148}Pm. However, the usefulness of this branch cannot yet be fully exploited because of the lack of information on the nuclear structure of ^{148}Pm. Until

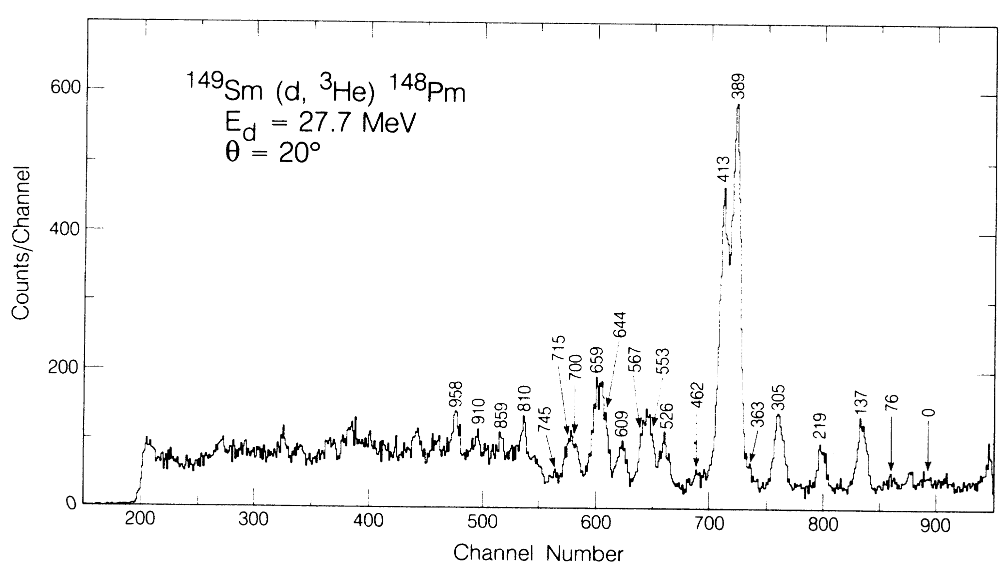

FIG. 1. The ^{149}Sm(d,^{3}He)^{148}Pm spectrum observed at 20 deg with an incident energy of $E_d = 27.7$ MeV.

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the present study was begun, only three levels in ^{148}Pm were known.[3] The ground state, ^{148}Pm^g, is a $J^\pi=1^-$ level with a 5.37-day beta-decay half-life. The first excited state at 76 keV is a $J^\pi=2^-$ level that gamma decays to the ground state. The second excited state at 137 keV is a $J^\pi=6^-$ isomer, ^{148}Pm^m, that decays almost entirely by beta-minus decay with a 41.3-day half-life. It has been estimated[2] that during the s process, the ^{147}Pm(n,γ) reaction produces roughly equal amounts of ^{148}Pm^g and ^{148}Pm^m. However, at the high temperatures at which the s process is believed to occur, $(1-4)\times 10^8$ K, the question arises as to whether this population will be preserved or whether ^{148}Pm^g and ^{148}Pm^m could come into thermal equilibrium. Winters *et al.*[2] have shown that the neutron density inferred from this s process branch point is a factor of 3 larger if equilibrium is reached than if the initial equal mixture of ^{148}Pm^g and ^{148}Pm^m is preserved.

There are many potential mechanisms by which ^{148}Pm^{g,m} could reach thermal equilibrium during the s process. One of the most important is undoubtedly photoexcitation. In the hot stellar environment at which the s process is thought to occur, there is an enormous flux of high energy photons. Thus it is possible that a nucleus, initially in the isomeric state, could absorb one of these photons and be excited to a higher-lying level which subsequently decays to the ground state. In order for the timescale for equilibration under s process conditions to be shorter than the half-life of ^{148}Pm^g, such mediating levels must lie below approximately 1 MeV excitation energy. Thus, to decide if this actually happens during the s process, the positions and gamma-decay properties of levels in ^{148}Pm must be known.

As a first step toward answering the question of whether ^{148}Pm^{g,m} reach thermal equilibrium in the s process, we have performed an experiment to locate low-lying levels in ^{148}Pm. The ^{149}Sm(d,^{3}He)^{148}Pm reaction was performed using a 27.7-MeV deuteron beam from the Princeton University cyclotron. The target consisted of 54 μg/cm^2 of metallic samarium enriched to 91.59% ^{149}Sm evaporated onto a 31 μg/cm^2 carbon backing. Beam currents of 200–300 nA were used in the present measurements. The reaction ^{3}He particles were momentum analyzed with the Princeton quadrupole-dipole-dipole-dipole (QDDD) spectrometer and were detected at the focal surface with a 60-cm long position-sensitive proportional counter in coincidence with a plastic scintillator. The spectrometer was calibrated using the (d,^{3}He) reaction on targets of ^{144}Sm and ^{150}Sm because these reactions have similar Q values to that of the ^{149}Sm(d,^{3}He)^{148}Pm reaction and because the levels in ^{143}Pm and ^{149}Pm populated via this reaction are well known.[3,4] The measured energy resolution was 16 keV full width at half maximum (FWHM).

Figure 1 illustrates the spectrum of ^{3}He particles observed at a laboratory angle of 20 deg. In addition to the three previously known levels in ^{148}Pm, many new states appear. Using our calibration of the spectrometer, we have been able to determine the positions of nineteen new levels below 1-MeV excitation energy with uncertainties of $\pm$6 keV. From these data, we have also measured the Q value for the ^{149}Sm(d,^{3}He)^{148}Pm reaction to be -2.064 ± 0.006 MeV.

If the (d,^{3}He) reaction proceeds by a direct one-step mechanism, then the low-lying states in ^{148}Pm we expect to populate should arise from couplings of an odd $2d_{5/2}$ or $1g_{7/2}$ proton with the odd $2f_{7/2}$ neutron of the target nucleus. Such couplings yield six pairs of negative parity states with spins of 1, 2, 3, 4, 5, 6, and single $J=0$ and $J=7$ negative parity states. A level scheme of this kind has been observed in a similar study[5,6] of the odd-odd nucleus ^{144}Pm. As a result of the ^{149}Sm target having $J^\pi=\frac{7}{2}^-$, $J^\pi=1^-\rightarrow 6^-$ states can all be populated via $L=2$ proton transfers. Thus, while the ^{149}Sm(d,^{3}He) reaction is not suitable for determining the spins and parities of the states we observe, it is likely that many of the levels seen in our spectrum do arise from these couplings of the odd proton and odd neutron. Figure 2 summa-

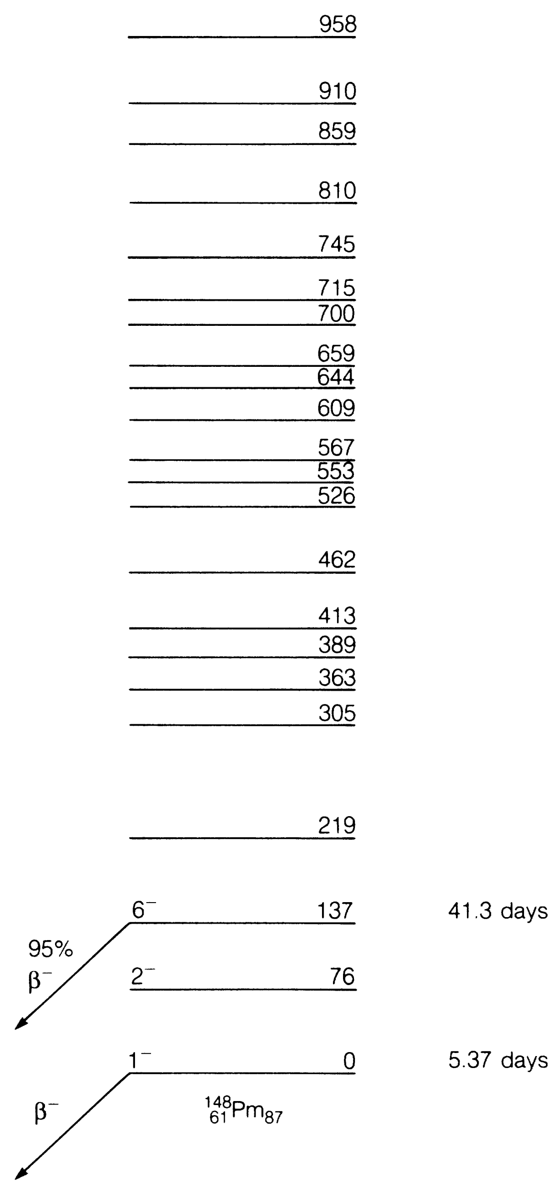

FIG. 2. Level scheme of ^{148}Pm based on the results of the present study and those of previous investigations.

rizes what is now known about the level scheme of ^{148}Pm from the results of the present study and those of previous investigations.[3]

An example of the type of state that could mediate transitions between ^{148}Pm^{g} and ^{148}Pm^{m} is one of the $J^{\pi}=4^{-}$ levels described above. Such a state should have sizable decay branches to both the $J^{\pi}=2^{-}$ level at 76 keV (which decays to the ground state) and to the isomer. To determine which, if any, of the levels observed in the present investigation serve as such a mediator during the *s* process, the gamma-decay properties of these levels must be known. Experiments are now under way at Lawrence Berkeley Laboratory to study electromag netic transitions in ^{148}Pm in hopes of answering this question.

We wish to thank the late W. H. Moore for assistance in operating the cyclotron. This work was supported at Lawrence Berkeley Laboratory by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and at Princeton University by the U.S. National Science Foundation.

[1]G. R. Burbidge, E. M. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 54 (1957).

[2]R. R. Winters *et al.*, Astrophys. J. **300**, 41 (1986).

[3]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).

[4]I. S. Lee *et al.*, Nucl. Phys. **A371**, 111 (1981).

[5]M. R. Macphail and R. G. Summers-Gill, Nucl. Phys. **A237**, 285 (1975).

[6]M. R. Macphail and R. G. Summers-Gill, Nucl. Phys. **A263**, 12 (1976).