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Low-Lying Levels in $^{148}_{\text{Pm}}$

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Abstract

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

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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 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\textsuperscript{2} that during the s-process, the $^{147}\text{Pm}(n,\gamma)$ reaction produces roughly equal amounts of $^{148}\text{Pm}^g$ and $^{148}\text{Pm}^m$. However, at the high temperatures at which the s-process is believed to occur, (1-4) x $10^8$ K, the question arises as to whether this population will be preserved or whether $^{148}\text{Pm}^g$ and $^{148}\text{Pm}^m$ could come into thermal equilibrium. Winters et al.\textsuperscript{2} have shown that the neutron density inferred from this s-process branch point is a factor of three larger if equilibrium is reached than if the initial equal mixture of $^{148}\text{Pm}^g$ and $^{148}\text{Pm}^m$ is preserved.

There are many potential mechanisms by which $^{148}\text{Pm}^g,m$ 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 $^{148}\text{Pm}^g$, 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 $^{148}\text{Pm}$ must be known.

As a first step toward answering the question of whether $^{148}\text{Pm}^g,m$ reach thermal equilibrium in the s-process, we have performed an experiment to locate low-lying levels in $^{148}\text{Pm}$. The $^{149}\text{Sm}(d,^3\text{He})^{148}\text{Pm}$ reaction was performed using a 27.7-MeV deuteron beam from the Princeton University cyclotron. The target consisted of 54 $\mu$g/cm$^2$ of metallic samarium enriched to 91.59% $^{149}\text{Sm}$ evaporated onto a 31 $\mu$g/cm$^2$ carbon backing. Beam currents of 200 - 300 nA were used in the present measurements. The reaction $^3\text{He}$ particles were
momentum analyzed with the Princeton 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,³He) reaction on targets of ¹⁴⁴Sm and ¹⁵⁰Sm because these reactions have similar Q-values to that of the ¹⁴⁹Sm(d,³He)¹⁴⁸Pm reaction and because the levels in ¹⁴³Pm and ¹⁴⁹Pm populated via this reaction are well known. The measured energy resolution was 16 keV (FWHM).

Figure 1 illustrates the spectrum of ³He particles observed at a laboratory angle of 20 degrees. In addition to the three previously known levels in ¹⁴⁸Pm, 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 ± 6 keV. From these data, we have also measured the Q-value for the ¹⁴⁹Sm(d,³He)¹⁴⁸Pm reaction to be -2.064 ± 0.006 MeV.

If the (d,³He) reaction proceeds by a direct one-step mechanism, then the low-lying states in ¹⁴⁸Pm we expect to populate should arise from couplings of an odd 2d⁵/₂ or 1g⁷/₂ proton with the odd 2f⁷/₂ 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 of the odd-odd nucleus ¹⁴⁴Pm. As a result of the ¹⁴⁹Sm target having Jπ = 7/2⁻, Jπ = 1⁻ → 6⁻ states can all be populated via L = 2 proton transfers. Thus, while the ¹⁴⁹Sm(d,³He) 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 summarizes what is now known about the level scheme of ¹⁴⁸Pm from the results of the present study and those of previous investigations.
An example of the type of state that could mediate transitions between $^{148}\text{Pm}^g$ and $^{148}\text{Pm}^m$ is one of the $J^T = 4^{-}$ levels described above. Such a state should have sizable decay branches to both the $J^T = 2^{-}$ 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 underway at Lawrence Berkeley Laboratory to study electromagnetic transitions in $^{148}\text{Pm}$ in hopes of answering this question.

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References


Figure Captions

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

Figure 2. Level scheme of $^{148}_{\text{Pm}}$ based on the results of the present study and those of previous investigations.
149Sm (d, 3He) 148Pm
E_d = 27.7 MeV
θ = 20°