Effect of Compound-Nucleus Spin-Parity Distribution on the Derivation of Neutron Capture Cross Sections in the Surrogate Ratio Method

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Date: 2024-01-12T00:00:00+00:00

Abstract

Neutron capture cross-sections of unstable nuclei are of great significance for studies of stellar nucleosynthesis and neutron density in stellar interiors, but due to difficulties in target preparation, direct measurements are extremely challenging. We have verified that the surrogate ratio method based on (18O, 16O) can be applied to derive neutron capture cross-sections of unstable nuclei; this work mainly discusses the influence of compound nucleus spin-parity states on the ratio of compound nucleus γ-decay probabilities, arguing that in the region of higher neutron incident energies, the influence of compound nucleus spin-parity states on the γ-decay probability ratio is very small, while in the low-energy region, the compound nuclei produced by the (18O, 16O) surrogate reaction tend to be populated in low spin-parity states similar to those of the compound nuclei produced by neutron capture reactions. This thereby demonstrates the reliability of the surrogate ratio method for deriving (n,γ) cross-sections.

Full Text

The Effect of Compound Nucleus Spin-Parity Distribution on Neutron Capture Cross Section Determination Using the Surrogate Ratio Method

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Abstract

Neutron capture cross sections of unstable nuclei are crucial for understanding stellar nucleosynthesis and internal neutron density in stars, yet direct measurements remain extremely challenging due to target preparation difficulties. This work validates the application of the (^{18}O, ^{16}O)-based surrogate ratio method for determining neutron capture cross sections of unstable nuclei, focusing specifically on how compound nucleus spin-parity states affect the ratio of gamma-decay probabilities. We demonstrate that at higher neutron incident energies, the spin-parity distribution has minimal impact on the gamma-decay probability ratio, while at low energies, the compound nuclei produced by (^{18}O, ^{16}O) surrogate reactions preferentially populate low spin-parity states similar to those generated by neutron capture reactions. This validates the reliability of the surrogate ratio method for deriving (n,γ) cross sections.

Keywords: surrogate ratio method; neutron capture cross section; unstable nuclei

Neutron capture processes play a fundamental role in the synthesis of heavy elements beyond iron in the universe, primarily through the slow neutron capture process (s-process) and rapid neutron capture process (r-process) occurring in stellar environments. The s-process operates in stable burning stars with relatively low neutron densities (~10^6–10^8 cm^{-3}), where unstable nuclei with half-lives longer than several years can compete with β-decay through neutron capture, producing heavier isotopes. Examples include ^{63}Ni, ^{79}Se, and ^{85}Kr. Nuclei with shorter half-lives predominantly decay to different elements via β-emission. Consequently, the s-process path follows the β-stability line closely, contributing approximately half of the heavy element abundances. However, in massive stars, convection processes within helium and carbon shells significantly elevate temperatures and boost neutron densities to ~10^{13} cm^{-3}. Under these conditions, nuclei with half-lives on the order of days, such as ^{59}Fe, ^{95}Zr, and ^{181}Hf, capture neutrons rather than decaying. These unstable nuclei in the s-process not only participate in heavy element synthesis but also follow different nucleosynthetic pathways depending on temperature and neutron density. Variations in these pathways create distinct abundance patterns in subsequent nuclei, providing valuable diagnostics for studying stellar evolution.

Direct measurement of neutron capture cross sections for short-lived nuclei remains extremely difficult due to target preparation challenges, particularly for isotopes with half-lives of tens of days or less. Consequently, most short-lived nuclei in the s-process lack reliable experimental data, with only stable nuclei and some long-lived unstable isotopes having well-determined cross sections [1]. The surrogate ratio method, recently developed from the surrogate approach, offers an indirect technique for measuring neutron capture cross sections of unstable nuclei. We previously validated this method using ^{90,92}Zr(^{18}O, ^{16}Oγ)^{92,94}Zr experiments and reference reactions ^{91}Zr(n,γ)^{92}Zr and ^{93}Zr(n,γ)^{94}Zr with known cross sections, establishing a surrogate ratio method based on (^{18}O,^{16}O) two-neutron transfer reactions [2]. This approach has since been successfully applied to determine the neutron capture cross sections of ^{59}Fe (half-life ~44 days) [3] and ^{95}Zr (half-life ~64 days) [4].

A potential concern arises because the “compound nuclei” produced in two-neutron transfer reactions differ in spin-parity distribution from those formed via neutron capture. Theoretical studies suggest that compound nucleus decay to the gamma channel is sensitive to spin-parity, which could introduce significant discrepancies between indirectly derived and directly measured cross sections. However, our validation experiments showed excellent agreement between the derived ^{93}Zr(n,γ)^{94}Zr cross section and direct measurements. This paper investigates the influence of spin-parity distribution differences on results obtained with the surrogate ratio method.

2. The Surrogate Ratio Method and Experimental Measurement

The surrogate ratio method [5] represents an advancement over the original surrogate approach, with the key advantage of not requiring compound nucleus population measurements or theoretical calculations. Based on Hauser-Feshbach compound nucleus theory and the Weisskopf-Ewing approximation, and assuming gamma-decay probability shows no strong dependence on compound nucleus spin-parity, the cross section for A(n,γ)B can be expressed as:

$\sigma\ ,\gamma(\mathrm{E}\ ) = \sigma\ \ (\mathrm{E}\ ) \times \mathrm{G}\gamma$

where $\sigma\ \ (\mathrm{E}\ )$ is the compound nucleus formation cross section, Gγ is the decay probability to the gamma channel (or neutron capture probability), and E is the neutron incident energy. In the surrogate ratio method, a reference reaction A_2(n,γ)B_2 with known cross section is used to determine the target reaction A_1(n,γ)B_1. The ratio of the two cross sections becomes:

$\sigma\ ,\gamma\ ^1\ ^1(\mathrm{E}\ )\ /\ \sigma\ ,\gamma\ ^2\ ^2(\mathrm{E}\ ) = [\sigma\ \ ^1(\mathrm{E}\ ) \times \mathrm{G}\gamma\ ^1]\ /\ [\sigma\ \ ^2(\mathrm{E}\ ) \times \mathrm{G}\gamma\ ^2]$

If the reference reaction is similar to the target reaction, we can approximate $\sigma\ \ ^1(\mathrm{E}\ )\quad \sigma\ \ ^2(\mathrm{E}\ )$, reducing the ratio of neutron capture cross sections to the ratio of gamma-channel decay probabilities. Experimentally, we employ accessible surrogate reactions d_1+D_1→b_1+B_1* and d_2+D_2→b_2+B_2* to produce compound nuclei B_1* and B_2, *measuring their gamma-decay probability ratio. This ratio, combined with the known cross section of the reference reaction* A_2*(n,*γ*)*B_2*, yields the target reaction cross section. In our validation experiments, we used* $^{90}Zr(^{18}O,^{16}O)^{92}Zr$ as a surrogate for ^{91}Zr+n forming ^{92}Zr*, and* $^{92}Zr(^{18}O,^{16}O)^{94}Zr$ as a surrogate for ^{93}Zr+n forming ^{94}Zr*. By measuring the gamma-decay probability ratio of* ^{94}Zr to ^{92}Zr* and combining it with the directly measured ^{91}Zr(n,γ)^{92}Zr cross section, we derived the ^{93}Zr(n,γ)^{94}Zr cross section.

In the experimental measurement, 117 MeV ^{18}O beams from an accelerator bombarded self-supporting targets of highly enriched ^{90}Zr and ^{92}Zr isotopes. A ΔE-E silicon telescope (consisting of a bowl-shaped ΔE array and a Micron S1 annular detector) covered emission angles from 22° to 39° (with angular resolution better than 1°) to detect and identify outgoing light particles. The particle identification spectrum is shown in [Figure 1: see original paper]. Using the energy and emission angle of ^{16}O particles from the ^{90},^{92}Zr(^{18}O,^{16}O)^{92},^{94}Zr* two-neutron transfer reactions, we reconstructed the excitation energies of ^{92}Zr* or ^{94}Zr* via two-body kinematics. Characteristic gamma rays from ^{92}Zr* or ^{94}Zr* were detected by lanthanum bromide detectors in coincidence with the ^{16}O particles identified by the silicon detectors. Experimental details are provided in reference [2]. After determining the excitation energies of ^{92}Zr* and ^{94}Zr* and detecting their characteristic gamma rays, we corrected for target and beam normalization as well as detector efficiency to obtain the gamma-channel decay probability ratio for compound nuclei ^{92}Zr* and ^{94}Zr* produced via two-neutron transfer. This measured ratio, combined with the directly measured ^{91}Zr(n,γ)^{92}Zr cross section, allowed us to derive the ^{93}Zr(n,γ)^{94}Zr cross section. Using the same experimental setup, we also measured the ^{94}Zr(^{18}O,^{16}O)^{96}Zr* reaction to determine the neutron capture cross section of ^{95}Zr.

[Figure 1: see original paper] shows the online color figure of the two-dimensional particle identification spectrum for the ^{18}O+^{94}Zr reaction, with energy loss in the ΔE detector on the vertical axis and total particle energy on the horizontal axis.

3. Compound Nucleus γ-Channel Decay Probability Ratio

Chiba & Iwamoto [6] demonstrated that in the low-energy region (E 3 MeV), the probability of compound nucleus decay to the gamma channel (capture probability) exhibits strong dependence on spin-parity. This sensitivity arises because the compound nucleus level density is relatively low at low energies, making discrete level transitions dominant and more sensitive to spin-parity selection rules. At higher energies, the level density increases dramatically, and continuous level transitions become dominant, reducing spin-parity sensitivity. As shown in [Figure 2: see original paper], we used the TALYS code to calculate the gamma-channel decay probability of ^{92}Zr* for various spin-parity states as a function of neutron incident energy. Below 3 MeV, the gamma-decay probability varies by 2–3 orders of magnitude depending on spin-parity, with 7^- and 8^- states showing probabilities more than two orders of magnitude higher than 1^-, 2^-, 3^-, and 4^- states. Above 3 MeV, the gamma-decay probabilities for different spin-parity states begin to converge.

Consequently, if the compound nuclei produced by surrogate reactions differ significantly in spin-parity distribution from those generated by neutron capture, their gamma-decay probabilities will show relatively small differences at high energies but dramatic, order-of-magnitude variations at low energies. This could lead to substantial discrepancies between indirectly derived and directly measured (n,γ) cross sections when using the surrogate method.

The surrogate ratio method addresses this issue by introducing a reference reaction A_2(n,γ)B_2 similar to the target reaction A_1(n,γ)B_1, utilizing the ratio of gamma-channel decay probabilities (or capture probabilities) of the two compound nuclei as expressed in equation (2). To investigate this ratio, we calculated the gamma-decay probability ratio of ^{94}Zr* to ^{92}Zr* for identical spin-parity states as a function of neutron incident energy. For example, when both ^{94}Zr* and ^{92}Zr* are in the 8^+ state at E $= 3.8$ MeV, the ratio is approximately 4.7. We systematically computed this ratio for spin values from 0 to 8 and both parities, as shown in [Figure 3: see original paper]. Compared to the 2–3 order-of-magnitude variation in ^{92}Zr* gamma-decay probabilities across different spin-parity states shown in [Figure 2: see original paper], the ratio of gamma-decay probabilities between ^{94}Zr* and ^{92}Zr* shows much smaller variations. Particularly above 6 MeV, the ratios for all spin-parity states converge tightly, indicating that even large differences in spin-parity distributions between surrogate and neutron capture reactions yield nearly identical gamma-decay probability ratios. Therefore, in high neutron energy regions, cross sections derived using the surrogate ratio method should agree well with direct measurements. However, below 2 MeV, the ratio varies between 0 and 2, while in the 2–6 MeV region, ratios for high-spin states (8^+, 7^+, 6^+, 8^-) exhibit dramatic fluctuations, whereas lower spin states (<4) show converging ratios.

Experimentally, we measured the gamma-decay probability ratio for ^{94}Zr* and ^{92}Zr* produced via (^{18}O,^{16}O) surrogate reactions, shown as hollow stars in [Figure 3: see original paper] (aligned with theoretical calculations in the high-energy region where ratios converge). Since experiments cannot resolve individual spin-parity states, the measured ratio represents contributions from all states. Comparing theory with experiment, the data do not support significant population of spin states >8 in (^{18}O,^{16}O) reactions, instead favoring lower spin states. In the region below 5 MeV, the ground state spins of ^{91}Zr, ^{93}Zr, and ^{95}Zr are $5/2^+$, and low-energy neutrons carry small angular momentum, so compound nuclei primarily populate spin states <5, matching the spin range populated by (^{18}O,^{16}O) surrogate reactions. Furthermore, theoretical calculations show that gamma-decay probability ratios for compound nuclei with spin <5 converge, making the experimentally measured ratio consistent with that from neutron capture reactions. This enables surrogate ratio method derived (n,γ) cross sections to agree with direct measurements within uncertainties of approximately 30%, primarily from experimental measurement errors, theoretical simplifications (the assumption that gamma-decay probability is independent of spin-parity and the cancellation of compound nucleus formation cross sections in the ratio method), and error propagation from the reference reaction.

Using the same experimental setup, we also measured the ^{94}Zr(^{18}O,^{16}O)^{96}Zr* reaction, allowing us to investigate the ratios of ^{96}Zr* to ^{92}Zr* ([Figure 4: see original paper]) and ^{96}Zr* to ^{94}Zr* ([Figure 5: see original paper]). The comparison between theoretical calculations and experimental data resembles the ^{94}Zr$/^{92}Zr$ case, suggesting that (^{18}O,^{16}O) two-neutron transfer reactions preferentially populate low-spin states similar to those populated by neutron capture, making surrogate ratio method derived cross sections converge toward direct (n,γ) values. However, in the low-energy region, particularly below 1 MeV, experimental data significantly exceed theoretical calculations, warranting deeper investigation of the reaction mechanism.

4. Conclusions and Discussion

Measuring neutron capture cross sections of unstable nuclei involved in the s-process is essential for understanding stellar nucleosynthesis and the temperature and neutron density conditions in stellar interiors. However, direct measurements are impossible for short-lived isotopes due to target preparation difficulties, necessitating indirect methods. The surrogate ratio method, recently developed from the surrogate approach, has been validated through ^{90,92}Zr(^{18}O,^{16}Oγ)^{92,94}Zr experiments and reference reactions ^{91}Zr(n,γ)^{92}Zr and ^{93}Zr(n,γ)^{94}Zr, establishing a robust method based on (^{18}O,^{16}O) two-neutron transfer reactions for indirect determination of (n,γ) cross sections of unstable nuclei.

The primary challenge for the surrogate ratio method stems from spin-parity distribution differences between compound nuclei produced by surrogate and neutron capture reactions, compounded by the sensitivity of gamma-decay probabilities to spin-parity. Using ^{92}Zr* and ^{94}Zr* as examples, this work demonstrates that spin-parity effects on gamma-decay probability ratios become negligible at high neutron incident energies, enabling indirect measurements to match direct results. At low energies, however, the ratios exhibit dramatic variations, particularly for spin states >7. Comparison between theoretical calculations and experimental measurements reveals that (^{18}O,^{16}O) two-neutron transfer reactions do not support high spin states but instead favor low-spin states similar to those populated by neutron capture, confirming the reliability and feasibility of the surrogate ratio method.

For lighter nuclei with lower level densities [7], gamma-channel decay probabilities are more sensitive to spin-parity, potentially increasing uncertainties in surrogate ratio method results. In contrast, for $A > 50$ where level densities are higher, sensitivity to spin-parity distribution decreases, yielding results that converge more closely to true values.

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