First Excited State of the s-Process Branching Nucleus ^{95}Zr ◇

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The nucleus ^{95}Zr is a branching point in the astrophysical s-process. Depending on the β^--decay half-life, neutron capture cross section, and the neutron density, the nucleosynthesis path proceeds either via ^{94}Zr(n,γ)^{95}Zr(β^-)^{95}Nb(β^-) ^{95}Mo(n,γ)^{96}Mo(n,γ)^{97}Mo on the neutron-deficient branch or via ^{94}Zr(n,γ)^{95}Zr(n,γ)^{96}Zr(n,γ)^{97}Zr(β^-)^{97}Nb(β^-)^{97}Mo on the neutron-rich branch. As a consequence, characteristic isotopic patterns have been found for various molybdenum isotopes in meteorites which are thought to be formed during thermal pulses of so-called AGB (asymptotic giant branch) stars. These stars are the astrophysical site of the main component of the s-process

A direct measurement of the neutron capture cross section of the unstable nucleus ^{95}Zr is extremely difficult because of its short half-life of $T_{1/2} = 64$ days. Theoretical predictions of the Maxwellian averaged neutron capture cross section (MACS) at a typical temperature of $kT = 30$ keV are based on statistical model calculations. The results vary significantly: between 23 mb and 126 mb.

Besides the very discrepant values for the MACS, one more essential problem appears for the nucleus ^{95}Zr. The adopted level scheme [2] lists the following levels of ^{95}Zr: the ground state has $J^\pi = 5/2^+$ and the next level at $E_x = 23$ keV is shown with a questionmark because it has been seen only in one (d,p) transfer experiment [1]. Because of the $L = 2$ transfer it is tentatively assigned to $J^\pi = 3/2^+, 5/2^+$. The next level is located at $E_x = 953.95$ keV with $J^\pi = 1/2^+$. It is obvious that the 23 keV level – if it exists – will be significantly populated at typical s-process temperatures of $kT = 30$ keV whereas the level at 954 keV is practically not populated and can be neglected in the following discussion. Such a thermal population of the 23 keV level may lead to two consequences. First, the effective half-life of ^{95}Zr will depend on temperature, because the β^--decay half-life of the 23 keV level may differ from the β^--decay half-life of the ground state. The difference will be large especially in the case when J^π of the excited state differs from J^π of the ground state. Second, the neutron capture cross section will depend on temperature, because the capture cross sections of the 23 keV level may differ from the capture cross section of the ground state. Again, the difference will be large especially in the case of different J^π. Consequently, there are huge uncertainties from nuclear physics for this important s-process branching nucleus.

It is the motivation of the present experiment to clarify this situation using the same (d,p) transfer reaction as in [1] and a high resolution magnetic spectrograph. Earlier (d,p) transfer experiments were limited in energy resolution. But [1] measured the ^{94}Zr(d,p)^{95}Zr reaction at 15.5 MeV with a quoted energy resolution of 13 keV, and a clear doublet structure is found.

To clarify this question a ^{94}Zr(d,p)^{95}Zr experiment has been performed. The outgoing protons were analyzed with the high resolution Q3D magnetic spectrograph in combination with a new focal plane detector [3]. An unpolarized deuteron beam with an energy of 22 MeV and an average current of 1 μA was used to irradiate a metallic zirconium target on carbon backing enriched in ^{94}Zr to 91.2% with a thickness of 100 μg/cm^2. The achieved energy resolution was 7 keV which certainly is sufficient to distinguish between the lines from the transitions to the ^{95}Zr ground state and the 23 keV level. The spectra at angles of 30° and 70°, measured for roughly 30 min each, are shown in Fig. 1. Obviously there is no excited state at 23 keV with a strength of more than 1% of the ground state strength. Thus it is clear that such an excited state, populated with similar cross section as the ground state as claimed in Ref. [1], does not exist in ^{95}Zr.

A more detailed account of this experiment is published [4].

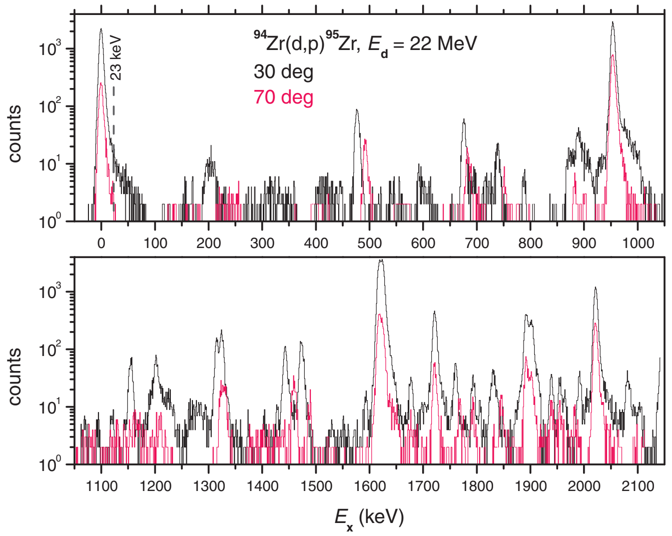

Fig. 1: Spectrum of ^{94}Zr(d,p)^{95}Zr at $\vartheta_{\rm lab} = 30°$ and in gray (red in online) at $\vartheta_{\rm lab} = 70°$. The expected position of a 23 keV state is marked. Some weak lines can be identified as contaminations by the other Zr isotopes in the target because of their kinematic shift. The FWHM is about 7 keV.

References

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