Research Group for Heavy Element Nuclear Science

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The heavy elements open unique opportunities for studies of relativistic effects in chemistry and atomic physics, for which single-atom chemistry is promoted. Determination of the limits of existence of the heaviest nuclei is among the most interesting and challenging topics in nuclear physics, and nuclear fission is our core subject in the nuclear physics program. Our experiments also include nuclear structure studies of a broad range of nuclides, in addition to super-heavy nuclei. The experiments are carried out at the JAEA tandem accelerator facility.

One of the highlights of our nuclear physics experiments is to quantify the angular momentum of excited compound nuclei (CN) populated in multinucleon transfer reaction ^{18}O+^{237}Np. Here, angular momentum was derived by measuring angular distributions of fission fragments relative to the rotational axis of the CN. The results are presented as a Research Highlight.

In this report, we describe a recent nuclear-structure study and a measurement of neutron-capture cross sections relevant to stellar nucleosynthesis achieved via the surrogate-reaction method.

Nuclear structure of ^{248}Cf and shell gaps in heavy nuclei

The limits of existence of the heaviest nuclei are strongly connected with the presence of shell gaps which enhance their stability against fission. The shell gaps in the superheavy element region are predicted by different models to occur in nuclei with proton number $Z = 114$, 120 or 126 and neutron number $N = 184$. Important benchmarks to improve theoretical models can be obtained from deformed actinides lying near smaller, "deformed" shell gaps, that are believed to be pronounced near $(Z, N) \sim (100,152)$. Still, different models predict different locations. Furthermore, in these heavy actinides, part of the nucleon orbitals above the predicted spherical shell gaps at Z=114 or N=184 can appear as excited states due to deformation of the nuclear shape, typical for such actinide nuclides.

^{248}Cf (Z=98, N=150) has only two protons and two neutrons below the deformed Z=100 and N=152 gaps, but the location of the gaps is debated and Z=98 is also suggested. To test the different claims, we searched for excited states in ^{248}Cf sensitive to the location of the proton shell gap.

^{248}Cf was produced at the JAEA Tandem accelerator via the ^{18}O+^{249}Cf multi-nucleon transfer reaction, and γ rays emitted by its excited states were detected. Several new transitions were observed and, for the first time, the mean lifetimes (τ) of excited states in the nanosecond range were measured. One of the isomers found in this work is shown in Fig. 1. We also found evidence of a long-lived (τ > 200 ns) excited state at (882) keV, to which we tentatively assigned a 5^- spin parity. The low energy of this (5^-) state, which was predicted since the 1970s by calculations, but until now not observed, corroborates that the deformed proton shell gap occurs at Z=100, not at Z=98.

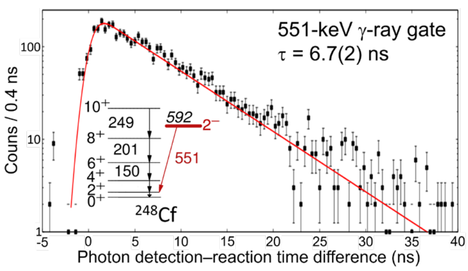

Fig. 1 Decay data of the 551-keV γ ray that represent the lifetime of the 592-keV state, shown in the level scheme. The red curve is the result of the decay-curve fit.

Study of ^{59}Fe(n,γ)^{60}Fe cross sections via a surrogate reaction

The radioactive isotope ^{60}Fe ($t_{1/2}$=2.62 Myr) is a key nucleus in astrophysical processes. Since its half-life is much shorter than the age of the galaxy, its detection permits us to study ongoing stellar processes in our galactic neighbourhood. ^{60}Fe is produced in stars with masses at least 8 times larger than the sun ($M \geq 8M_{\odot}$), through capture reactions in the high neutron fluxes reached during the carbon (C-shell) burning stage and the core-collapse supernova explosion.

To elucidate the production of ^{60}Fe, accurate knowledge of the ^{59}Fe(n,γ)^{60}Fe neutron-capture reaction is required. The short half-life of ^{59}Fe ($t_{1/2}$=44.5 days) prevents the production of a ^{59}Fe target. Thus, at the JAEA Tandem accelerator, the neutron capture cross sections were determined using the surrogate ratio method. In this method, the ratio of the γ-decay probability of the compound nuclei ^{60}Fe* and ^{58}Fe*, $R = P_\gamma(^{60}\mathrm{Fe}^*)/P_\gamma(^{58}\mathrm{Fe}^*)$, produced by the ^{58}Fe(^{18}O,^{16}O)^{60}Fe* and ^{56}Fe(^{18}O,^{16}O)^{58}Fe* transfer reactions, respectively, were measured. The ^{59}Fe(n,γ)^{60}Fe cross sections were then determined by multiplying the known ^{57}Fe(n,γ)^{58}Fe cross sections by R. Figure 2 shows the measured cross sections as a function of equivalent neutron energy. The impact of our new results is that now the main uncertainties in the ^{60}Fe yields from massive stars are related to the models of the progenitor star and of the supernova explosion, rather than to the value of the ^{59}Fe(n,γ)^{60}Fe rates.

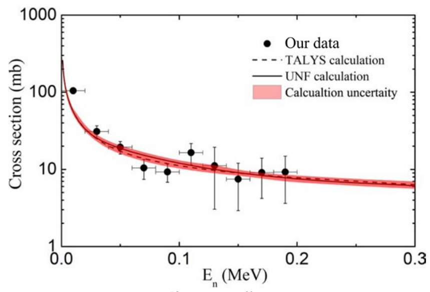

Fig. 2 The cross sections of ^{59}Fe(n,γ)^{60}Fe as a function of equivalent neutron energy. Our data are shown by solid circles. The results of the UNF and TALYS code, with their parameters constrained by the γ-decay probability ratios measured in this work, are also shown.

References

[1] R. Orlandi *et al,* "K isomers in ^{248}Cf and the Z=100 shell gap" 100 Years of Nuclear Isomers Workshop, Berlin, Germany, 2022.
[2] S.Q. Yan *et al*., The Astrophys. J. **919**, 84 (2021).