# New *K* isomers in the actinide nucleus californium-248 ($^{248}$Cf)

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One of the major quests of nuclear physics is the search for long-lived superheavy elements (SHEs). They are believed to exist in proximity of the next spherical shell gaps, predicted at neutron number $N$=184 and proton number $Z$=114 (or 120, or 126), in the so-called "Island of Stability" (IoS). The location of the IoS is however still not known. Current predictions could be improved by extending our knowledge of the proton and neutron orbits in heavy nuclei, in particular by studying deformed actinides near $Z$=100 and $N$=152. The reason is that part of the orbits associated with the IoS are lowered in energy by nuclear deformation and come near the ground state in heavy actinides. Knowledge of the nucleon orbits in the actinide region will therefore permit reliable extrapolations to the IoS. Furthermore, neutron-rich actinides can be produced in sufficiently large quantities to study their γ-ray spectrum, that is the source of information to deduce the spin and energy of the underlying nucleon orbits. With this aim, we developed a technique that can generate in the same experiment several actinides, not measured till now, and investigate their nuclear structure.

In our method, several actinides are generated using multi-nucleon transfer (MNT) reactions. In the reaction, when an actinide target is irradiated by a heavy-ion beam, neutrons and protons are exchanged in various patterns between the colliding nuclei, resulting in the production of several isotopes (Fig. 1). It is therefore necessary to determine what nuclei are produced in each reaction event. In our setup, we detect and identify the light ejectiles, and from reaction kinematics determine the mass and proton number of the complementary heavy nucleus. To achieve this, we developed an array of Si telescope detectors, where the ejectiles implant and are discriminated on an event-by-event basis from their partial vs. total energy loss properties. Immediately after the reaction, the nuclei produced are in a highly excited state, and from the kinetic energy of the ejectile we also determine the excitation of the compound nucleus with a very good resolution of about 250 keV. The excited actinides in turn de-excite by emitting γ-ray photons, which are detected by an array of Ge detectors and $LaBr_3$ scintillators. The Ge detectors are used for their excellent energy resolution (~2 keV); the $LaBr_3$ scintillators time resolution (~2 ns) permits instead to measure half-lives of decays in the nanosecond range.

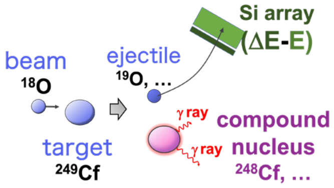

Fig. 1 Schematic diagram of the reaction mechanism and method of identification. In this example, nuclei are generated in the MNT reaction of a $^{18}$O beam colliding onto $^{249}$Cf. In each reaction event, the heavy compound nucleus produced is determined by detecting and identifying the complementary light ejectile in the Si array.

An example of the results obtained with this setup is the γ-ray spectrum of californium-248 ($^{248}$Cf, $Z$=98, $N$=150) [1]. $^{248}$Cf was produced at the JAEA Tandem accelerator, by irradiating a $^{249}$Cf target with a beam of $^{18}$O. The γ-ray spectrum of $^{248}$Cf, shown in Fig. 2, was obtained by selecting those events in which $^{19}$O was identified in the Si array. New γ rays were found and placed in the level scheme. The most significant aspect in the structure of $^{248}$Cf is the presence, at low excitation energy, of long-lived excited states, called *K* isomers. *K* is a quantum number that reflects the orientation of the nuclear spin with respect to the deformation of the nucleus, and corresponds to the projection of the spin onto the symmetry axis (see Fig. 2). When a γ decay involves states with different *K*, the transition is hindered, which results in the long isomer half-life. Unlike the ground-state, where protons and neutrons are coupled in pairs to spin 0, the spin of low-lying *K* isomers arises from the spin of only two nucleons in outer orbits. The spin and energy of *K* isomers thus permit to identify the orbits of the nucleons involved. In $^{248}$Cf, we measured for the first time the half-life of a state at 592 keV and confirmed that it is a $K$=2 isomer, with $t_{1/2}$=4.6(1) ns. Furthermore, we found evidence of an additional *K* isomer lying at 0.9(3) MeV, with $K$≥5 and $t_{1/2}$≥150 ns. Although further experiments are needed to measure its half-life, the lower limit determined in our work already points to the most likely nucleon configuration. *K* isomers are particularly important in the search for SHEs, since sometimes their half-lives can be even longer than that of the ground state [2]. This implies that some SHEs may be easier to discover as *K* isomers.

In the experiment, several actinide isotopes were produced, and the ongoing analysis reveals new γ rays in other isotopes of einsteinium ($Z$=99) and fermium ($Z$=100). In future, using heavier ion beams, we aim to extend this method to study the nuclear structure of trans-actinides and SHEs.

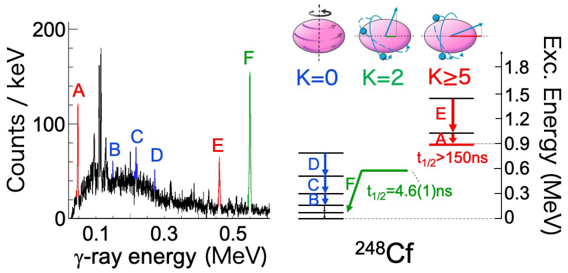

Fig. 2 (Left) γ-ray spectrum of $^{248}$Cf obtained by selecting events in which $^{19}$O was detected. (Right) Partial level scheme of $^{248}$Cf, that includes γ-ray transitions labelled in the γ-ray spectrum. The simple diagrams on top show the differences between the ground state band and *K* isomers. The energy of the 0.9(3)-MeV *K*-isomer state was deduced from the excitation energy measured in the Si array.

## References

[1] R. Orlandi *et al*., Phys. Rev. C **106**, 064302 (2022).
[2] H.M. David *et al.,* Phys. Rev. Lett. **115**, 132502 (2015).