Nuclear isomers: structures and applications

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Abstract. Isomeric states in the nuclei along the rapid proton capture process path are studied by the projected shell model. Emphasis is given to two waiting point nuclei $^{68}$Se and $^{72}$Kr that are characterized by shape coexistence. Energy surface calculations indicate that the ground state of these nuclei corresponds to an oblate-deformed minimum, while the lowest state at the prolate-deformed minimum can be considered as a shape isomer. Due to occupation of the orbitals with large $K$-components, states built upon two-quasiparticle excitations at the oblate-deformed minimum may form high $K$-isomers. The impact of the isomer states on isotopic abundance in X-ray bursts is studied in a multi-mass-zone X-ray burst model by assuming an upper-lower limit approach.

Keywords: Nuclear isomers, rp-process, projected shell model, multi-mass-zone X-ray burst model

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INTRODUCTION

It has been suggested that in X-ray binaries, nuclei are synthesized via the rapid proton capture process (rp-process) [1, 2], a sequence of proton captures and $\beta$ decays responsible for the burning of hydrogen into heavier elements. Recent reaction network calculations [3] have shown that the rp-process can extend up to the heavy Sn-Te mass region. The rp-process proceeds through an exotic mass region with $N \approx Z$, where the nuclei exhibit unusual structure properties. Since the detailed reaction rates depend on the nuclear structure, information on the low-lying levels of relevant nuclei is thus valuable for the isotopic abundance study.

Depending on the shell filling, some nuclei along the rp-process path can have excited metastable states, or isomers [4], by analogy with chemical isomers. Of particular interest are two kinds of isomers, as illustrated in Fig. 1. It is difficult for an isomeric state either to change its shape to match the states to which it is decaying, or to change its spin orientation relative to an axis of symmetry. Therefore, isomer half-lives can be very long. If such states exist in nuclei along the rp-process path, the astrophysical significance could be that the proton-capture on long-lived isomers may increase the reaction flow, thus reducing the timescale for the rp-process nucleosynthesis during the cooling phase.

Coexistence of two or more stable shapes in a nucleus at comparable excitation energies has been known in nuclei with $A \approx 70 - 80$. The expected nuclear shapes include, among others, prolate and oblate deformations. In an even-even nucleus, the lowest state with a prolate or an oblate shape has quantum numbers $K^\pi = 0^+$. An excited $0^+$ state may decay to the ground $0^+$ state via an electric monopole (E0) transition. For lower excitation energies, the E0 transition is usually slow, and thus the excited $0^+$
state becomes a “shape isomer”. There are also excited states based on two-quasiparticle (qp) excitation. If the two quasiparticles occupy the orbitals having large $K$ (where $K$ is the quantum number representing the projection of the total nuclear spin along the symmetry axis), the decay path to lower energy states having a small or zero $K$ requires a large change in $K$ quantum number, and therefore the emission of radiation with high multipolarity is required to match the change. Such emissions are usually strongly hindered, and thus the excited high-$K$ state becomes a “$K$-isomer” (see the schematic illustration in Fig. 1).

**SHAPE-ISOMERS AND K-ISOMERS IN $^{68}$Se AND $^{72}$Kr**

Calculations on the structure are performed by the projected shell model [5]. Fig. 2 shows calculated total energies as a function of deformation variable $\varepsilon_2$ for different spin states in $^{68}$Se and $^{72}$Kr. The configuration space and the interaction strengths in the Hamiltonian are the same as those employed in the previous calculations for the
same mass region \cite{6}. Under these calculation conditions, it is found that in both nuclei, the ground state takes an oblate shape with $\varepsilon_2 \approx -0.25$. As spin increases, the oblate minimum moves gradually to $\varepsilon_2 \approx -0.3$. Another local minimum with a prolate shape ($\varepsilon_2 \approx 0.4$) is found to be 1.1 MeV ($^{68}$Se) and 0.7 MeV ($^{72}$Kr) high in excitation. Bouchez et al. \cite{7} observed the 671 keV shape-isomer in $^{72}$Kr with half-life $\tau = 38 \pm 3$ ns. The one in $^{68}$Se is our prediction, awaiting experimental confirmation. Similar isomer states have also been calculated by Kaneko et al. \cite{8}.

Most nuclei near the $N=Z$ line with $A \sim 70-80$ are well-deformed. At the deformed potential minimum, the high-$j$ $g_{9/2}$ orbit intrudes into the $pf$-shell. With an oblate shape, one finds the largest $K$ components ($K = \frac{7}{2}$ and $\frac{9}{2}$) of this $j$-orbit near the Fermi levels of $^{68}$Se and $^{72}$Kr. Thus, a 2-qp state can have $K = \frac{7}{2} + \frac{9}{2} = 8$, and a 4-qp state $K = 16$ which is built from a neutron 2-qp and a proton 2-qp state. If $K$ is approximately a conserved quantum number, the $K$ value in these 2- and 4-qp states is much larger than that of the ground state band ($K = 0$). Once having been populated, this makes it rather difficult for such 2- or 4-qp states to decay back to the ground state.

In Figs. 3, we present the energy levels calculated by the projected shell model, and compare them with available experimental data \cite{9}. For $^{72}$Kr, with the newly confirmed $0^+$ isomer \cite{7} which should be the bandhead of the prolate band, the rotational band at the prolate minimum is now known. However, there have been no experimental data to compare with the predicted oblate band. In contrast, an oblate band in $^{68}$Se was observed and a prolate one was also established \cite{9}, except for the missing bandhead which we predict as a shape isomer. For both nuclei, we predict low-lying high-$K$ isomers, indicated by bold lines. In particular, the spin-16 states are so low in excitation (much lower than the spin-16 state in the ground band) that one may consider them as a spin trap \cite{4}.
IMPACT ON ISOTOPIC ABUNDANCE IN X-RAY BURSTS

The recent observation of a low energy $0^+$ shape isomer in $^{72}$Kr [7] has opened new possibilities for the rp-process reaction path. A similar shape isomer has been predicted for $^{68}$Se in this paper. Since the ground states of $^{73}$Rb and $^{69}$Br are bound with respect to these isomers, proton capture on these isomers may lead to additional strong feeding of the $^{73}$Rb($p, \gamma$)$^{74}$Sr and $^{69}$Br($p, \gamma$)$^{70}$Kr reactions. However, whether these branches have any significance depends on the associated nuclear structure parameters, such as

- how strong is the feeding of the isomer states?
- what is the lifetime of the isomer with respect to $\gamma$-decay and also to $\beta$-decay?
- what are the lifetimes of the proton unbound $^{69}$Br and $^{73}$Rb isotopes in comparison to the proton capture on these states?

Two processes can be envisioned to populate the isomeric states in appreciable abundance, through thermal excitation of the ground state at high temperatures, or through proton capture induced $\gamma$-feeding. Thermal excitation is very efficient for feeding levels at low excitation energy since the population probability scales with $e^{-E_x/kT}$. Contributions of low energy states ($E_x \leq Q$) are negligible since proton capture on those states is balanced by inverse proton decay [2]. This is not the case for proton capture on the isomeric states. The peak temperature in the here used X-ray burst model is around 1.1 GK, the isomer states in $^{68}$Se at 1.1 MeV and in $^{72}$Kr at 0.67 MeV are therefore only very weakly populated with $\leq 0.02\%$ and $\leq 0.5\%$, respectively. Feeding through $^{67}$As($p, \gamma$)$^{68}$Se* ($Q \approx 3.19$ MeV) and $^{71}$Br($p, \gamma$)$^{72}$Kr* ($Q \approx 4.1$ MeV) is a more likely population mechanism. A quantitative prediction of the feeding probability requires a more detailed study of the $\gamma$-decay pattern of low spin ($J \leq 3$) states above the proton threshold in $^{68}$Se and $^{72}$Kr, respectively.

The lifetime of the isomeric states must be sufficiently long to allow proton capture to take place. No information is available about the lifetime of the $^{68}$Se* isomer while the 55 ns lifetime of the isomer in $^{72}$Kr is rather short [7]. Based on Hauser Feshbach estimates [2] the lifetime against proton capture is in the range of $\approx 100$ ns to 10 $\mu$s depending on the density in the environment. Considering the uncertainties in the present estimates a fair fraction may be leaking out of the $^{68}$Se, $^{72}$Kr equilibrium abundances towards higher masses.

This however also depends on the actual proton decay lifetimes of $^{69}$Br and $^{73}$Rb. Based on model dependent fragmentation cross section predictions for these isotopes lifetimes have been estimated to be less than 24 ns and 30 ns respectively [10]. Again, within the present systematic uncertainties this is in the possible lifetime range of proton capture processes in high density environments.

While it is likely that equilibrium is ensued between all these configurations within the presently given experimental limits a considerable flow towards higher masses through the isomer branch cannot be excluded. Fig. 4 shows the comparison between the two extreme possibilities for the reaction sequence calculated in the framework of a multi-mass-zone X-ray burst model [11]. The left-hand figure shows the mass fractions of $^{64}$Ge, $^{68}$Se, and $^{72}$Kr as a function of time neglecting any possible isomer contribution to the flow. The right-hand figure shows the results from the same model assuming
full reaction flow through the isomeric states in $^{68}\text{Se}$ and $^{72}\text{Kr}$ rather than through the respective ground states. The K-isomers predicted in this paper have not been considered. The main differences in $^{68}\text{Se}$ and $^{72}\text{Kr}$ mass fractions are due to rapid initial depletion in the early cooling phase of the burst. This initial decline is compensated subsequently by decay feeding from the long lived $^{64}\text{Ge}$ abundance. The results of our model calculations shown in Fig. 4 are based on upper and lower limit assumptions about the role of the shape isomer states. The possible impact on the general nucleosynthesis of $^{68}\text{Se}$ and $^{72}\text{Kr}$ turns out to be relatively modest. These assumptions are grossly simplified. Improved calculations would require better nuclear structure data to identify more stringent limits on the associated reaction and decay rate predictions.

We are just beginning to look at the impact that isomers may have on various nucleosynthesis processes such as the rp-process. We look for cases in which an isomer of sufficiently long lifetime (probably longer than microseconds) can change the paths of reactions taking place and lead to a different set of elemental abundances. This aspect of nuclear isomers is very much in its infancy [12].

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