^{67}Kr TWO-PROTON RADIOACTIVITY: RESULTS AND THEORETICAL INTERPRETATIONS*

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The two-proton radioactivity is a unique tool to study the nuclear structure beyond the proton drip-line. Since its discovery in 2002, the known emitters have been ^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn and ^{67}Kr. ^{67}Kr was observed for the first time at the RIKEN Nishina Center in 2015. Its decay energy was measured at 1690(17) keV with a branching ratio of 37(14)%. The half-life, 7.4(30) ms, was found in contradiction with theoretical calculations, pointing out effects of decay dynamics and nuclear deformation.

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1. Introduction

Proton-rich nuclei mostly decay by β^+ emission. Further from stability, the Q_{β^+} value increases and it becomes possible to populate excited states above the proton separation energy S_p. Thus, the β^+ daughter nucleus de-excites by the emission of one proton: the β-delayed proton emission (βp). For a nucleus for which S_p is negative, the direct proton emission from the ground state can be observed (one-proton radioactivity). If the two-proton separation energy S_{2p} is negative, direct two-proton emission from the ground state is observed (two-proton radioactivity). One- ($1p$) and two-proton ($2p$) radioactivities were predicted in 1960 by Goldansky [1]. The $2p$ radioactivity is observed for nuclei with an even number of protons, $S_p > 0$ and $S_{2p} < 0$. The $1p$ emission is energetically forbidden and the two valence protons are not bound with respect to the strong interaction. They can be emitted by tunneling the Coulomb barrier of the nucleus.

The most simple approach to calculate the $2p$ half-life consists in calculating the penetrability of the Coulomb barrier: this is the di-proton approach. A second approach, considering the dynamics of the decay, was elaborated by Grigorenko *et al.* [2]. This model, called "three-body model", consists in solving the three-body Schrödinger equation with hyper-spherical harmonics. Calculations require the Q_{2p} values, which are estimated from local mass models, more precise than global models.

The $2p$ radioactivity was discovered in 2002 with the observation of the $2p$ radioactivity of ^{45}Fe [3, 4]. Today, four other emitters are known: ^{48}Ni [5, 6], ^{54}Zn [7], ^{19}Mg [8] and ^{67}Kr [9].

2. Discovery of ^{67}Kr at RIBF in 2015

The local mass models pointed out ^{59}Ge, ^{63}Se and ^{67}Kr as the most probable candidates in the heavier mass domain. They were studied in 2015 during a fragmentation experiment at the Radioactive Ion Beam Factory (RIBF) of the RIKEN Nishina Center, reported in [9, 10]. After a separation-identification with BigRIPS, the fragments were implanted in the DSSSDs

(Double-Sided Silicon Strip Detectors) of WAS3ABi to correlate in time and position the implantations with subsequent decays.

^{63}Se, ^{67}Kr and ^{68}Kr were observed for the first time (see left part of figure 1). ^{59}Ge was also observed after a previous experiment at NSCL with four counts [11]. $2p$ radioactivity was seen for ^{67}Kr, and only βp decay for the other nuclei. The Q_{2p} value of ^{67}Kr was measured at 1690(17) keV with a branching ratio of 37(14)% and a global half-life at 7.4(30) ms (see right part of figure 1), leading to $T^{2p}_{1/2} = \frac{T_{1/2}}{\mathrm{BR}_{2p}} = 20(11)$ ms.

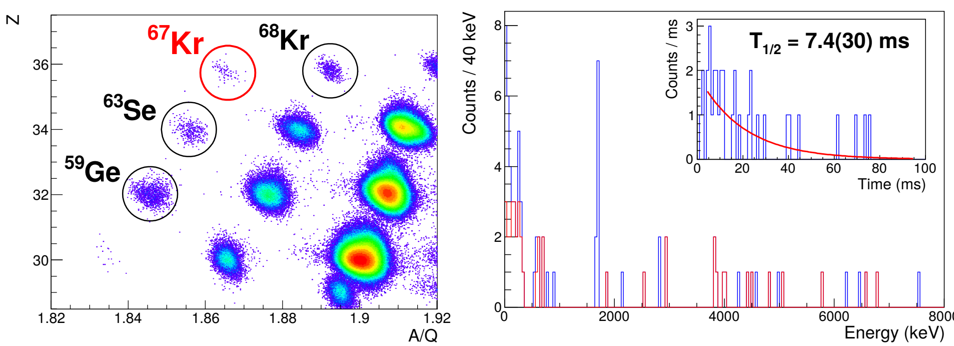

Fig. 1. Left: BigRIPS identification matrix of the fragments. Right: spectra of ^{67}Kr decays correlated with implantation events. The grey/red distribution shows events with a β particle detected in coincidence (βp emission). The black/blue one is obtained without this condition. The prominent peak at 1690(17) keV is assigned to the $2p$ decay. The inset shows the time spectrum of the decay events and the exponential fit.

3. A half-life in disagreement with calculations

The ^{67}Kr ground-state spin and parity are assumed to be $J^\pi = \frac{3}{2}^-$, deduced from its mirror nucleus ^{67}Ga. The valence shells related to ^{67}Kr $2p$ emission are $1f_{5/2}$ and $2p_{3/2}$. Three-body model half-lives corresponding to the experimental decay energy are 13.5 s and 0.28 s for pure f^2 and p^2 configurations, respectively [12]. These values have to be corrected with shell-model removal amplitudes to take into account the structure of the nucleus. The $L = S = 0$ removal amplitudes were calculated by B.A. Brown from NSCL (see [9]), they are 0.655 and 0.556 for f^2 and p^2 configurations, respectively. The shell-model corrected half-lives are given by $T_{1/2}(f^2) = \frac{13.5}{(0.655)^2} = 31$ s and $T_{1/2}(p^2) = \frac{0.28}{(0.556)^2} = 0.90$ s. By adding them coherently, one obtains

$$\frac{1}{\left[T^{2p}_{1/2}\right]^{\frac{1}{2}}} = \frac{1}{\left[T_{1/2}(f^2)\right]^{\frac{1}{2}}} + \frac{1}{\left[T_{1/2}(p^2)\right]^{\frac{1}{2}}} \,. \tag{1}$$

It leads to a half-life of 660 ms, a factor 30 longer than the experimental value of 20(11) ms. A possible explanation considering the dynamics of the decay was proposed by Grigorenko *et al.* [13]. Another possibility could be the absence of deformation effects in emission models. ^{67}Kr is in a region where deformation is expected according to calculations from [14].

3.1. Influence of the decay dynamics

New calculations were proposed by Grigorenko *et al.* [13] based on an improved three-body model: the IDDM (Improved Direct Decay Model) [15]. This latter provides a description of the transition between direct ($2p$ radioactivity) and sequential $2p$ decay. It studies the width of the ground-state resonance of the core+p subsystem.

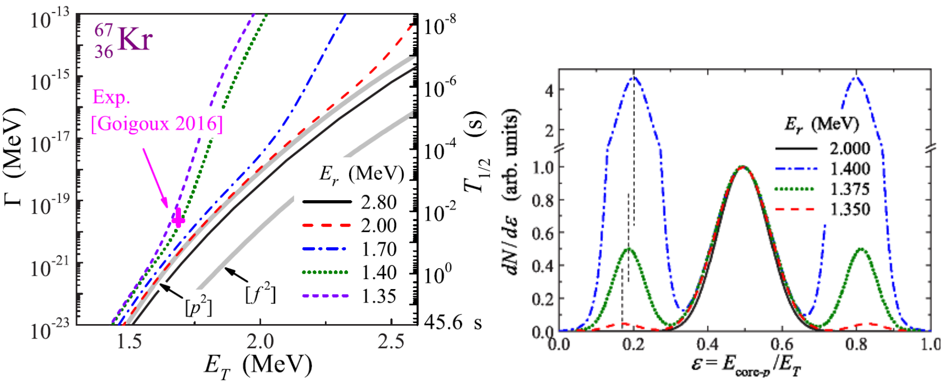

Fig. 2. IDDM calculations of ^{67}Kr for various resonance energies E_{r} in the ^{66}Br+p system. Left: correlation between $2p$-decay width and Q_{2p} value (E_{T}), compared with the experimental value reported in these proceedings. The grey curves are three-body model calculations for pure p^2 and f^2 configurations. Right: energy sharing distribution between the two protons. The vertical dashed lines are the centroids of the peaks. Taken from [13].

In the left part of figure 2, one sees that the IDDM agrees with the experimental value for a narrow range of E_{r} values ($E_{\mathrm{r}} = -S_p$ of ^{66}Br), contrary to the three-body calculations. The agreement range could indicate a "transitional dynamics" between true and sequential $2p$ decay according to [13]. An influence of E_{r} on the distribution of the energy sharing between the two protons is also expected (right part of figure 2). The true $2p$ decay is expected for $E_{\mathrm{r}} \in [1.45, 2.0]$ MeV (^{67}Kr $S_p \in [-240, 310]$ keV). In this case, the distribution is composed of one peak (black line in figure). The region $E_{\mathrm{r}} \in [1.35, 1.42]$ MeV ($S_p \in [-340, -270]$ keV) corresponds to a transitional dynamics on the borderline between the true and sequential $2p$ emission. A lower value of E_{r} gives a pure sequential decay.

3.2. Influence of the deformation

The deformation hypothesis was investigated by Wang and Nazarewicz [16]. The authors used a Gamow-Coupled Channel approach (GCC) to describe the structure and the decay of three-body systems [17]. They made GCC calculations with a deformed ^{65}Se core. The results are shown in figure 3. According to [14], an oblate quadrupole deformation $\beta_2 \sim -0.3$ is expected. With a small deformation $|\beta_2| \leq 0.1$, the valence protons are on the $f_{5/2}$ shell and the calculated half-life is $T^{2p}_{1/2} > 218$ ms, in agreement with the shell-model corrected three-body half-life of equation (1). As the deformation increases, the valence proton orbital changes from the 9/2[404] to the 1/2[321] orbital. At $\beta_2 \sim -0.3$, GCC calculations give a theoretical half-life of 24^{+10}_{-7} ms [16], in a good agreement with the experimental one.

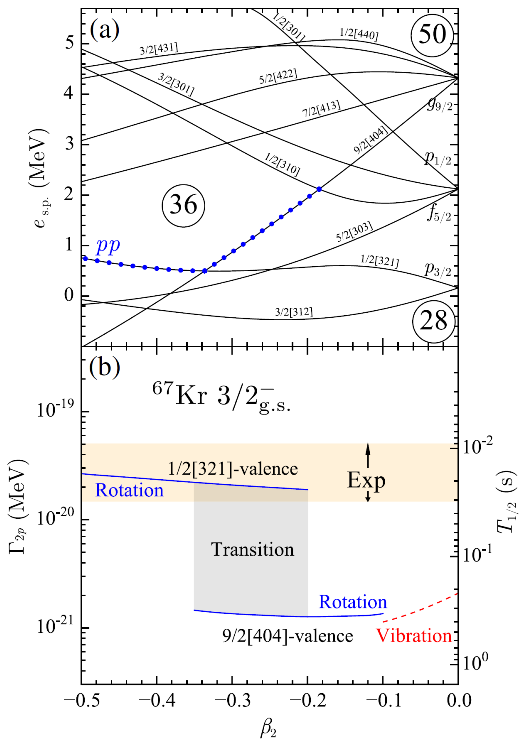

Fig. 3. Top: Nilsson levels ($\Omega[Nn_z\Lambda]$) of deformed core+p potential as a function of the parameter β_2. The dotted line is the occupied valence level. Bottom: $2p$-decay width of ^{67}Kr as a function of β_2. The solid and dashed lines are obtained with rotational and vibrational couplings respectively. Taken from [16].

4. Conclusion

^{67}Kr is the heaviest and most recently discovered $2p$ emitter. Despite a measured decay energy in good agreement with local mass models, there is a strong disagreement between the measured half-life and the one calculated with the three-body model. A hypothesis invoked by Grigorenko *et al.* [13] is a competition between direct and sequential $2p$ emission. The second possible explanation is a deformation of the nucleus. Recent calculations by Wang and Nazarewicz [16] including an oblate quadrupole deformation of ^{67}Kr give a good agreement with the measured half-life.

Further experiments will be necessary to study more accurately the structure of ^{67}Kr, with a Time Projection Chamber to measure the angular and energy distributions between the two protons. This will also allow to test the hypothesis of the decay dynamics. A proposal to study ^{67}Kr with ACTAR TPC [18] was accepted by the RIBF advisory committee. This experiment will bring new insights on ^{67}Kr and the $2p$-decay models.

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