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Technique for Resolving Low-lying Isomers in the Experimental Storage Ring (ESR) and the Occurrence of an Isomeric State in ^{192}Re

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Abstract. A recent experiment using projectile fragmentation of a ^{197}Au beam on a ^{9}Be target, combined with the fragment recoil separator and experimental storage ring at ring at GSI, has uncovered an isomeric state in ^{192}Re at 267(10) keV with a half-life of ∼60 s. The data analysis technique used to resolve the isomeric state from the ground state is discussed.

1. Introduction

Gaining access to neutron-rich long-living isomers presents an experimental challenge. For isomers far from the line of stability on the neutron-rich side, methods such as deep-inelastic or fusion-evaporation reactions are limited, as cross sections for neutron-rich nuclei decrease rapidly once the line of stability has been left. Projectile fragmentation provides a convenient tool to

reach the isotopes which are otherwise unavailable by the more conventional reactions. Projectile fragmentation in combination with in-flight fragment separation [1] has enabled microsecond isomers to be found some distance from the line of stability. In $^{192}_{75}$Re a microsecond isomer is known from work with the RISING array at GSI [2]. In that work a 160 keV γ-ray was seen with a half-life of 120^{+210}_{-50} μs. It was suggested that this γ-ray does not depopulate the isomer directly but is part of a cascade which occurs after a low-energy M1 transition which is the cause the extended lifetime [3]. This technique for detection of isomers is insensitive to γ-decaying states with half-lives greater than a few milliseconds. However, recently highly-excited isomeric states in the $A \approx 180 - 190$ region have been found using the Fragment Recoil Separator (FRS) and Experimental Storage Ring (ESR) at GSI [4]. The ESR enables direct measurement of the isomeric state without requiring its decay to be observed. Building on earlier work [5], detailed analysis has now been employed to reveal lower-energy long-living isomers which in general are harder to observe in the storage ring. The physics motivation is to understand the neutron-rich $A \approx 190$ shape transition region [6].

2. Experiment

Projectile fragmentation was employed to access the $A \approx 190$ region. This was performed using the coupled accelerator system at GSI (the UNILAC and SIS 18). A ^{197}Au beam was produced with energies of $478 - 492$ A·MeV and impinged on a 1035 mg/cm^2 ^{9}Be target. The subsequent fragments were then separated using the FRS [7]. The fragments produced in the reaction were in general of a high charge state (bare, hydrogen-like, helium-like and Li-like) and were separated using the $B\rho$-ΔE-$B\rho$ method [1] with a 200 μm aluminium plate installed at the degrader position to enable Z selection ($Z^2 \sim \Delta E$). These ions after separation were then injected into the ESR.

Once injected into the ESR the circulating ions require cooling so that a high-resolution frequency spectrum can be produced. Stored ions in the ESR obey (to the first approximation) the equation [8];

$$\frac{\Delta f}{f} = -\alpha_p \frac{\Delta \frac{m}{q}}{\frac{m}{q}} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right) \tag{1}$$

where α_p is the 'momentum compaction factor' and is dependent on the path length and magnetic rigidity ($B\rho$), f is the revolution frequency, $\frac{m}{q}$ is the mass to charge ratio of the stored ion, v is the velocity of the ion, γ is the Lorentz factor and γ_t is the transition point for the ESR defined by $\gamma_t^2 = \frac{1}{\alpha_p}$ [9]. By cooling the ions the velocity of the stored ions is reduced from $\frac{\Delta v}{v} \sim 10^{-2}$ to $\frac{\Delta v}{v} \sim 10^{-7}$. This makes the second term that is proportional Δv of Eq. 1 tend to zero. A measurement of the revolution frequency of a stored ion thus becomes a measurement of the mass to charge ratio of that ion. Cooling is performed by two methods; electron cooling [10] and stochastic cooling [11]. Stochastic cooling is used at a fixed energy 400 A·MeV. Therefore, for each setting the energy gained from the SIS primary beam was adjusted so as to fix the fragment energy to 400 A·MeV after the aluminium degrader. The ions once injected into the ring circulate with a frequency of ~ 2 MHz around the 108.4 m circumference. Measuring revolution frequencies at the 30th harmonic allowed a fast Fourier transform (FFT) to be applied to the data and so ion frequencies could be extracted [12, 13]. Masses of traversing ions could then be determined from the data with very high precision, so as to resolve the difference in mass between ground and isomeric states. This technique is known as time-resolved Schottky Mass Spectrometry (SMS), which relates the mass to charge ratio (m/q) of an ion to its revolution frequency [8].

3. Data Analysis

The primary objective of the experiment was to search for predicted isomers in the ^{190}W, ^{184}Hf and ^{186}Hf nuclides [4]. However, in the data, other nuclides were produced which could also be studied, some of which have already been reported [4]. In that work, the standard operational mode was to inject ions approximately once per minute, and to empty the ESR before each injection. However, when a specific candidate isomer was produced (and seen online) the subsequent injection was delayed so as to observe the decay of the candidate isomer. Other ions were not monitored online and hence in general it is unlikely that when a candidate isomer is produced it would be in an extended injection. Hence ions with half-lives $t_{\frac{1}{2}} > 1$ min are unlikely to yield information about their half-lives. There is also the problem of the cooling of the secondary isotopes. The experiment was setup such that stochastic cooling was optimised for the primary isotope. This means the cooling time for the secondary isotopes is significantly longer. This slow cooling limits the observation time of a secondary ion. If an ion for instance has $t_{\frac{1}{2}} \sim 10$ s and is well cooled it is likely to be seen. However, if that ion is poorly cooled it is possible it will have decayed prior to being observed in the storage ring. Effective investigation of these secondary ions therefore can become difficult. To gain adequate time resolution for such an investigation requires that the frequency resolution is low. This can cause a problem as low frequency resolution (9.76 Hz/bin with ~ 16 keV/Hz) can make it difficult to observe ions with a similar $\frac{m}{q}$ value i.e. low-lying isomers. There is also the problem of beam crystallisation which can cause what seems like 'merging' of the beam-ions when revolution frequencies are similar [13]. This can cause ambiguity in the identification and make analysis of the isomers impossible.

To avoid the problems of poor frequency resolution and beam crystallisation, a criterion is imposed on the data, that within a certain frequency range around the region of interest a measurement is only accepted when a single ion is measured. Thus the problems of poor frequency resolution and beam crystallisation are eliminated. However, with this technique it

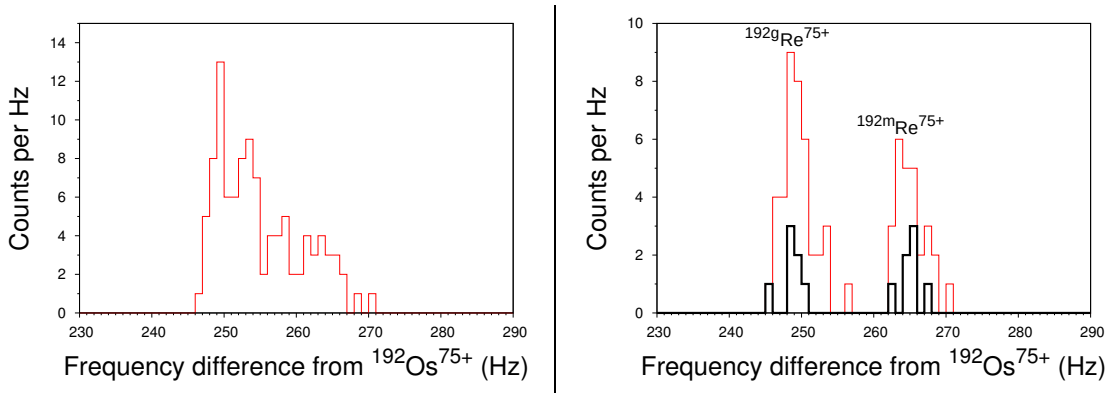

Figure 1: Figure 1[a] represents 24 hours of data taken for all ^{192}Re^{75+} ions without any discrimination on numbers of ions. Each count corresponds (for a given injection) to an observation time of 10 s, sometimes with multiple ions of ^{192}Re^{75+} present in the storage ring. It can clearly be seen that there is a distribution of ion frequencies. However, resolving these into different $\frac{m}{q}$ values is impossible. Figure 1[b] shows the data restricted to single ^{192}Re^{75+} ions. It can be seen clearly that two peaks have been observed with different frequencies. In the figure the lower frequency peak corresponds to the ground state of the ion and the higher frequency peak arises from an isomeric state. The bold trace represents ions prior to and post γ-decay events from the isomeric state.

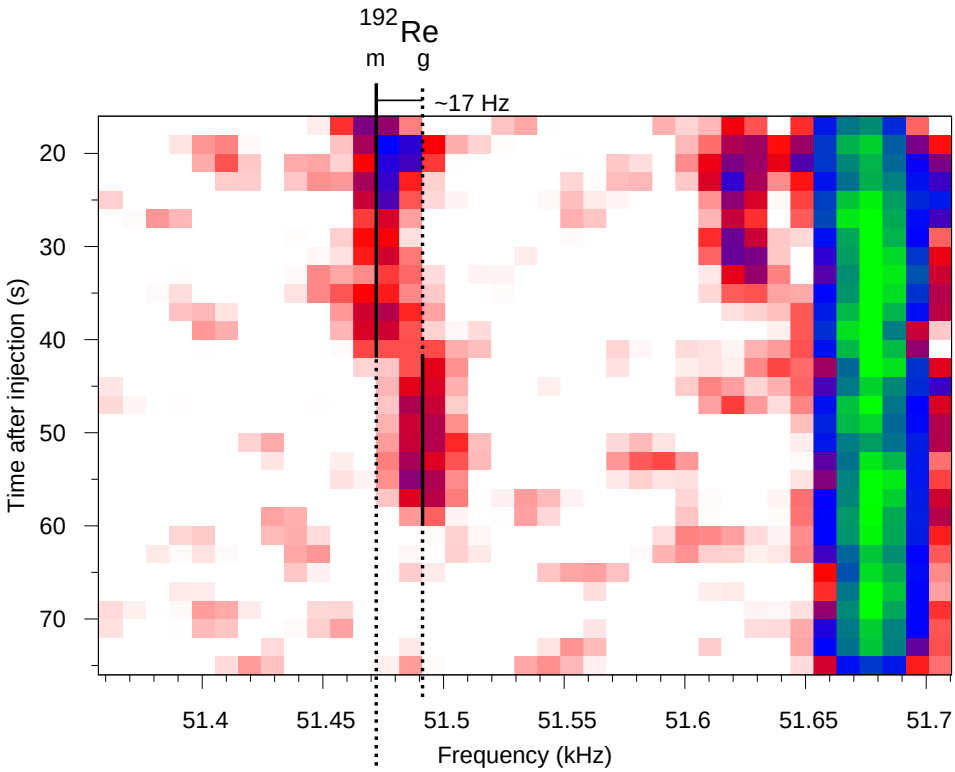

Figure 2: The Figure shows a γ-decay event in ^{192}Re, corresponding to the shift in frequency at $\sim$ 40 s after injection. Following the γ-decay of the isomer, the ground state ultimately β decays after $\sim$16 s (seen by a disappearence of the ion trace). The frequency measured on the horizontal axis is the difference in frequency from a local oscillator set at 59.15 MHz. The highest line in frequency comes from a mixture of ^{192g,m1,m2}Ir, the next is a 2MeV isomer in ^{192}Os which subsequently β decays. The lowest line in frequency is the ^{192m,g}Re line (51.47-51.49 kHz).

can still be difficult to distinguish the ground state from a low-lying isomeric state. To further improve the identification, a reference line is chosen close to the frequency region of interest, and the difference in frequency is measured between this reference line and the unknown single ion. Collating these data for ^{192}Re^{75+} ions, it is seen that two Gaussian peaks appear at different relative frequencies, and these indicate the ground and isomeric states of that ion (fig. 1). This method benefits from good statistics of both the isomer and the ground state, so as to achieve confident identification and accurate energy measurements. In figure 1b it can clearly be seen that there is a low-lying isomeric state in ^{192}Re, at an energy of 267(10) keV. This isomer is also seen to γ-decay. In the ESR a γ-decay is observed as a sudden shift in the frequency of the ion trace from the frequency of the isomer to that of the ground state (see Fig. 2). For a single-ion γ-decay in the storage ring, this kind of sudden shift in frequency has been observed prior to this analysis in ^{187m1}Ta [4]. In the present work the ^{192m}Re single-ion isomer has been seen to γ-decay 7 times. The observation time for this ion (per injection) was reduced as this is in a region of relatively poor cooling and so an ion could in general only be viewed for $\sim$ 55s during each $\sim$ 70s injection. Analysis of the measured isomeric ions gives a Lorentz-corrected half-life for the isomer of $t_{\frac{1}{2}} = 61^{+40}_{-20}$s. This was determined by counting the total unambiguous

time that the single ions were observed in the ESR. Errors were analysed using the techniques in Ref. [14].

4. Discussion

The presence of a long-living isomer at relatively low energy can possibly be explained by as a spin-trap, where the high-Ω proton and neutron orbitals at the Fermi surface can couple to form both high-spin and low-spin states. Calculations [15] show that the ground state could be a $K^\pi = 8^+ \left\{ \nu \left(\frac{11}{2}^+ [615] \right) \otimes \pi \left(\frac{5}{2}^+ [402] \right) \right\}$ state which when coupled anti-parallel would give a 3^+ state at around 250 keV. Alternatively, other calculations [16] show the ground state to be a $K^\pi = 2^- \left\{ \nu \left(\frac{9}{2}^- [505] \right) \otimes \pi \left(\frac{5}{2}^+ [402] \right) \right\}$state and that there are a plethora of high-spin states at ~ 200 keV level. In both calculations, there could be long-lived isomeric states.

Another interpretation is that of the coexistence of oblate and prolate shapes. Total Routhian surface plots [17] predict that the ground state of the nucleus exhibits a γ-soft but prolate shape. However, a small addition of collective angular momentum drives the system to a well defined oblate shape. Additional data are required to distinguish between these two types of isomerism.

5. Summary

A low-lying isomer in ^{192}Re has been discovered through the use of projectile fragmentation. The relative masses of the produced fragments were measured with accuracies down to 10 keV with the ESR. The storage ring is powerful in its ability to resolve nuclear isomeric states from the corresponding ground states. When many ^{192}Re fragments were stored in the ring during a single injection an ambiguity in the identification of both ground and isomeric states was caused (Fig 1a). By applying the criterion that only single-ion measurements were accepted, this ambiguity was removed and thus the ground and isomeric states could be resolved (Fig.1b). The energy and half-life have been measured as $E^* = 267(10)$ keV and $t_{\frac{1}{2}} = 61^{+40}_{-20}$ s.

Future work of this kind with the ESR aims to identify high-lying isomers in ^{188}Hf, which are predicted [6] to be particularly favoured in energy. Furthermore, with the ILIMA storage rings at FAIR it will be possible to reach the astrophysical r-process path for these high-Z values.

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