Angular Momentum Population in Projectile Fragmentation

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Abstract. Isomeric states in neutron-deficient nuclei around $A \approx 190$ have been identified following the projectile fragmentation of a relativistic energy ^{238}U beam. The deduced isomeric ratios are compared with a model based on the abrasion-ablation description. The experimental isomeric ratios are lower by a factor of ≈ 2 than the calculated ones assuming the 'sharp cutoff' approximation. The observation of the previously reported isomeric $I^{\pi}=43/2^{-}$ state in ^{215}Ra represents the current record for the highest discrete spin state observed following a projectile fragmentation reaction.

INTRODUCTION

During the last few years the application of projectile fragmentation reactions at intermediate and relativistic energies to studies of nuclei far from stability has made enormous progress. However, experimental information on the population of states as a function of angular momentum is still somewhat rare. In particular, for projectile energies above 100 MeV/nucleon, information is very scare. According to our knowledge, the first information regarding the population of isomeric states after projectile fragmentation at relativistic energies was presented by Schmidt-Ott *et al.* for ^{43}Sc populated in the fragmentation of 500 A·MeV ^{46}Ti beam [1]. Recently, Pfützner *et al.* published isomeric ratios for heavy neutron-rich and close to the stability line nuclei, populated in the fragmentation of ^{238}U [2] and ^{208}Pb [3].

Here we present results from the first systematic study on the angular momentum population in relativistic projectile fragmentation for heavy neutron-deficient nuclei.

EXPERIMENTAL DETAILS

Preliminary results from two recent experiments, performed at GSI, Darmstadt, are presented. *(a)* Neutron-deficient nuclei in the A$\sim$190 region were populated following the projectile fragmentation of a 750 MeV/nucleon ^{238}U primary beam impinging on a natural beryllium target. *(b)* Neutron-deficient nuclei around $^{216}_{89}$Ac were populated following the projectile fragmentation of a 950 MeV/nucleon ^{238}U primary beam on

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a natural beryllium target. In both experiments, the nuclei of interest were separated using the Fragment Separator (FRS) [4], then subsequently implanted into a catcher. The catcher was surrounded by a germanium detector array, in order to record the γ rays emitted from isomeric decays in the implanted ions. The delay of gamma-rays (with respect to the implantation time of a corresponding heavy ion) was measured up to 80 μs.

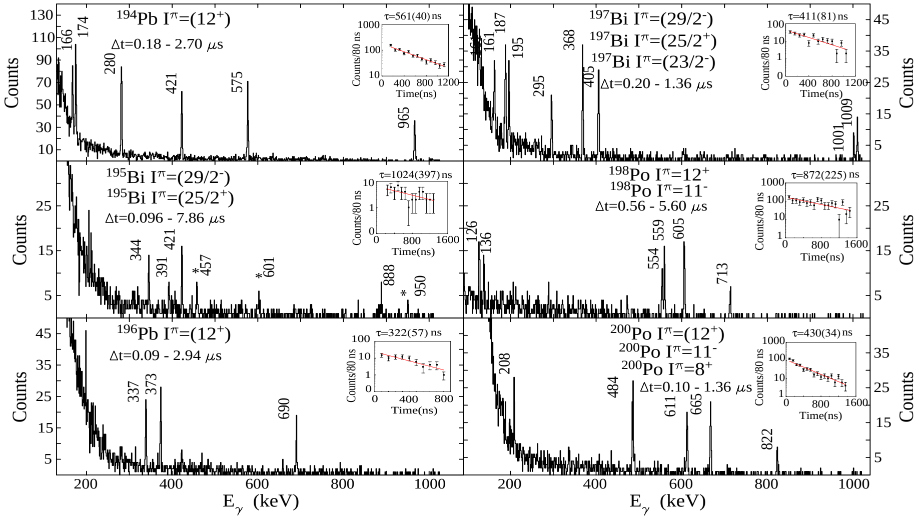

FIGURE 1. Delayed γ-ray spectra associated with ^{194}Pb, ^{195}Bi, ^{196}Pb, ^{197}Bi, ^{198}Po and ^{200}Po. The time spectra with fitted lifetimes are given in the insets.

The method is sensitive to isomers with half-lives in the range from about 100 ns up to several milliseconds. The lower limit is determined by the time of flight through the FRS ($\sim$ 300 ns). However, as reported in previous works, if the electron conversion branch is blocked in a highly stripped ion, the effective ionic lifetime in flight is increased, which allows shorter neutral atom delay half-lifes to be measured [5, 6]. The upper limit is determined by the need to correlate the individual ions to the delayed γ rays.

RESULTS AND DISCUSSION

Isomeric ratios

Isomeric decays were identified in the ^{188}Hg, ^{192}Tl, ^{192,193,194,195,196}Pb, ^{195,197}Bi, and ^{198,200,202}Po [7]. Examples of delayed γ-ray energy spectra, as well as time spectra are presented in fig.1. The extracted isomeric ratios for the yrast I^{π}=12^{+} isomers in ^{192,194,196}Pb and ^{198,200}Po are listed in Table I and shown in fig.2a.

Isomeric ratios can be determined theoretically in the framework of the abrasion–ablation model of the fragmentation reaction. In the initial abrasion phase a hot prefragment is created by removing a number of nucleons from the projectile. In the ablation

TABLE 1. Isomeric ratios of yrast metastable states produced in high energy, >100 A·MeV, projectile fragmentation. The results from the present work are preliminary.

Nucleus	J^{π}	Projectile	R_{exp}	R_{th}	R_{exp}/R_{th}	reference
^{205}Tl	$25/2^{+}$	^{238}U	0.25(5)	0.23	1.09(9)	[2]
^{205}Pb	$25/2^{-}$	^{238}U	0.29(5)	0.23	1.26(22)	[2]
^{206}Pb	12^{+}	^{238}U	0.29(5)	0.25	1.16(20)	[2]
^{208}Pb	10^{+}	^{238}U	0.34(9)	0.34	1.00(26)	[2]
^{175}Hf	$35/2^{-}$	^{208}Pb	0.025(6)	0.038	0.66(16)	[3]
^{180}Ta	15^{-}	^{208}Pb	0.10(3)	0.061	1.64(49)	[3]
^{200}Pt	7^{-}	^{208}Pb	0.30(5)	0.355	0.85(14)	[3]
^{192}Pb	12^{+}	^{238}U	0.14(2)	0.282	0.50(7)	present work
^{194}Pb	12^{+}	^{238}U	0.16(3)	0.280	0.57(11)	present work
^{196}Pb	12^{+}	^{238}U	0.17(4)	0.278	0.61(14)	present work
^{198}Po	12^{+}	^{238}U	0.089(12)	0.200	0.45(6)	present work
^{200}Po	12^{+}	^{238}U	0.067(12)	0.222	0.30(6)	present work

phase of the reaction, the highly excited prefragment evaporates nucleons until the final fragment is formed with an excitation energy below the particle emission threshold. Subsequently, a statistical gamma cascade proceeds down to the yrast line and then along this line to the ground state. If a long-lived state lies on this decay path, part of the cascade may be hindered or effectively stopped depending on the life-time of the isomer. The isomeric ratio is equal to the probability that gamma decay from the initial excited fragments proceeds via this isomeric states.

The angular momentum distribution can be calculated with the ABRABLA Monte Carlo code [8]. Furthermore, for a large mass difference, $\Delta A > 10$, between the projectile and the fragment this distribution can be approximated by a simple analytical formulae [9]:

$$P_I = \frac{2I+1}{2\sigma_f^2} exp\left[-\frac{I(I+1)}{2\sigma_f^2}\right], \tag{1}$$

where σ_f is called spin-cutoff parameter of the final fragments.

Given the angular momentum distribution of the final fragment, one can consider the probability that gamma decay will lead to an isomeric state of spin I_m. First, it is assumed that the initial excitation energy is well above the excitation energy of the isomer. Second, the extreme simplifying assumption is made that all states with $I \geq I_m$, and only those, decay to the isomer. A similar approach, known in the literature as the "sharp cutoff model", has been used in studies of angular momentum distributions in compound nuclei [10, 11, 12] and in fission fragments [13].

It has been shown that the approximative formulae effectively reproduces the angular momentum distribution predicted by the ABRABLA code when the mass difference between projectile and fragment is higher than 10 mass units [2], in the case of nuclei close to the stability line. However, in our case, far from stability the situation is different. The analytical formula predicts much higher angular momentum than the ABRABLA code. As shown in fig.2b, the difference increases as more 'exotic' nuclei

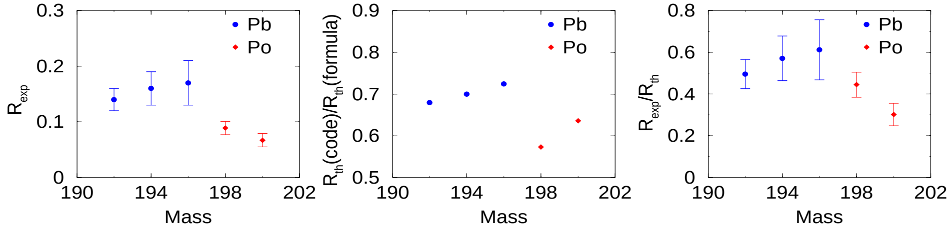

FIGURE 2. (a) Experimental isomeric ratios for the 12^+ isomers in ^{192,194,196}Pb and ^{198,200}Po. (b) The ratio of the calculated isomeric ratios using the ABRABLA code and the analytical formulae, for the same isomers. (c) The ratio of the experimental and theoretical (ABRABLA) isomeric ratios.

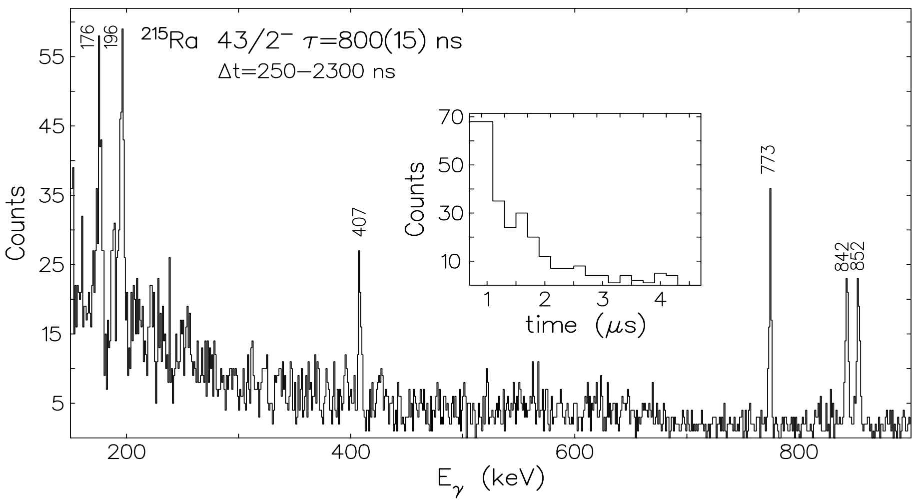

FIGURE 3. Delayed γ-ray spectra associated with ^{215}Ra. The 407 keV and 842 keV γ-ray transitions prove the population of the $43/2^-$ isomeric state [15]. The other labelled transitions are from a lower lying $29/2^-$ isomer.

are produced. Since the ABRABLA code is expected to give more reliable results, we have compared the experimental values with its predictions, as given in fig.2c and Table I. The experimental isomeric ratios are on average a factor 2 lower than the theoretical ones. In contrast, for the case of yrast isomers in nuclei close to stability the theory is in good agreement with the experiment [2, 3] (see Table I). One of the reason of the large discrepancy between theory and experiment in our case might be the extreme simplification considered, namely that all the states with spin higher than the isomer ultimately decay to the isomer. However, this is certainly not always the case, and when the level schemes are well known, the partial population can be determined By taking into account the decay properties of the states around the isomer a better agreement between the experimental and calculated angular momentum population can be obtained [14].

The I^{π}=43/2^{-} isomer in ^{215}Ra

One of the highlights of the experiment performed with the 950 MeV/nucleon ^{238}U beam was the observation of the previously reported I^{π}=43/2^{-} isomer in ^{215}Ra [15] (see fig.3). This represent the highest discrete spin state observed to date following a projectile fragmentation reaction, adding $4\hbar$ of angular momentum to the previous highest recorded value of I=35/2 [3, 5].

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