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ISOMERIC DECAY STUDIES WITH FRAGMENTATION BEAMS*

Zsolt Podolyák

Department of Physics, University of Surrey
Guildford GU2 7XH, UK

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Results from several isomeric decay studies with fragmentation beams are discussed, with special emphasis on heavy ions (above the fission limit). Both nuclear structure and reaction studies have been examined. It has been shown that the structure of the nucleus has to be considered in order to get agreement, within a factor of 2, between the experimental and calculated angular momentum populations.

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1. Introduction

Projectile fragmentation has proved to be an effective tool for the population of exotic nuclei on both sides of the valley of stability [1–3]. Facilities operate at GSI (Germany), RIKEN (Japan), GANIL (France), MSU (USA) and Lanzhou (China). GSI is a high energy, $E/A = 0.5$–1.5 GeV, facility, while all the others operate at intermediate energies, $E/A = 50$–100 MeV. A large number of different types of experiment have been performed in these laboratories, including interaction cross section measurements, Coulomb excitation, isomeric decay, γ-ray spectroscopy at the production target, g-factor measurements of ground and excited states, secondary fragmentation, proton decay, two-proton decay *etc.* (see references in [4]).

In this paper we review the results obtained in decay studies of isomeric states produced in projectile fragmentation. A schematic view of the experimental setup used in these experiments is given in Fig. 1 (for more details

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see, for example, [5,6]). The nuclei of interest produced in fragmentation are separated and identified, then subsequently implanted into a catcher. The delayed γ rays emitted from isomeric states are recorded and correlated with the implanted ion. Due to the ion–γ correlation and off-beam measurement these experiments are extremely sensitive. Isomeric decays can be identified with a yield of just few ions per hour [7]. The technique is sensitive to isomers which have lifetimes longer than the flight-time through the fragment separator (of order of 200–300 ns at GSI). The upper limit is determined by the need to correlate individual ions with the delayed γ rays, which is of the order of milliseconds when passive stoppers are used. We note that the same experimental setup can be used to study isomeric states produced in projectile-fission [8].

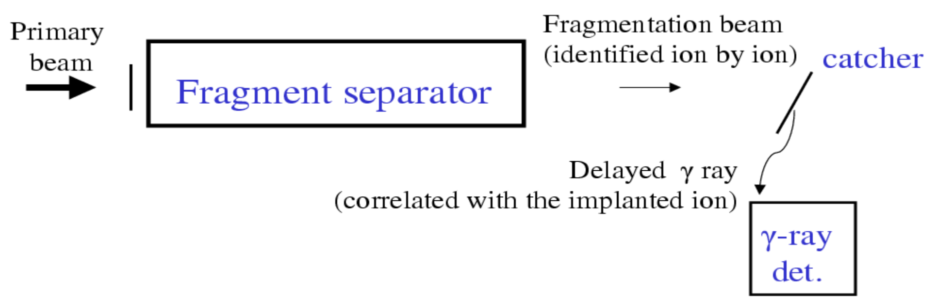

Fig. 1. Schematic view of the experimental setup.

Isomeric decay following fragmentation has been used both in nuclear structure and reaction mechanism studies. In the following we present some examples for both types of work. Special emphasis will be given to heavy nuclei ($Z > 60$). In order to obtain a good separation of ions using magnetic fields they have to have a narrow charge distribution (practically the majority of them has to be fully stripped), which in the case of heavy ions implies very high velocities. As a consequence, these nuclei presently can be studied at only one fragmentation facility, GSI, where both high-energy accelerators and a fragment separator with the appropriate specifications are available. Heavy nuclei have been produced following the fragmentation of relativistic ^{208}Pb and ^{238}U beams [6, 9–13]. The nuclear regions studied and the approximative number of observed isomers are shown in Fig. 2.

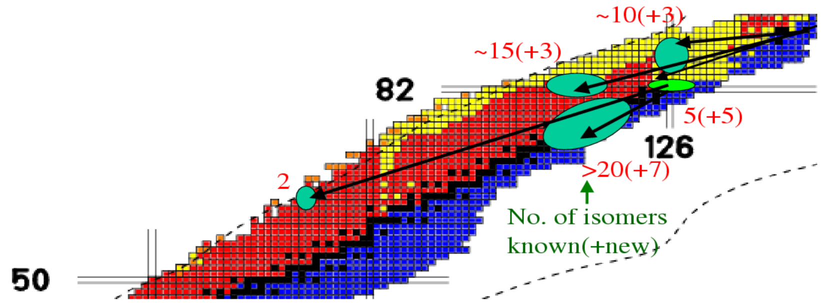

Fig. 2. Regions of heavy nuclei where isomeric states have been observed following fragmentation of relativistic energy ($E/A = 750$–1000 MeV) ^{208}Pb and ^{238}U beams. The approximative number of observed isomeric states is also indicated.

2. Nuclear structure studies

Observations of a metastable state give information on the isomeric state as well as all the levels populated in its decay. From the lifetime of the isomer the transition strength can also be determined. The first experiment using isomer decay following projectile fragmentation in order to study nuclear structure was performed by Grzywacz *et al.* [5]. In this work, performed at GANIL, a ^{112}Sn beam with an energy of $E/A \approx 60$ MeV was fragmented and over forty isomeric states, including a new isomer in ^{66}As, were observed. Since then several experiments have been performed both at intermediate energy and high energy fragmentation facilities. As mentioned earlier, here we discuss in more detail the results obtained for heavy ($Z > 60$) nuclei (see Fig. 2). The first experiment in this mass region was performed by Pfützner *et al.* [9]. In the fragmentation of $E/A = 1$ GeV ^{238}U beam several isomeric states in spherical nuclei in the vicinity of ^{208}Pb, seven of them previously unobserved, were identified. A good example which illustrates the power of the technique is the observation of the decay of the 8^+ isomeric state in ^{212}Pb with only 370 ions implanted into the catcher. In another experiment, a $E/A = 1$ GeV ^{208}Pb beam was fragmented and K-isomers in the region of deformed nuclei around both neutron-rich $Z \approx 74$ [11] and proton-rich $N \approx 74$ have been populated. Results include the observation of the yrast band in ^{190}W [10]. In this nucleus the energy ratio of the 4^+ and 2^+ states deviates, being lower, from that expected from the systematics. The underlying reason is not fully understood, and possible explanations include the presence of a sub-shell closure or an oblate–prolate transition in the region. Subsequent measurements used ^{238}U beams in order to populate neutron-deficient nuclei in two mass regions: $Z \approx 82$ (fragmentation at $E/A = 750$ MeV energy) [12] and $Z \approx 88$ ($E/A = 950$ MeV) [13].

An example from the results in the neutron-deficient $Z \approx 88$ region is a new isomer identified in ^{211}Ra. The two delayed transitions, based on systematics, decay from a $13/2^+$ $\nu i^{-1}_{13/2}$ isomer. The level scheme of ^{211}Ra, together with the lighter $N = 123$ isotones, is shown in Fig. 3. We note that the gamma-ray transitions at 801 and 395 keV have been observed in a previous fusion–evaporation experiment [14] using isomer decay tagging, devoted to ^{209,210}Ra. However, their origin could not be identified.

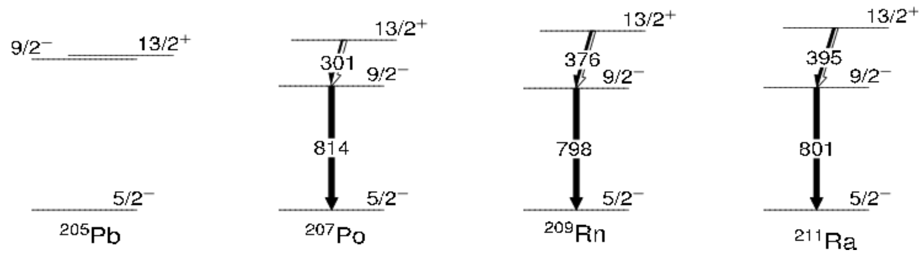

Fig. 3. The systematics of the $13/2^+$ isomeric states in the $N = 123$ isotones. The data on ^{211}Ra are from projectile fragmentation of ^{238}U [13].

3. Reaction studies

At the fragmentation target discrete γ-ray spectroscopy can be carried out only for a very small number of nuclei, those which are very close (in number of neutrons and protons) to the fragmented ion. In the case of nuclei further away from the fragmented ion, the γ rays originating from the nucleus of interest cannot be distinguished from the much more intense radiation background originating from the nuclei populated with higher cross sections and atomic processes. One way to solve this challenge is to study the population of longer lived, isomeric states, giving time for the separation and transportation of the species of interest, and performing the γ-ray detection far away from the fragmentation target. Thereby, isomers can provide a tool to study the reaction mechanism of fragmentation. In these experiments, the most widely determined quantity is the isomeric ratio, $R_{\rm exp}$, defined as the probability that in the reaction a nucleus is produced in an isomeric state, relative to the total production of that nucleus.

According to our knowledge, the first reaction studies of projectile fragmentation using the decay of isomeric states were performed by Schmidt-Ott *et al.* [15]. They studied the decay of the $19/2^-$ isomeric state in ^{43}Sc populated in the fragmentation of a $E/A = 500$ MeV ^{46}Ti beam. Both the spin alignment and the isomeric ratio were found to be dependent on the longitudinal momentum of the fragments. A positive spin alignment was observed in the centre and negative alignment in the wings of the distribution. In the case of the isomeric ratio, a much higher value was measured in the wings of the longitudinal momentum distribution than in the centre of it. Subsequently, isomeric ratios have been determined from several other experiments (see for example [5, 9]).

In the heavy mass region, which is the focus of this paper, isomeric ratios have been determined from all the experiments mentioned in the previous section and Fig. 2. Pfützner *et al.* published isomeric ratios for nuclei populated in the fragmentation of both ^{238}U [9] and ^{208}Pb [6]. While in Ref. [9] ~10 isomeric ratios are given for nuclei in the vicinity of ^{208}Pb, in Ref. [6] ~20 isomeric ratios are published, mainly in near stable rare-earth and transitional nuclei with $A \sim 180$. Gladnishki *et al.* [12] reported isomeric ratios for fifteen isomers in the neutron-deficient $Z \sim 82$ region, populated in the fragmentation of ^{238}U. The isomeric ratios determined for the neutron-deficient $Z \approx 88$ region are still unpublished.

The large number of isomeric states identified in the heavy nuclei [6,9,12] gives the possibility to perform a quantitative analysis covering a large range of angular momentum and mass. The isomeric ratios are summarised in Fig. 4(a). Information on isomers which were populated through the decay of higher lying isomers is not included. It can be concluded that in general the isomeric ratios decrease with increasing angular momentum (but it depends also on other factors like mass loss and nuclear structure).

Isomeric ratios can be and have been [6, 9, 12] determined theoretically in the framework of the abrasion–ablation model of the fragmentation reaction [16]. Within this model the angular momentum distribution of the fragments can be calculated with the ABRABLA Monte Carlo code [16]. Furthermore, this distribution can be approximated by a simple analytical formula [17]:

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

where $\sigma_{\rm f}$ is called the spin-cutoff parameter of the final fragments.

It has been shown that the approximative formula reproduces well the angular momentum distribution predicted by the ABRABLA code for nuclei close to the stability line when the mass difference between the projectile and the fragment is higher than 10 mass units [9, 17]. Far from stability the analytical formula predicts higher angular momentum than the ABRABLA code in the case of neutron-deficient nuclei. The opposite is true for the neutron-rich side of stability.

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. The extreme simplifying assumption is made that all states with $I \geq I_m$, and only those, decay to the isomer. This approach is known in the literature as the "sharp cutoff approximation".

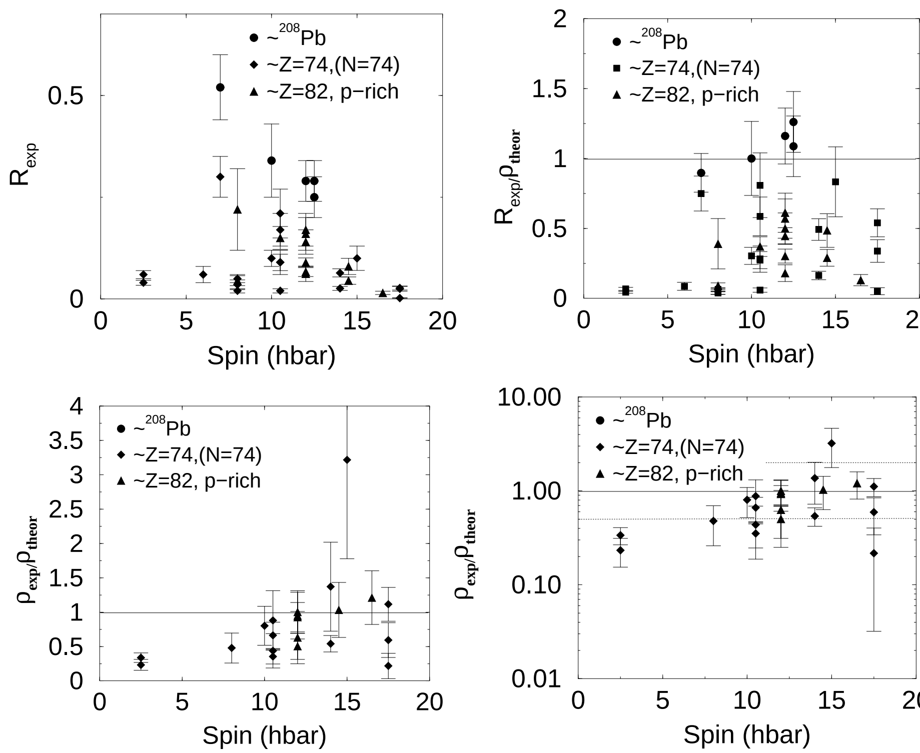

Fig. 4. (a) Experimentally determined isomeric ratios (data from [6, 9, 12]). (b) The ratio of the experimental and theoretical (ABRABLA in the sharp cutoff approximation) isomeric ratios. (c) and (d) Ratio of the experimental and theoretical angular momentum population in linear and logarithmic scales, respectively. For details see the text.

The ABRABLA calculations with the sharp cutoff approximation [6,9,12] are compared to the experimental values, and are shown in Fig. 4(b). It seems that the theoretical values give an upper limit.

One reason for the large discrepancy between theory and experiment 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. One might expect that the sharp cutoff approximation would be justified only for isomers lying on the yrast line and the isomeric ratio should decrease with increasing excitation energy of an isomer above the yrast line. Such a tendency was indeed observed, as described in Ref. [6]. It also has been suggested that the isomeric ratio depends on the nuclear structure [18]. By taking into account the decay properties of the states around the isomer a better agreement between the experimental and calculated angular momentum population might be obtained.

The near yrast structures of several nuclei are well known from studies using fusion–evaporation reactions with heavy-ion beams. These reactions are somewhat similar to projectile fragmentation with a large mass difference between fragment and projectile, in the sense that they both populate states close to the yrast line. Therefore, the fraction (φ) of intensity passing through the isomer as compared to the total intensity at that excitation energy determined from fusion–evaporation reactions can be used to correct the isomeric ratio: $\rho_{\rm exp} = R_{\rm exp}/\varphi$. The quantity $\rho_{\rm exp}$ gives the probability of populating states with higher angular momentum than the isomer and can be directly compared with the theory. For ρ in the following we use the term "angular momentum population" to refer to the fractional population at and above a specified spin value. This procedure was introduced in Ref. [12] and it was used for $I^\pi{=}12^+$ isomers in neutron-deficient $Z \approx 82$ nuclei. In this paper we use this technique for all the available experimental data in the heavy mass region [6, 9, 12]. The results are summarised in Table I and Figs. 4(c) and 4(d).

The accuracy of φ depends on the sensitivity of a given experiment, more sensitive experiments tending to lead to lower φ values. A good illustration of this is the case of the 10^+ isomer in ^{182}W. While one experiment gives $\varphi = 0.38$ [30], another using lower γ-ray detection efficiency gives $\varphi = 0.8$ [31]. The uncertainties in φ indicated in Table I have been increased relative to the statistical value to take account of such uncertainties in the level scheme.

We can conclude that in general there is an agreement within a factor of 2 between the experimental and theoretical angular momentum population. There are only two isomers for which there seems to be a serious disagreement between theory and experiment: the $5/2^-$ isomers in ^{177}Ta and ^{181}W. In these cases the extracted φ might be incorrect because of the difference between the angular momentum population in fusion–evaporation and fragmentation reactions (see Fig. 5). One could expect that the population of non-yrast states is stronger at the maximum of the cross sections: it is stronger for low-spin states in the case of fragmentation and larger at high spin in fusion–evaporation reactions. Therefore, the φ value determined from fusion–evaporation reactions is much lower than it would be in fragmentation for low spin states like $I = 5/2$. In line with this, it might be that φ is overestimated for high spin states. In some cases (^{175}Hf, ^{176}Ta, ^{177}Ta, ^{179}Ta), higher lying isomers decaying into the isomers of interest are known (although not observed in the fragmentation experiments). If these states are populated, this might reduce the observed isomeric ratio $R_{\rm exp}$.

We note that the φ could not be determined for any of the isomers around ^{208}Pb [9] since it is difficult to populate these nuclei in fusion–evaporation

TABLE I

Comparison of experimental and theoretical angular momentum population. For details see the text.

Ion	I^π	$R_{\rm exp}$ (%)	φ	$\rho_{\rm exp}$(%)	$\rho_{\rm exp}/\rho_{\rm theor}$
^{136}Sm	8^-	3.5(12) [6]	0.10(3) [19]	37(17)	0.48(22)
^{175}Hf	$35/2^-$	2.5(6) [6]	0.57(20) [20]	4.4(19)	0.59(25)$^{\rm (a)}$
^{175}Ta	$21/2^-$	2.0(5) [6]	0.17(3) [21]	12(4)	0.35(11)
^{176}Ta	14^-	2.6(5) [6]	0.30(4) [22]	8.6(19)	0.54(12)$^{\rm (a)}$
^{177}Ta	$21/2^-$	9(2) [6]	0.41(8) [23]	22(6)	0.66(19)$^{\rm (a)}$
^{177}Ta	$5/2^-$	4.0(6) [6]	0.13(2) [23]	31(6)	0.34(7)
^{179}Ta	$21/2^-$	9(3) [6]	0.64(33)$^{\rm (b)}$ [24]	14(8)	0.44(25)$^{\rm (a)}$
^{180}Ta	15^-	10(3) [6]	0.26(9) [25, 26]	39(17)	3.21(144)
^{179}W	$35/2^-$	2.7(5) [6]	0.49(6) [27]	5.6(12)	1.11(25)
^{180}W	14^-	6.4(10) [6]	0.36(16) [28]	18(8)	1.37(65)
^{181}W	$21/2^+$	17(4) [6]	0.67(29) [28]	26(13)	0.88(43)
^{181}W	$5/2^-$	6(1) [6]	0.29(9) [29]	21(7)	0.23(8)
^{182}W	10^+	10(2) [6]	0.38(11) [30]	27(10)	0.80(28)
^{181}Re	$35/2^-$	0.2(1) [6]	0.23(16) [32]	0.9(7)	0.22(19)
^{188}Hg	(12^+)	6.2(19) [12]	0.29(15) [33]	21(13)	0.63(38)
^{193}Pb	$(33/2^+)$	1.5(4) [12]	0.11(2) [34]	14(4)	1.21(39)
^{194}Pb	(12^+)	16(4) [12]	0.60(15) [35]	27(9)	0.95(34)
^{196}Pb	(12^+)	17(4) [12]	0.61(12) [36]	28(9)	1.00(31)
^{197}Bi	$(29/2^-)$	8(2) [12]	0.47(14) [37]	17(7)	1.03(40)
^{198}Po	12^+	8.9(12) [12]	0.48(9) [38]	19(4)	0.93(21)
^{200}Po	(12^+)	6.7(12) [12]	0.6(2) [39]	11(4)	0.50(19)

(a) Higher lying isomeric states are known to decay into this isomer. These might cause a reduction of the observed isomeric ratio $R_{\rm exp}$.
(b) Corrected for the effect of the above lying $25/2^+$ $T_{1/2} = 11$ ms and $23/2^-$ $T_{1/2} = 1.6\,\mu$s isomers (but not for the $37/2^+$ isomer).

reactions. However, for all these nuclei $R_{\rm exp} \approx \rho_{\rm theor}$, so a possible $\varphi < 1$ would indicate a higher angular population than that predicted by the ABRABLA code.

Fragmentation is generally considered a reaction which populates low spin states of the order of $I = 3 - 10\hbar$ [16]. Therefore, it is interesting to note that the highest angular momentum observed to date is the $I^\pi = 43/2^-$ isomer in ^{215}Ra [40], populated in the fragmentation of a $E/A = 950$ MeV ^{238}U beam [41] (see Fig. 6).

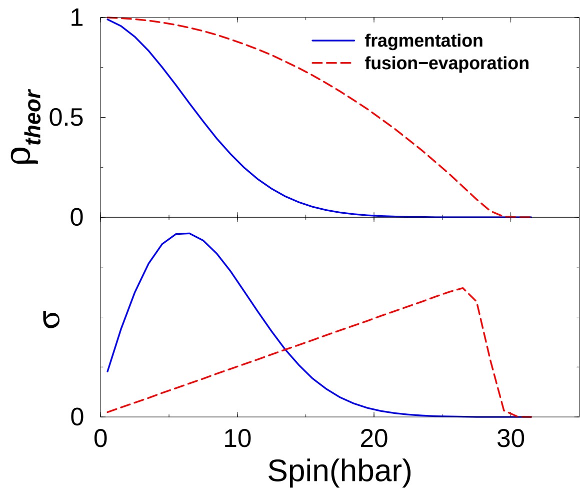

Fig. 5. Comparison of the angular momentum input in fusion–evaporation and fragmentation reactions. The lower panel shows the cross section as function of spin for ^{179}W produced in the ^{170}Er(^{13}C,4n) reaction at 67 MeV bombarding energy (dashed line). The continuous line shows the cross section of ^{179}W produced in the fragmentation of ^{208}Pb at relativistic energies calculated using the simple analytical formula. The upper panel shows the angular momentum input obtained from these cross sections in the sharp cutoff approximation ($\rho_{\rm theor}{=}\sum_{I_m}^{\rm inf}\sigma(I)$).

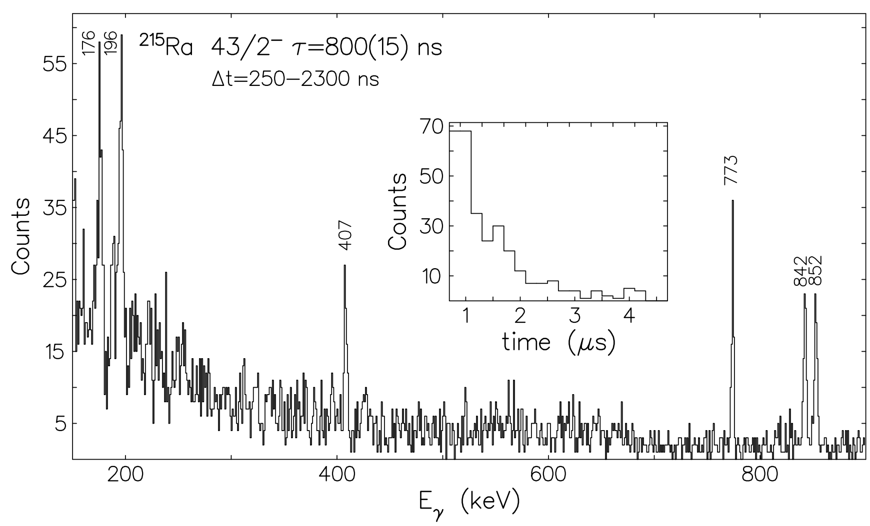

Fig. 6. Delayed γ-ray spectra associated with ^{215}Ra [41]. The 407 keV and 842 keV γ-ray transitions prove the population of the 43/2$^-$ isomeric state [40]. The other labelled transitions are from a lower lying 29/2$^-$ isomer.

4. Conclusions and future

Isomeric decay following projectile fragmentation is a powerful technique to study exotic nuclei. It is very sensitive, due to the off-beam measurement and correlation with the implanted ion. The technique has been used both for nuclear structure and reaction mechanism studies. In order to get agreement between the experimental and calculated angular momentum population, the structure of the nucleus has to be considered.

Technical developments will further increase the sensitivity. The use of digital electronics and active stoppers could increase the efficiency of the γ-ray detection and the possible ion-γ correlation time, respectively.

The present paper presents results from several experiments. We thank all those involved in these measurements. The author acknowledges the receipt of an EPSRC Advanced Fellowship Award (GR/A10789/01).

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