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The population of metastable states as a probe of relativistic-energy fragmentation reactions


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** A B S T R A C T **

Isomeric ratios have been measured for high-spin states in $^{198,200,206,208}$Po, $^{208,209,210,211}$Rn, and $^{215}$Ac following the projectile fragmentation of a 1 AGeV $^{238}$U beam by a $^9$Be target at GSI Helmholtzzentrum für Schwerionenforschung. The fragments were separated in the fragment separator (FRS) and identified by means of energy loss and time-of-flight techniques. They were brought to rest at the centre of the RISING gamma-ray detector array and intensities of gamma rays emitted in the decay of isomeric states with half-lives between 100 ns and 40 μs and spin values up to 55/2 were used to obtain the corresponding isomeric ratios. The data are compared to theoretical isomeric ratios calculated in the framework of the abrasion–ablation model. Large experimental enhancements are obtained for high-spin isomers in comparison to expected values.

The need for an understanding of relativistic heavy-ion collisions spans a number of scientific fields, from the safety of human space exploration [1] and cosmic-ray astrophysics [2], to the struc-
However, this requires special circumstances for study to be possible. Following a given collision, the excited nuclear products typically de-excite in less than $10^{-15}$ s. Such a short time is insufficient to apply separation techniques that would enable the initial excitation energies and angular momenta to be determined, since the de-excitation radiations all occur in close proximity to the reaction target.

A breakthrough came with the ability to separate the products of projectile-fragmentation reactions according to their mass and charge [8], combined with the detection of $\gamma$ rays from nuclear isomeric states [9,10]. Excellent sensitivity was achieved for isomer halflives in the 0.1–100 μs range, after the recoiling ions had been transported to a remote measurement station in less than 1 μs. In the present context, a key feature of nuclear isomers is that in many cases they carry high angular momentum, which is itself closely associated with their extended half-lives [11].

The measurement of isomer production probabilities following fragmentation reactions initially supported the validity of the model calculations [12,13], with angular momenta up to 20 h being studied. However, when higher angular momenta were identified, a large production excess became apparent [14]. At that time, the evidence rested heavily on a single data point, from a source containing $^{241}$Am, $^{133}$Ba, $^{137}$Cs and $^{60}$Co. Data were collected using two different stoppers and the efficiency information for each has been used in the analysis. In the case of $^{212}$Ra, the half-lives that have been used in the determination of the isomeric ratio is from the literature. From the current data it was possible to confirm these values but better accuracy could not be obtained. The values measured in the current work for $^{210}$, $^{211}$Ra, are in general agreement with previous values [20,21] but have a smaller error and therefore have been used in the analysis. In the case of $^{212}$Ra, half-lives of 480(40) ns and 7.1(2) μs for the $^{11-}$ and $^{8+}$ isomeric states respectively, have been measured in this experiment and used for the calculation of the isomeric ratios. The value obtained for the $^{11-}$ state is about half the value of 850(13) ns quoted in [18] while the value for the $^{8+}$ state compares with previous values of 9.1(6) μs in [21] and 10.9(4) μs in [18].

Although Table 1 shows that there are 12 cases where the excitation energy of the isomeric state is unknown, there are only 3 ($^{12+}$ in $^{158}$Po and $^{55+}$ in $^{213}$Rn) where the unobserved transition depopulates the isomer directly and therefore affects the isomeric ratio. The effect of the multipolarity of the unobserved transition on the isomeric ratio was discussed in detail in [13] for the case of the $^{12+}$ level in $^{158}$Po. Table 2 of [13] shows that for a missing transition of energy $E_\gamma$, the multipolarity of the transition has no effect on the isomeric ratio (to 3 significant figures). The $^{55+}$ level in $^{213}$Rn has the highest spin value for which an isomeric ratio has been measured in the current work. Fig. 1 shows the gamma-ray energy spectrum obtained in coincidence with implanted $^{213}$Rn ions within a time gate of $\Delta t = 50–1450$ ns. The isomeric ratio for the $^{55+}$ level at $E_\gamma = 5929$ keV has been obtained from the intensity of the 1010 keV transition which is clearly observed in the figure. Assuming no in-flight decay, the isomeric ratio is 0.8/2 which is the same as would have been used in the determination of the isomeric ratio.
be obtained for an E2/M1 transition of 100 keV. If the transition were to be an E1, then the ratio increases to 1.3(4) which is the maximum possible compatible with the lack of observation of the direct gamma decay from the isomer.

Table 1 lists the isomeric ratios measured for these states in previous works. Most of the other strong transitions in the spectrum in Fig. 1 have been used to obtain isomeric ratios ordered by increasing Elev. The third last column contains the results of previous measurements and the last two columns calculated values. Data obtained for Po from [22–25], for At from [26–30], for Rn from [31–35], for Fr from [20,36–41], for Ra from [18,20,21,42–44] and for Ac from [45].

Table 1

<table>
<thead>
<tr>
<th>Z</th>
<th>( 1^+ )</th>
<th>Elev (keV)</th>
<th>( t_{1/2} ) (μs)</th>
<th>( \rho_{iso}(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>198Po</td>
<td>12^+</td>
<td>x + 2692</td>
<td>0.75(5)</td>
<td>4(2)(^a)</td>
</tr>
<tr>
<td></td>
<td>11^-</td>
<td>2566</td>
<td>0.20(2)</td>
<td>20(5)(^b)</td>
</tr>
<tr>
<td>200Po</td>
<td>12^+</td>
<td>x + 2804</td>
<td>0.26(8)</td>
<td>7(3)(^c)</td>
</tr>
<tr>
<td></td>
<td>11^-</td>
<td>2596</td>
<td>0.014(9)</td>
<td>48.0(23)(^d)</td>
</tr>
<tr>
<td>200Po</td>
<td>9^+</td>
<td>2262</td>
<td>1.05(6)</td>
<td>15(2)(^e)</td>
</tr>
<tr>
<td></td>
<td>8^+</td>
<td>1586</td>
<td>0.23(2)</td>
<td>12(2)</td>
</tr>
<tr>
<td>208Po</td>
<td>8^+</td>
<td>1528</td>
<td>0.35(2)</td>
<td>27(2)</td>
</tr>
<tr>
<td>206At</td>
<td>16^-</td>
<td>2276</td>
<td>1.5(2)</td>
<td>8.6(9)</td>
</tr>
<tr>
<td>200At</td>
<td>(29/2)^+</td>
<td>2429</td>
<td>0.89(4)</td>
<td>17(1)</td>
</tr>
<tr>
<td>210At</td>
<td>19^-</td>
<td>4028</td>
<td>5.66(7)</td>
<td>8.9(9)</td>
</tr>
<tr>
<td>211At</td>
<td>39/2^-</td>
<td>4815</td>
<td>4.2(4)</td>
<td>6.6(4)</td>
</tr>
<tr>
<td>210Rn</td>
<td>(17^-)</td>
<td>x + 3812</td>
<td>1.06(5)</td>
<td>10(1)</td>
</tr>
<tr>
<td></td>
<td>(8^+)</td>
<td>x + 1665</td>
<td>0.64(4)</td>
<td>19(5)</td>
</tr>
<tr>
<td>211Rn</td>
<td>35/2^+</td>
<td>x + 3926</td>
<td>0.040(1)</td>
<td>14(3)</td>
</tr>
<tr>
<td></td>
<td>17/2^-</td>
<td>x + 1578</td>
<td>0.60(3)</td>
<td>38(3)</td>
</tr>
<tr>
<td>212Rn</td>
<td>22^2</td>
<td>6174</td>
<td>0.109(5)</td>
<td>3.4(5)</td>
</tr>
<tr>
<td></td>
<td>8^+</td>
<td>1694</td>
<td>0.91(3)</td>
<td>34(2)</td>
</tr>
<tr>
<td>219Rn</td>
<td>(55/2^-)</td>
<td>y + 5929</td>
<td>0.16(1)</td>
<td>0.8(2)(^h)</td>
</tr>
<tr>
<td></td>
<td>43/2^-</td>
<td>x + 3495</td>
<td>0.028(1)</td>
<td>9(5)(^i)</td>
</tr>
<tr>
<td></td>
<td>31/2^-</td>
<td>x + 2187</td>
<td>1.36(7)</td>
<td>17(2)(^j)</td>
</tr>
<tr>
<td>215Fr</td>
<td>25/2^-</td>
<td>x + 1664</td>
<td>1.02(3)</td>
<td>8(3)</td>
</tr>
<tr>
<td>214Rn</td>
<td>(22^-)</td>
<td>4595</td>
<td>0.25(3)</td>
<td>4.8(9)</td>
</tr>
<tr>
<td>208Fr</td>
<td>10^-</td>
<td>826</td>
<td>0.43(1)</td>
<td>16(1)</td>
</tr>
<tr>
<td>211Fr</td>
<td>45/2^-</td>
<td>4657</td>
<td>0.12(1)</td>
<td>2.8(3)</td>
</tr>
<tr>
<td></td>
<td>29/2^+</td>
<td>2423</td>
<td>0.15(1)</td>
<td>16(1)</td>
</tr>
<tr>
<td>212Fr</td>
<td>15^-</td>
<td>2492</td>
<td>0.58(2)</td>
<td>19(1)</td>
</tr>
<tr>
<td></td>
<td>11^-</td>
<td>1551</td>
<td>2.7(1)(^k)</td>
<td>21(2)</td>
</tr>
<tr>
<td>213Fr</td>
<td>29/2^-</td>
<td>2538</td>
<td>0.238(6)</td>
<td>23(2)</td>
</tr>
<tr>
<td></td>
<td>21/2^-</td>
<td>1590</td>
<td>0.51(1)</td>
<td>22(2)</td>
</tr>
<tr>
<td>214Fr</td>
<td>11^-</td>
<td>638</td>
<td>0.103(4)</td>
<td>69(10)(^g)</td>
</tr>
<tr>
<td>210Ra</td>
<td>8^+</td>
<td>2050</td>
<td>2.1(1)(^d)</td>
<td>31(2)</td>
</tr>
<tr>
<td>211Ra</td>
<td>(13/2^-)</td>
<td>1198</td>
<td>9.4(4)(^d)</td>
<td>35(2)</td>
</tr>
<tr>
<td></td>
<td>(11^-)</td>
<td>2613</td>
<td>0.48(4)(^d)</td>
<td>25(2)</td>
</tr>
<tr>
<td>212Ra</td>
<td>(8^-)</td>
<td>1958</td>
<td>7.1(2)(^k)</td>
<td>18(2)</td>
</tr>
<tr>
<td>214Ra</td>
<td>17^-</td>
<td>4147</td>
<td>0.225(4)</td>
<td>13(1)(^k)</td>
</tr>
<tr>
<td></td>
<td>14^-</td>
<td>3478</td>
<td>0.279(4)</td>
<td>13(1)</td>
</tr>
<tr>
<td></td>
<td>8^-</td>
<td>1865</td>
<td>68(1)</td>
<td>64(2)</td>
</tr>
<tr>
<td>215Ra</td>
<td>(43/2^-)</td>
<td>x + 3757</td>
<td>0.55(1)</td>
<td>7.9(8)</td>
</tr>
<tr>
<td></td>
<td>(29/2^-)</td>
<td>x + 2438</td>
<td>0.34(1)</td>
<td>20(4)^a</td>
</tr>
<tr>
<td></td>
<td>21/2^-</td>
<td>1796</td>
<td>0.19(3)</td>
<td>20(5)</td>
</tr>
</tbody>
</table>

\(\text{\footnote{a}}\) The intensity of only one transition has been used in Eq. (1) to calculate the isomeric ratio.

\(\text{\footnote{b}}\) Statistical error, assuming no in-flight decay. The corresponding values of \(\rho_{iso}\) for an E2/M1 or E1 decay of 100 keV are 0.8(2) and 1.3(4) respectively. The latter value is the maximum possible compatible with the lack of observation of the direct gamma decay from the isomer.

\(\text{\footnote{c}}\) No error is quoted in the original reference [38].

\(\text{\footnote{d}}\) The half-life measured in this work has been used in the analysis.

Table 1 also lists the isomeric ratios measured for these states in previous works. In the case of the Po nuclei, the values measured in the current work agree with those measured by Gladnishki et al. [13] to within 2 standard deviations. However in the case of the Fr and Ra nuclei measured in [14], there is a factor of at least 2 between the values presented here and previous ones, with those in the current work being larger. The results presented in both [13] and [14] used the same reaction at the same experimental facility although Gladnishki et al. [13] used a beam energy of 750 A MeV and Podolyák et al. [14] 900 A MeV. At the higher beam energy (1 A GeV) used in the current experiment, there were fewer problems with contamination and with charge state identification, and therefore the isotopic identification should be cleaner and the data more reliable. It should also be noted that the experimentally observed value is always a lower limit as there is a possibility that some of the higher-spin population bypasses the measured isomer.
Such an effect could originate from a type of friction or viscosity as model was pointed out in [14] and attributed to the lack of inclusion of the fragment. The underestimation of the data by the ABRABLA codes and, on average, does not change the angular momentum of the fragment. The underestimation of the data by the ABRABLA codes and, on average, does not change the angular momentum by [14] (discussed above) differ somewhat from the values measured in this work, which seems to increase in an approximately linear manner with the logarithmic scale in Fig. 2, i.e. suggesting an exponential dependence. The figure also shows that there is a range of isomeric ratios for each value of spin and that while the values measured in the current work, they are not outside the overall band. It should be noted that an analogous graph plotted against excitation energy shows the same trend of increasing underestimation by the models as the energy increases.

In the ABRABLA model [46,47], the fragmentation process is considered in two steps, an ABRasion stage where there is a clean cut of both the target and the projectile and the angular momentum generated in the target fragment is dependent solely on the angular momentum of the removed nucleons. In the ABLation stage, the excited prefragment either fissions or emits nucleons. In the case of the nuclei discussed here, it is the nucleon emission process that is relevant and once below the particle emission threshold, the nuclei continue to cool via the statistical emission of gamma rays. This part of the decay is modelled using Monte Carlo codes and, on average, does not change the angular momentum of the fragment. The underestimation of the data by the ABRABLA model was pointed out in [14] and attributed to the lack of inclusion of any collective effect in the angular-momentum generation. Such an effect could originate from a type of friction or viscosity as the target and projectile pass through each other. An attempt was made to estimate the magnitude of this effect in [14] and it was shown to make a sizable difference (a factor of 4 at spin 43/2 h).

The new measurements for I > 20h, presented here, now demand a more sophisticated theoretical treatment. We speculate that the exponential nature of the experimental enhancement could perhaps also be due to the level density term in the calculations, which does have this form and has not been validated at such high excitation energies.

The subsequent development of the ART + SBD model [19] also did not include any collective features. Although it uses a relativistic transport model to describe the size and excitation energy of the prefragment, the initial angular momentum is again generated only from single-particle excitations. This distribution is then broadened in the sequential binary decay process. While Table 1 shows that the ratios predicted using this model are systematically higher than those using ABRABLA, they also overestimate the data (by a factor ranging from ~2 at spin 14 h to ~10 at spin 21 h). No ART + SBD predictions are currently available for the isomeric ratio for the 55/2 h state measured in this work.

In summary, isomeric ratios for states with spin values between 13/2 and 55/2 h, in neutron-deficient N ~ 126 nuclei produced in projectile fragmentation reactions, have been measured at the GSI facility. Although the data show the expected decrease of the isomeric ratio as a function of spin, this decrease is much slower than predicted by model calculations, an effect which could be due to the lack of a collective component in current models. Given the recent increase in the number and diversity of beams which are being produced by fragmentation, it is important that this discrepancy is investigated and understood in the near future.

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