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High angular momentum states populated in fragmentation reactions

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Abstract

The population of metastable states produced in relativistic-energy fragmentation of a ^{238}U beam has been measured. For states with angular momentum $\gtrsim 20\hbar$, a much higher population than expected has been observed. By introducing a collective component to the generation of angular momentum the experimental data can be understood. This is the first time that a collective degree of freedom has be shown to play a major role in such high-energy collisions.

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Fragmentation is the reaction which occurs during the collision between two nuclei at relative energies higher than the Fermi velocity of the nucleons ($v_F \sim 10^6$ m/s). Successful reaction models developed for such high energies treat only the individual-nucleon character of nuclei, yet it is of basic interest to know to what extent collective degrees of freedom may be important. This interplay between individual-particle and collective character is a feature that is key to understanding the interactions between any mesoscopic systems, be it nucleon clusters or atom clusters. We here find evidence that the generation of large amounts of angular momentum during high-energy collisions gives remarkable sensitivity to the collective contribution.

From the point of view of basic science, fragmentation has been used to study, for example, the equation of state of nuclear matter [1], and the formation of heavy nuclei in supernova explosions [2]. On the more applied side, fragmentation is an almost universal reaction, producing nuclei of any mass up to the

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fragmented ion, both proton- and neutron-rich. It is integral to many of the present and next-generation radioactive beam facilities [3,4]. Our results have immediate consequences, not only for the production and use of radioactive beams in high angular-momentum states, but also for the general understanding of the dynamics of collisions involving mesoscopic systems.

Peripheral relativistic-energy heavy-ion collisions, resulting in fragments with masses close to those of the projectile and target, can be described by the two-step abrasion–ablation model rather successfully [5]. The macroscopic abrasion model, the most successful so far, relies on the concept of a clean cut of the projectile nucleus by the target (and vice versa). According to this model, if the relative velocity of the reaction partners is much higher than the Fermi velocity of the nucleons, the nucleon–nucleon collisions are restricted to the overlap zone. The parts of the nuclei outside the overlap zone, called spectators or prefragments, are not affected. The impact parameter determines the number of nucleons removed from the projectile (and target). A key aspect of this fragmentation model is the estimation of the excitation energy and angular momentum of the prefragments. According to a statistical approach during the fast abrasion phase, a number of single-particle levels are vacated and the excitation energy is given by the sum of the energies of these holes with respect to the Fermi surface (diabatic approximation). In the second, ablation stage the hot prefragment either fissions or emits nucleons until the final fragment is formed with excitation energy below the particle emission threshold. This stage of the fragmentation process is better understood, and is generally treated by numerical statistical-model codes. Similar evaporation processes are encountered in other types of reaction, such as fusion–evaporation, and thus it has been more thoroughly tested than the first abrasion stage.

So far the main experimental observables to test the theory of peripheral fragmentation are the production cross sections and the longitudinal momenta of the fragments. The determination of these quantities is straightforward from the experimental data. It is more difficult to study the angular momenta of the fragments. Experimentally we cannot determine the population of a single state with a given angular momentum, but only the total population of all the states decaying into the level of interest. Therefore, the study of the population at high angular momentum from the tail of the distribution, provides a much more stringent test of the theory than populations at lower angular momenta. Here we present results obtained for the population of high angular-momentum states produced in peripheral fragmentation, exploiting the selectivity offered by long-lived isomeric states.

Neutron-rich nuclei close to the $N = 126$ neutron shell-gap were populated in relativistic energy projectile fragmentation. A beryllium target of thickness 1 g/cm^2 was bombarded with an $E/A = 900$ MeV ^{238}U beam provided by the SIS accelerator at GSI, Darmstadt, Germany. The typical on-target beam intensity was 6×10^7 uranium ions per 15 second beam spill. The nuclei of interest were separated and identified using the FRagment Separator (FRS) [6] operated in standard achromatic mode. The identification of the fragments is based on the determined A/q, the energy loss in the ionisation chamber ($\approx q$), and the longitudinal position of the nuclei at the intermediate and final focal planes of the FRS. At the final focal plane of the FRS the separated ions were implanted into a 5 mm thick plastic stopper, surrounded by an array of six clover-style germanium detectors. The γ-rays in prompt and delayed coincidence with the individually identified fragments were recorded. For more details about the setup and the identification procedure see Ref. [7].

As a result of the fragmentation process (abrasion and ablation) the final fragment is formed with an excitation energy below the particle emission threshold. Subsequently, a statistical γ cascade proceeds down to the yrast line and then along this line to the ground state. If an isomeric state lies on this decay path, part of the cascade may be held up by the corresponding life-time. The isomeric ratio is equal to the probability that γ decay from the initial excited fragment proceeds via the isomeric state. It can be determined experimentally as $R_{\mathrm{exp}} = Y/(N_{\mathrm{imp}}FG)$, where N_{imp} is the number of implanted heavy ions, Y is the isomeric yield. F and G are correction factors for the in-flight isomer decay losses and the finite detection time of the γ radiation, respectively. The isomeric yield is given by: $Y = N_\gamma/(\epsilon_{\mathrm{eff}} b_\gamma)$, where N_γ is the number of counts in the γ-ray line depopulating the isomer, b_γ is the absolute γ-ray branching ratio, and ϵ_{eff} is the γ-ray detection efficiency. For more details see Refs. [7,8].

Several previously known long-lived states were observed in one magnetic rigidity setting of the fragment separator, centered on ^{216}Ac. The properties of these metastable states together with the determined experimental isomeric ratios are listed in Table 1. We note that the $43/2^-$ isomer in ^{215}Ra (see Fig. 1) represents the highest angular momentum state observed in fragmentation reactions. The uncertainties in the isomeric ratios are of the order of 20–50%, and are dominated by errors in the number of implanted ions (≈10–25%), γ-ray detection efficiency (≈10%) and the statistical uncertainties in the number of counts in the γ-ray lines (≈10%).

The isomeric ratios are compared to the predictions of the ABRABLA Monte Carlo code [5,10], based on the geometrical abrasion picture of fragmentation. This code represents the state-of-the-art for calculations of angular momentum population and it has been used for discussion of the majority of the existing experimental data [7–9,11,12]. The angular momentum [5,10] is treated in the same way as the longitudinal momentum [14], the distribution reflecting the Fermi motions of the nucleons in the nucleus. Accordingly, the angular mo-

Table 1
Isomeric ratios of metastable states observed in the present experiment. See the text for details

Ion	I^π [Ref.]	E_{lev} [keV]	R_{exp} [%]	ρ_{the} [%]	$R_{\mathrm{exp}}/\rho_{\mathrm{the}}$
^{211}Fr	$29/2^+$ [25]	2423	5.7(19)	9.4	0.61(21)
^{212}Fr	15^- [25]	2492	7.5(18)	8.5	0.88(21)
^{213}Fr	$29/2^+$ [25]	2538	12(8)	11.1	1.08(72)
^{214}Ra	17^- [26]	4147	6.8(23)	2.4	2.87(98)
^{215}Ra	$43/2^-$ [27]	$3757 + \Delta$	3.1(6)	0.21	14.5(30)
^{215}Ac	$(29/2^+)$ [28]	$2438 + \Delta$	4.8(12)	3.8	1.25(33)

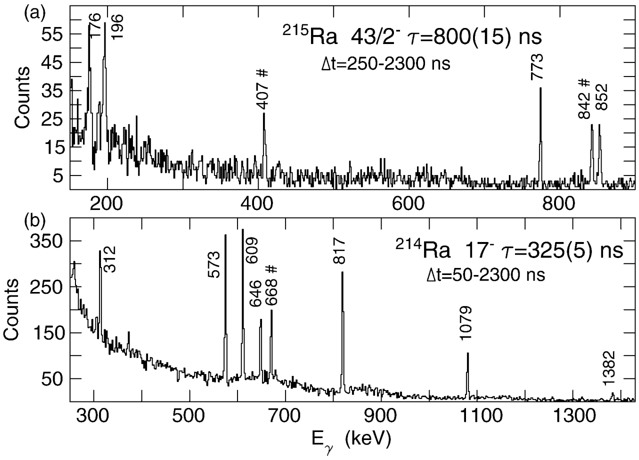

Fig. 1. Delayed γ-ray transitions associated with (a) ^{215}Ra and (b) ^{214}Ra. The transitions marked with # are exclusively from the decay of the high angular momentum isomers: $I^\pi = 43/2^-$ in ^{215}Ra and $I^\pi = 17^-$ in ^{214}Ra. The other labelled transitions are from the decay via lower lying isomeric states.

mentum population (from the single-particle motion) induced in the abrasion stage has a width

$$\sigma^2 = \langle j_z^2 \rangle \frac{A'_f(A_p - A'_f)}{A_p - 1}$$

and a root mean square value $I_{\mathrm{rms}} = \sqrt{2}\sigma$ [10]. The above equation is obtained in analogy to the linear-momentum description given by the Goldhaber formula [14], and is based on simple momentum conservation considerations. A'_f and A_p are the mass numbers of the prefragment and the projectile, respectively. $\langle j_z^2 \rangle$ is the mean square value of the angular-momentum projection of a nucleon, and it is calculated from the shell model [10]. A constant excitation energy of 27 MeV per abraded nucleon is assumed. This is double that expected from just the single-hole excitations, and was obtained by fitting the experimental production cross sections of Pt and Ir isotopes observed in the fragmentation of $E/A = 1$ GeV ^{197}Au [15]. It is considered that the ablation stage does not change this distribution. This is reasonable, since the evaporated nucleons tend to have low angular momentum due to the centrifugal barrier.

To be able to compare the experimental results with the theory, the population of the isomer has been calculated by assuming that all states with angular momentum higher than that of the isomeric state will decay into it. One might expect this sharp-cutoff limit to be justified for isomers lying on the yrast line. (This is the case for all of the isomers observed in the present work.) In general, a more realistic theoretical estimate for the isomeric ratio would be equal to or less than that obtained with the above assumption.

One can observe a general trend from Fig. 2 and Table 1: the new experimental data for high angular momentum states ($I = 17\hbar$ and $I = (43/2)\hbar$) contradict the model: the isomeric ratio is larger than the calculated one (see Fig. 2), and the discrepancy increases with the angular momentum. The discrepancy is more than a factor of 10 at $I = 43/2$.

As a global tendency, the isomeric ratios, both experimental and theoretical, decrease with spin and increase with the fragment-projectile mass difference. The earlier results showed that the theoretical values represent the upper limit for the isomeric ratios [7–9,11–13,16,17], a fact which can be (at least partially) explained by the simplistic application of the sharp cutoff limit. Indeed, it has been demonstrated that there is a strong dependence of the isomeric ratio on the structure of the isomer [11] and its proximity to the yrast line [8], and these effects can be accounted for [18]. The application of any such considerations to the present data could only increase the values shown in Fig. 2.

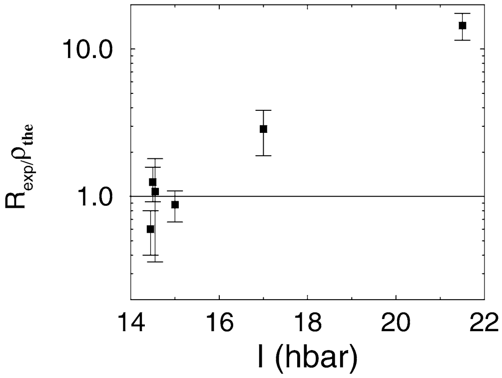

Fig. 2. The ratios of experimentally measured isomeric ratios and the calculated values using the sharp cutoff approximation. For details see the text.

Other types of experiment related to the angular momentum input in fragmentation are the spin-alignment and spin-polarisation measurements. The products of fragmentation-like reactions at intermediate energies are spin polarised [19–21]. For fragments with mass close to that of the projectile a strong dependence of isomer population on fragment velocity has been observed [11,13]. At relativistic energies, there is a strong spin alignment [13], but very small spin polarisation (up/down asymmetry) [22]. All these effects can be explained, at least qualitatively, based on kinematical arguments [19,20]: the angular momentum is generated by the recoil of the removed nucleons in the abrasion phase of the fragmentation. Thus, the direction of the angular momentum is determined by the direction of the momentum of the removed nucleons. The small polarisation at relativistic energies can be explained based on an additional effect, namely the forward/backward asymmetry in the abrasion process [20,22].

Both the statistical ABRABLA code employed here and the kinematical fragmentation model [19,20], consider the angular momentum of the fragments to originate solely from the angular momenta of the removed nucleons. According to the new experimental data, this assumption contradicts the experiment, by underestimating the population of the high angular momentum states. One way to obtain agreement with the experiment in the case of the $I = 43/2$ isomer is arbitrarily to increase the single-particle angular momentum width, σ^2, by ~80%. However, this conflicts with the constraints from the shell model. Therefore, an additional source of angular momentum has to be considered. Experimentally a clear negative correlation between the mean velocity of the projectile-like fragment and the mass loss in very peripheral collisions was observed (e.g., [1,23]). The velocity decreases as more nucleons are removed from the projectile (up to about 1/3 of the mass). This momentum shift, described by the empirical formula of Morrissey [23], can be interpreted [24] as a consequence of a type of friction in the nucleus–nucleus collision. Since the nucleons removed from the projectile are at the periphery, the shift in the longitudinal momentum will also be accompanied by additional angular momentum. This angular momentum can be considered as a collective contribution, as opposed to that originating from the angular momenta of the individual nucleons.

In order to estimate the effect of the collective contribution to the angular momentum a simplified calculation has been performed. The Goldhaber description [14] was used for the single-particle contribution and the Morrissey formula [23] for the collective part. By coupling these two angular momenta an increase in the population of the 17^-, ^{214}Ra and $43/2^-$, ^{215}Ra isomers by a factor of 2.5 and 4, respectively, was obtained. The increase for the lower angular-momentum states is much less, for example, 25% for $I = 8$. Therefore, the coupling of the angular momenta representing the single-particle and collective motions significantly improves the description of the experimental data.

In conclusion, the population of metastable states produced in the fragmentation of $E/A = 900$ MeV ^{238}U has been measured. The $I = (43/2)\hbar$ state in ^{215}Ra represents the highest discrete spin state observed following a projectile fragmentation reaction. For states with high angular momentum, $I \geqslant 17\hbar$, a higher population has been observed than predicted. The expectations were based on a model where the angular momentum is generated solely by the internal angular momenta of the removed nucleons. We have shown that by coupling the collective angular momentum that corresponds to the longitudinal momentum shift characteristic of fragmentation to the single-particle contribution, a better understanding of the data can be obtained. According to these findings it might be expected that the frictional effect would lead to a beam-energy dependence of isomer population and this will be a focus of future study.

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