Neutron-deficient N≈126 nuclei produced in ^{238}U fragmentation: population of high-spin states

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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 high angular momentum, I=17$\hbar$ and I=21.5$\hbar$, a higher population than expected has been observed, with the discrepancy increasing with angular momentum. By considering two sources for the angular momentum, related to single-particle and collective motions, a much improved description of the experimental results can be obtained. In addition, new results on the structure of ^{208}Fr, ^{211}Ra and ^{216}Ac are reported.

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INTRODUCTION AND EXPERIMENT

The main experimental observables to test the theory of peripheral fragmentation, so far, are the production cross sections and the longitudinal momenta of the fragments. 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 at lower angular momenta. Here we present results obtained for the population of high angular-momentum states produced in peripheral fragmentation. It has immediate consequences for the production of radioactive beams in long-lived states with high angular momentum, where production rates can be a critical factor.

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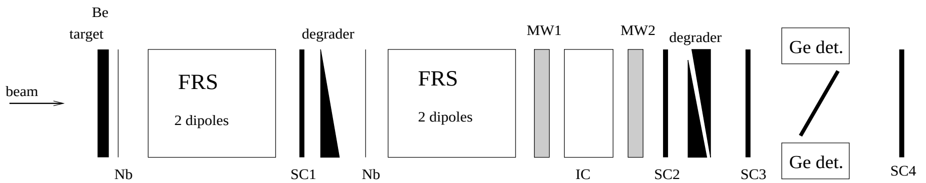

FIGURE 1. Schematic view of the experimental setup. For details see the text.

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) [1] operated in standard achromatic mode (see fig.1). An additional degree of selectivity for the ions reaching the final focus of the FRS was achieved by placing a wedge-shaped aluminium degrader in the intermediate focal plane of the separator. Niobium foils of thicknesses 221 mg/cm^2 and 108 mg/cm^2 were placed after the target and the degrader, respectively, in order to maximise the electron stripping. Typically 84% of the ions of a given isotope with $Z\sim$88 were fully stripped after the target. In the second part of the FRS approximately 42% of the ions were fully stripped, 43% H-like, carrying a single electron and 14% He-like, according to GLOBAL calculations [2]. The mass-to-charge ratio of the ions, A/Q, was determined from their time of flight in the second part of the FRS. The energy deposition of the identified fragments was measured as they passed through a gas ionisation chamber. Following this, they were slowed down in a variable thickness aluminium degrader and finally stopped in a $\sim$5 mm thick plastic catcher. Scintillator detectors were placed both in front of and behind the catcher, allowing the offline suppression of those fragments destroyed in the slowing down process or those which were not stopped in the catcher (totalling $\approx$20% for elements with Z=86–90). The identification of the fragments is based on the determined A/Q, the energy loss in the ionisation chamber ($\approx Q$), and the longitudinal position of the nuclei at the intermediate and final focal planes of the FRS.

The catcher was surrounded by an array of six clover-style germanium detectors. The photopeak γ-ray efficiency of this array was measured to be 12% at 661 keV. The effective detection efficiency was however reduced in practise due to the ions stopping in the catcher, each of which gives rise to a prompt burst of low energy X-rays and bremsstrahlung [3]. This had the effect of 'blinding' on average 6-8 (depending on the species) of the total of 24 detector elements in each event.

At the catcher, the γ-rays in prompt and delayed coincidence with the individually identified fragments were recorded. The time difference was measured between the implantation of the fragment in the stopper (as measured by the time signal from a plastic scintillator placed in front of the stopper) and a subsequently detected γ-ray in the Ge-array, over ranges of 8 μs and 100 μs. Since the time of flight through the FRS was approximately 320 ns, this setup allowed the detection of isomeric decays with half-lives in the typical range of 100 ns to several hundred microseconds.

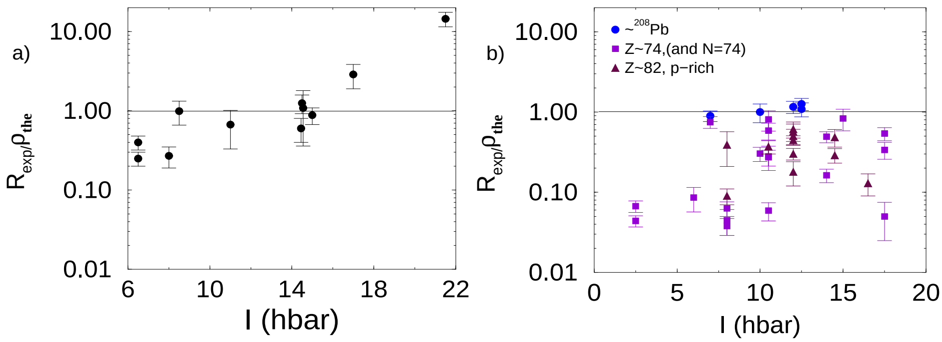

FIGURE 2. The ratios of the experimentally measured isomeric ratios and the calculated values using the sharp cutoff limit. a) Results from the present work. b) Results on heavy ions from previous experiments [4, 5, 7].

ANGULAR MOMENTUM POPULATION: HIGH-SPIN STATES

Several previously known long-lived states were observed in one magnetic rigidity setting of the fragment separator, centred on ^{216}Ac. The population of these metastable states (isomeric ratios) has been determined (for details of the procedure see [4, 5]). The theoretical angular momentum distribution has been calculated using the Monte Carlo code ABRABLA [6]. In this model the angular momentum is generated by the internal angular momenta of the nucleons removed in the abrasion phase of the fragmentation. To be able to compare the experimental results with the theory, the population of the isomer has been calculated in the simplifying assumption that all states with angular momentum higher than that of the isomeric state will decay into it. One might expect that this sharp cutoff limit to be justified for isomers lying on the yrast line. (This is the case for all the isomers observed in the present work.) In general, the theoretical isomeric ratio should be equal to or less than that obtained with the above assumption.

The new experimental data for high angular momentum states, $I \geq 17\hbar$, contradict the model: the isomeric ratio is larger than the calculated one, and the discrepancy increases with the angular momentum (see figure 2a). The discrepancy is a factor of $\approx$15 at I=43/2$^-$ (the I=43/2$\hbar$ state in ^{215}Ra represents the highest discrete spin state observed following a projectile fragmentation reaction). This is in stark contrast to previous experimental results obtained from relativistic energy fragmentation of heavy nuclei [4, 5, 7], summarised in figure 2b. The earlier results suggest that the theoretical values represent the upper limit for the isomeric ratios, a fact which can be (at least partially) explained by the of the sharp cutoff limit. Indeed, it has been shown that by considering the nuclear structure above a metastable state a good agreement, within a factor of 2, between theory and experiment can be obtained [8].

In order to account for the strong population of the high-spin states, 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 collision was observed [9]. The velocity decreases as more nucleons are

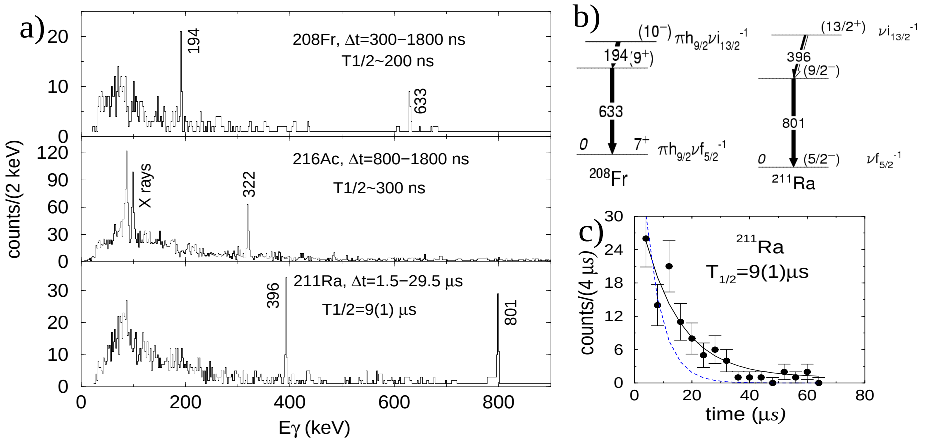

FIGURE 3. a) Delayed gamma-ray spectra associated with ^{208}Fr, ^{211}Ra and ^{216}Ac. b) Proposed level schemes for ^{208}Fr and ^{211}Ra [11]. c) Lifetime determination of the $(13/2^{+})$ isomer in ^{211}Ra. The continuous and dashed lines correspond to 9 μs and 4 μs lifetimes, respectively.

removed. This can be interpreted as the consequence of a kind of friction [10] 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 momentum of the individual nucleons.

In order to estimate the angular momentum produced by the two mechanisms, single nucleons and collective motion, we perform a simple calculation. In the ablation phase of the fragmentation we considered a 27 MeV excitation energy per abraded nucleon, which corresponds to two evaporated nucleons for each abraded one [6]. This means, for example, that ^{214}Ra is produced predominantly from prefragments with mass 230. In this, simplified, case by using the analytical formula of de Jong *et al.* [6] we obtain the r.m.s. of the angular-momentum I_{rms}=8.8$\hbar$. On the other hand, the longitudinal-momentum shift can be described by the empirical formula of Morrissey [9]: $p_{\parallel} = 8(A_p - A_f)\frac{\gamma+1}{\beta\gamma}$ (MeV/c), where A_f is the mass of the fragment. Assuming that the nucleons are removed from the outer layer of the nucleus, e.g. at r=4 fm, the related angular momentum for ^{214}Ra is I_{rms}=6.8$\hbar$. According to our simple estimates the angular momenta generated by the two processes are comparable. The coupling of the angular momenta representing the single-particle and collective motions significantly improves the description of the experimental data.

NEW ISOMERIC STATES

In the present experiment previously unobserved isomeric states have been populated in ^{208}Fr and ^{216}Ac. The delayed gamma-ray spectra are shown in figure 3. The proposed level scheme of ^{208}Fr is also shown and it is based on the similarities with the ^{206}At isotone [12]. The internal conversion coefficient of the 194 keV transition extracted from intensity balance consideration, as well as the preliminary deduced transition strength is consistent with this interpretation.

The spectrum of the odd-odd ^{216}Ac shows only one gamma ray (322 keV) and intense X rays. Indications that this is what we should expect comes from the comparison with ^{218}Ac [13]. The 322 keV gamma-ray probably populates a known (9^-) 37(10) keV isomer [14].

We confirm the existence of a previously reported ($13/2^+$) isomeric state in ^{211}Ra [11]. The determined lifetime $T_{1/2}$=9(1) μs (see figure) is about a factor of two longer than the previously reported [11] value of $T_{1/2}$=4.0(5) μs. The B(M2) transition strength derived form our lifetime fits well in the systematics of the lighter N=123 isotones.

CONCLUSIONS

New results indicating a stronger than expected population of high-spin states populated in fragmentation reactions have been presented. The introduction of a new source of angular momentum, corresponding to the longitudinal momentum shift characteristic of fragmentation, improves significantly the description of the experimental data. In, addition new nuclear structure results have been presented on ^{208}Fr, ^{211}Ra and ^{216}Ac.

All these results on the heavy (Z>82) neutron-deficient nuclei were obtained from a single FRS setting with a beam time of only three hours. A ^{238}U fragmentation experiment dedicated to this mass region could extend our knowledge even further.

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