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Study of near-stability nuclei populated as fission fragments in heavy-ion fusion reactions

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Abstract. Examples are presented to illustrate the power of prompt γ-ray spectroscopy of fission fragments from compound nuclei with $A \sim 200$ formed in fusion-evaporation reactions in experiments using the Gammasphere Ge-detector array. Complementary methods, such as Coulomb excitation and deep-inelastic processes, are also discussed . In other cases $(n,xn\gamma)$ reactions on stable isotopes have been used to establish neutron excitation functions for γ-rays using a pulsed "white"-neutron source, coupled to a high-energy-resolution germanium-detector array. The excitation functions can unambiguously assign γ-rays to a specific reaction product. Results from all these methods bridge the gaps in the systematics of high-spin states between the neutron-deficient and neutron-rich nuclei. Results near shell closures should motivate new shell model calculations.

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INTRODUCTION

During the fission of heavy nuclei the main part of the energy is released as kinetic energy in the fragments. A large amount of energy remains stored as excitation of the fragments in the form of rotation, vibration, deformation, and internal heat. The stored energy is subsequently released first by evaporation of neutrons and then decay towards the yrast line by emission of γ rays (statistical or discrete). The complementary fission fragment technique is based on the observation of coincidences between the discrete γ-rays emitted by the fragments produced in this process. This technique is used frequently in the study of neutron-rich and near-stability nuclei that cannot be studied as evaporation residues in heavy-ion fusion reactions since they cannot be populated with stable beam-target combinations in such reactions. In the complementary fission fragment technique the assigning of γ-rays and high-spin states to fission fragments for which no high-spin spectroscopic information exists is achieved by establishing γ-γ coincidences between these transitions and those previously known from one or more complementary fission fragments.

The γ-ray spectroscopy of fragments from spontaneous fission sources or light-ion or neutron-induced fission of actinide targets can provide a wealth of information for high-spin states in neutron-rich nuclei. However, less information exists on high-spin excitations in nuclei near stability, or only slightly neutron rich. This information can come from heavy-ion induced Coulomb excitation, which is limited to stable species and to excitations connected to the ground state by strong matrix elements. Additional information can be obtained in some cases with deep-inelastic processes (see, for instance, Refs. [1, 2, 3]). These heavy-ion multi-nucleon transfer reactions bring significant angular momentum into the reacting nuclei, although the relative cross-sections are small (typically less than 10 mb). Frequently it is not possible to uniquely identify the isotope or even element to which the γ-ray transitions belong (see, for instance, Ref. [4]), i.e., where a level scheme is relatively easy to build, additional complementary data are needed in order to assign it to an isotope. In the special case of $(n,xn\gamma)$ reactions on stable isotopes using a pulsed "white"-neutron source, the deduced neutron excitation functions for the detected γ-rays unambiguously assign the transitions to a specific reaction product. This provides the additional complementary data needed to assign transitions to an isotope for which no previous high-spin spectroscopic information exists. Such a method has been used recently to establish high-spin states in ^{135}Xe, populated in the ^{136}Xe$(n,2n)$ reaction, at the Los Alamos Neutron Science Center facility [5]. Some of the isotopes studied with these methods are located near shell or sub-shell closures where the excitations are amenable to shell model calculations. Hence, the experimental results can be compared with predictions from shell-model calculations (for instance, in Ref. [5] the experimental results on ^{135}Xe are compared with previous calculations from Ref. [6]).

A source of additional information for several nuclei near stability, or slightly neutron rich, is achieved by studying them as fragments following fission of compound nuclei populated in heavy-ion fusion reactions. This technique is complementary to the Coulomb excitation and deep-inelastic studies and enables the study of high-spin excitations in nuclei near stability, including unstable odd-mass isotopes, as well as slightly neutron-rich species, without the limitations of the Coulomb excitation method and the difficulties present in deep-inelastic studies.

EXPERIMENTAL TECHNIQUE

Over the past decade we have studied a large number of nuclei populated as fragments following fission of compound nuclei near $A \sim 200$ formed in heavy-ion fusion reactions. Gamma-ray spectroscopy was accomplished with the Gammasphere array. Transitions were assigned to a specific nucleus by gating on the previously known transitions of a complementary fragment following the symmetric fission of the compound system (complementary fission fragment technique). Typically 3-7 neutrons are emitted as the compound nucleus undergoes fission, which competes with neutron evaporation. This is a very powerful technique because one can identify transitions in nuclei for which no previous spectroscopic information exists by gating on the known transitions of the complementary fragments and search for the same unknown transition in all gated spectra. For instance, in Ref. [7] transitions of ^{108}Rh were identified in coincidence with previously known transitions of the ^{106,107,108}Pd complementary fragments (7, 6, and 5 neutron channels) with respect to the ^{221}Pa compound nucleus formed in the

^{24}Mg + ^{197}Au fusion-evaporation reaction, and in Ref. [8] the 1808.5-keV transition was assigned to ^{83}Sr because it was observed in all gates on the $^{138,139,140}Ba$ complementary fragments (5, 4, and 3 neutron channels) with respect to the ^{226}Th compound nucleus formed in the ^{18}O + ^{208}Pb fusion-evaporation reaction.

The fission of a compound system populated in a fusion-evaporation reaction is an effective way to populate high-spin states in the fragments. For example, relative intensities of the transitions in ^{92}Zr [9] at the highest spins are about an order of magnitude more intense than relative intensities in $^{146,148}Ba$ at $16\hbar$ [10] populated as fragments from the ^{248}Cm spontaneous fission source. Moreover, the prompt γ-ray spectroscopy of fission fragments from compound nuclei in a fusion-evaporation reaction can lead to significant extensions of the previously known level schemes of the isotopes studied. For example, the level scheme of ^{94}Zr was extended from the previously known 2605-keV level up to $\sim$9 MeV excitation energy in Ref. [9] using Gammasphere data and this extension was confirmed in Ref. [11] using Euroball data.

However, obtaining experimentally spin-parity assignments from fusion of compound nuclei remains a challenge. The presently available data sets (mostly from Gammasphere experiments) usually do not have sufficient statistics to enable angular correlation measurements to deduce multipolarities. Only in the cases of prompt γ-ray spectroscopy of fragments from spontaneous fission sources can one overcome this limitation by collecting sufficiently large amounts of data (see, for instance, Ref. [12]). Such experiments can be performed during the "down-time" of accelerators, and, hence, can run for much longer periods than an average experiment. For the studies of fragments in fusion-evaporation reactions the spin-parity systematics in neighboring nuclei can play an essential role in assigning tentative J^{π} values to newly observed levels (see, for instance, Ref. [8]). However, this is not always feasible, e.g., it is difficult to assign even tentative J^{π} values to spherical nuclei based on systematics.

DISCUSSION: BRIDGING THE GAPS IN HIGH-SPIN SYSTEMATICS

The N=56 isotones especially those near the double-subshell closures at ^{94}Sr and ^{96}Zr should be amenable to shell model calculations. However, nothing was known about high-spin excitations in ^{97}Nb, with Z=41, beyond its $9/2^+$ ground state. Shell model predictions of the energy of the $13/2^+$ state differed by a factor of 2.5 [13, 14]. For the other N=56 isotones, ^{94}Sr was studied as a fission fragment in the spontaneous fission of ^{248}Cm [15]. ^{95}Y was studied as a fission fragment in the spontaneous fission of ^{248}Cm and ^{252}Cf, and in the neutron-induced fission of ^{235}U [16]. ^{96}Zr [17] and ^{98}Mo [18, 19], which are stable, have been studied in a variety of methods including Coulomb excitation and the fission fragment method following heavy-ion-induced fusion-evaporation reactions. The neutron-deficient ^{99}Tc [20] and ^{100}Ru [21] have been studied in a variety of methods including fusion-evaporation reactions.

^{97}Nb was studied following the decay of the compound nucleus in two fusion evaporation reactions: ^{24}Mg + ^{173}Yb and ^{23}Na + ^{176}Yb [22]. A level scheme up to 6.6 MeV and ($29/2^+$) was established from γ-γ coincidences, including with complementary fission fragments. The ($13/2^+$) state identified in ^{97}Nb at 1.641 MeV completes the systematics

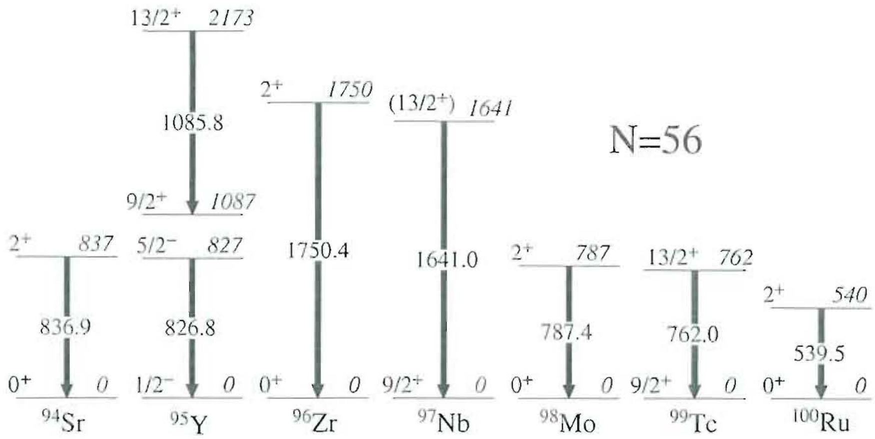

FIGURE 1. Systematics of the N=56 isotopes between Sr and Ru and high-spin excitations in ^{97}Nb [22].

of the N=56 isotones, as displayed in figure 1. Its measured energy is in agreement with the 1.5 MeV value from shell model calculations [13]. The subshell closure at N=56 (and the shell closure at Z=50) result in high energies of the $13/2^+$ states in the Nb isotopes, as displayed in figure 2. In general, the ground and $13/2^+$ states originate from the coupling of the $g_{9/2}$ orbital to the ground and 2^+ states of the corresponding $^{88-96}$Zr cores. The $13/2^+$ state in ^{99}Nb remains elusive, while the underlying structure in ^{101}Nb changes to a deformed one, with a $5/2^+$ ground state. ^{101}Nb was studied as a fission fragment in the spontaneous fission of ^{252}Cf [23]. ^{95}Nb was studied with a combination of the fission fragment method following a heavy-ion-induced fusion-evaporation reaction and the deep-inelastic method [24]. ^{93}Nb, which is stable, has been studied with a variety of methods [25] including Coulomb excitation. Finally, ^{89,91}Nb have been studied in particle pick-up and fusion-evaporation reactions [26, 27].

CONCLUSIONS

A wealth of spectroscopic information has been obtained recently from the prompt γ-ray spectroscopy of fragments following fission of compound nuclei populated in heavy-ion fusion reactions. Such studies enable the identification of high-spin excitations in nuclei near stability, measurements which are difficult to obtain with other reactions or asymmetric fission of actinides, and are extremely helpful in bridging the gap in the systematics between the neutron-deficient and neutron-rich areas. This work discussed only a small fraction of these results focusing on excitation in ^{135}Xe and ^{97}Nb. Many of these excitations are in nuclei near shell or sub-shell closures and should be amenable to shell model calculations.

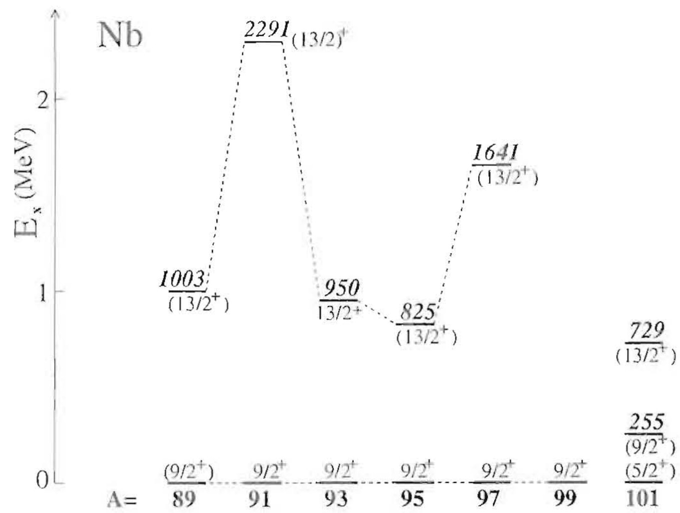

FIGURE 2. Systematics of the $13/2^+$ states in odd-mass Nb isotopes with masses A=89-101. The excitation energy of this state in ^{97}Nb was identified in the present data [22].

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