New μs isomers in $T_z=1$ nuclei produced in the ^{112}Sn(63A MeV)+ ^{nat}Ni reaction

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The short-lived isomeric states in the $T_Z=1$ nuclei, ^{94m}Pd [$T_{1/2}=0.6(1)$ μs] and ^{96m}Ag [$T_{1/2}=0.7(2)$ μs], were identified among the fragmentation products of the ^{112}Sn (63A MeV) + ^{nat}Ni (93.5 mg/cm^2) reaction at GANIL. The separation and identification of the reaction products was done by means of the Alpha and LISE3 magnetic spectrometers combined with time-of-flight, energy-loss, and total kinetic energy measurements. Evidence for isomeric states in ^{80}Y, ^{98}Cd, and ^{102}Sn was also obtained. [S0556-2813(97)03903-4]

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I. INTRODUCTION

Fragmentation of a neutron-deficient ^{112}Sn beam at intermediate energies by a ^{nat}Ni target studied by means of the magnetic spectrometers Alpha and LISE3 at GANIL has been proven to be a method to produce and identify very exotic nuclei in the ^{100}Sn region [1,2]. It was also found that the fragments can be observed in their excited μs-isomeric states due to the high isomeric ratio (typically from 30 to 50 %), characterizing such reactions [3]. The time correlation in the μs range between the implantation of the identified fragments into the Si-stack detector and the gamma radiation following the isomer decay allowed one to record the respective gamma spectra in practically background-free conditions. Therefore, even a very limited intensity of gamma signals can be used for the identification and study of new isomeric decays, see, e.g., the ^{66m}As case [3–5].

Continuation of the experiments based on the fragmentation of the ^{112}Sn beam at GANIL allowed for the identification of new isomers in the vicinity of ^{100}Sn. We already briefly reported on the data presented below in [6].

II. EXPERIMENTAL TECHNIQUE

This experiment was performed at GANIL using the ^{112}Sn beam accelerated to 63A MeV. A 93.5 mg/cm^2 thick ^{nat}Ni rotating target was placed between the SISSI superconducting solenoids [7]. A thin carbon foil (10 mg/cm^2) was backing the target in order to reduce the width of the charge state distribution of the produced ions. Fragments were transported over about 118 m by the ion-optical system of the Alpha and LISE3 spectrometers. Unwanted light products were removed from the beam using a thin (3 μm) charge-changing aluminium foil at the entrance of the LISE3 spectrometer (in the usual target position) and applying an asymmetric setting of magnetic rigidities of Alpha and LISE3 [1].

The transmitted fragments were implanted into a stack of three subsequent silicon detectors, 300 μm, 150 μm, and 500 μm thick, respectively. The first two Si detectors recorded the energy-loss signals providing redundant information on the atomic number of each transmitted fragment. The third one was a square shape strip detector consisting of 12 strips, each 2 mm wide. The strip detector was implemented in order to obtain the spatial correlation between the implanted ion and the following beta, alpha, or proton decay [8]. The sum of all energy-loss signals gave the total kinetic energy for each implanted heavy ion. The time of flight for each transmitted ion was measured in two different ways, with the standard TAC modules having the time range from 1 to 100 ns. The ''start'' signal was always a signal of the stopped heavy ion. As the ''stop'' signals served the cyclotron high frequency pulse and the signal from a position sensitive μ-channel-plate detector [9] placed in a dispersive plane of the first stage of the LISE3 spectrometer [10]. The position determined by this detector together with the measured magnetic field inside the magnets provides the event-by-event information about the magnetic rigidity ($B\rho$) for the heavy ion.

The magnetic field of the spectrometers was adjusted to transmit tin ions undergoing charge changing from 49+ to 48+ corresponding to $B\rho$ values of 1.9756 Tm for Alpha and 2.0016 Tm for LISE3. The slits in the dispersive planes of the spectrometers were set to a momentum acceptance of $\Delta p/p=1\%$ in Alpha and about 1.4% in LISE3.

The silicon stack was placed inside a stainless steel tube (thickness 0.5 mm) surrounded by gamma counters. The

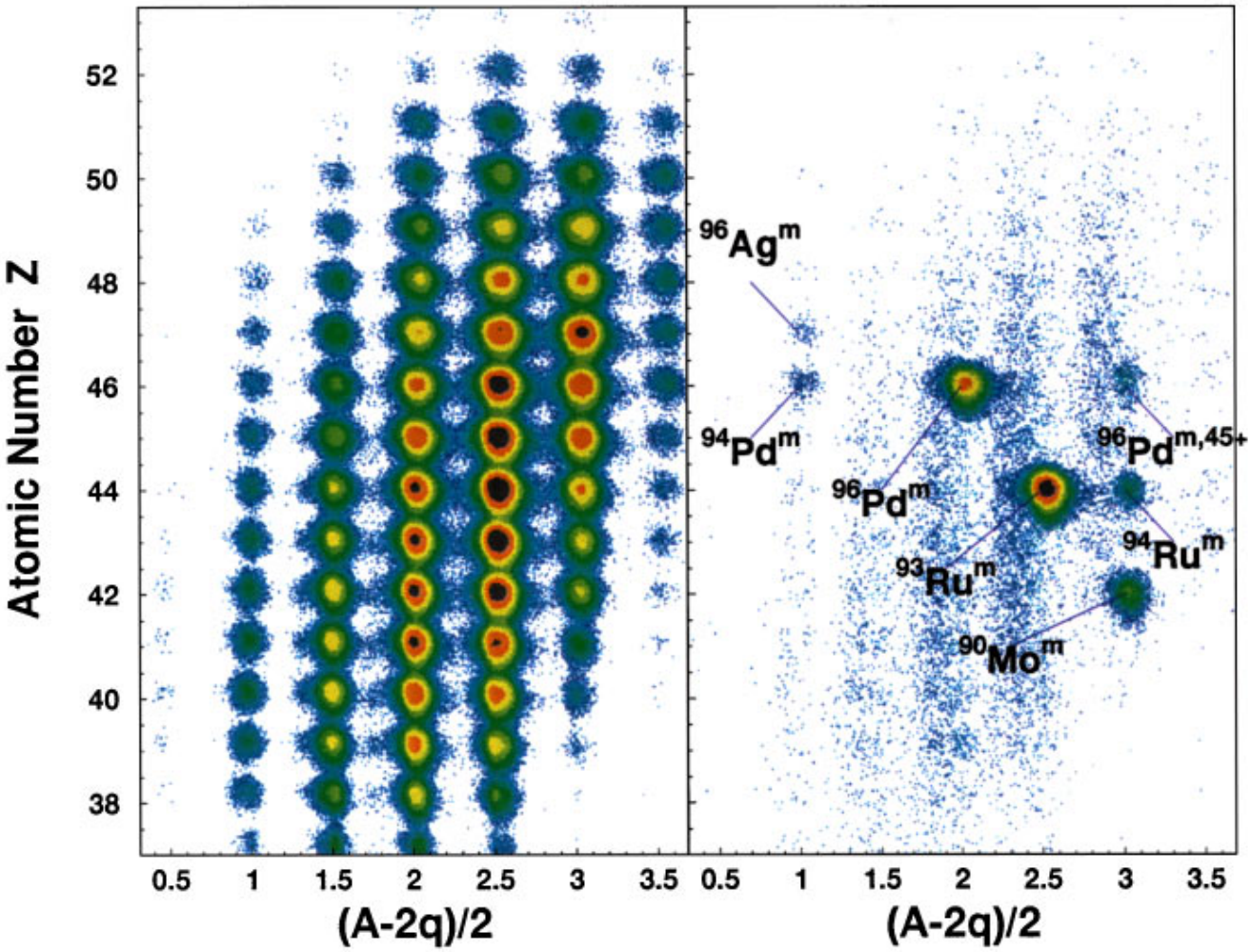

FIG. 1. Color identification plot of all nuclei observed (left panel) and those in correlation with gamma radiation (right panel). The $(A\text{-}2q)/2$ variable is equal to the T_Z of the nucleus for fully stripped ion ($q=Z$). A symbol ''^{96m}Pd^{45+}'' denotes ^{96m}Pd nuclei transmitted and detected as a hydrogen like ions.

gamma detection setup consisted of one 70% Ge detector placed behind the silicon stack in about 1 cm distance from the implantation detector (a photo-peak efficiency of about 4% at 1.33 MeV) and a segmented BGO ring around the silicon stack [1,2,11]. Since the diameter of the Ge detector (9 cm) was too large to fit inside the BGO ring, the Si stack was positioned close to the edge of the ring, reducing the solid angle for the photon detection in the BGO crystals.

The results presented below were obtained during about 64 h of irradiation with an average intensity of 1.7×10^{10} projectiles per s.

The standard DE-TOF-TKE technique was applied for the selection and identification of the fragments [1,2,12]. Observation of known μs isomers like ^{93m}Ru and ^{96m}Pd gave the independent reference for the assignment of mass (A), atomic number (Z), and charge (q) for the transmitted ions [2,3], see Fig. 1. The advantage of the μs correlation method for the study of isomers is related to the fact that the electronic signals of the implantation and of the delayed photon are recorded in the same event of the data acquisition. It is therefore possible to project a gamma spectrum coincident with selected ions and to obtain practically background-free information on the radiation following the decay of the isomeric state, as shown in Fig. 2 for the ^{96m}Pd case. By measuring the time distribution of the time intervals between the implantation and the signal from one of the photon counters within a range of the respective TAC module, one gets the information about the half-life of the observed isomer. The decay of ^{96m}Pd was used for a test of the method. An exponential one-component decay curve assuming absence of background and fitted over a time range of 2 μs, see Fig. 2, gave a result of $T_{1/2}=1.7(1)$ μs. This value is consistent with a half-life of 2.2(3) μs measured earlier with an ''in-beam'' technique [13].

III. EVIDENCE FOR NEW μS ISOMERIC STATES IN $T_Z=1$ NUCLEI

The spectra related to the observation of $T_Z=1$ nuclei produced in the studied reaction are presented in Fig. 3. All recorded $T_Z=1$ fragments [Fig. 3(a)] are compared to the ones coincident to the delayed gamma radiation within the time range of about 2.2 μs after implantation registered by the BGO detector [Fig. 3(b)]. There is already very clear evidence for the correlated decay for the ^{94}Pd and ^{96}Ag nuclei. The contributions to the background from the secondary reactions in the detector and from random counts related to the laboratory background and beta-delayed decays were es-

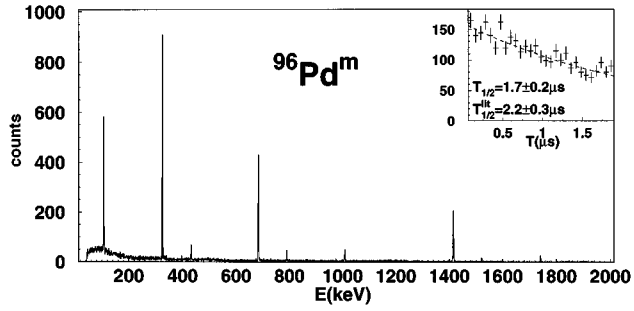

FIG. 2. The measured gamma energy spectrum for ^{96m}Pd decay and decay time spectrum with fitted exponential decay curve.

timated. This was done for a number of nuclei without a gamma-decaying isomeric state within the half-life range of 100 ns–100 μs (as known up to date). The calculation was done for the following implanted nuclei ^{90,91}Ru, ^{89,90}Tc, ^{88,89}Mo [14–17]. A factor of $6.56(7)\times10^{-3}$ was obtained, which corresponds to about one gamma event registered per 150 implanted ions. The background corrected spectrum is presented in Fig. 3(c).

The projection of the time distribution of registered gamma quanta with fitted exponential decay curve gives the half-life values of 0.6 ± 0.1 μs for ^{94m}Pd and 0.7 ± 0.2 μs for ^{96m}Ag (see Fig. 4).

The remaining [see Fig. 3(c)] Fig. 8 and 4 counts, correlated with the ^{98}Cd and ^{102}Sn ions, respectively, represent evidence for decay of isomeric states. In particular, the absence of such counts correlated with the implantation of ^{100}In ions, primarily six-times more intense than ^{102}Sn ones, gives confidence to the purity of the spectra obtained within the described procedure.

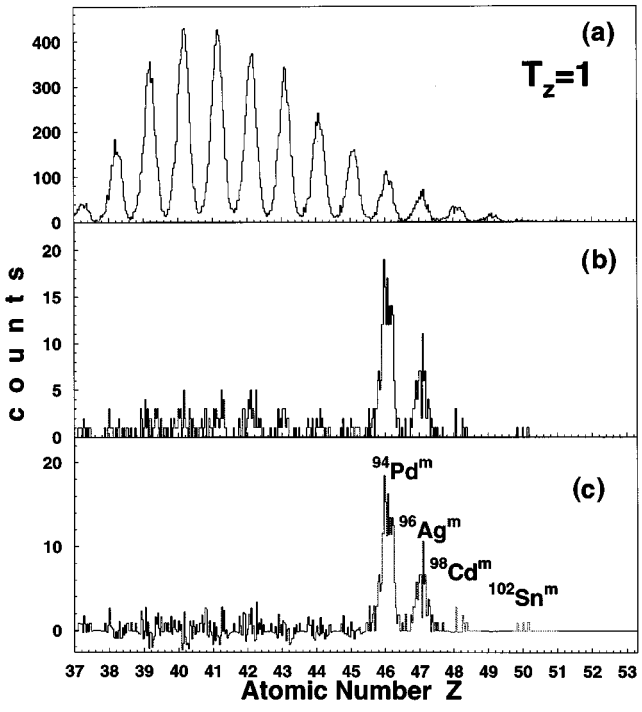

FIG. 3. Identification plots (a) all observed nuclei with $T_Z=1$, (b) selected those in coincidence with gamma radiation, (c) same as (b) but with random background subtracted.

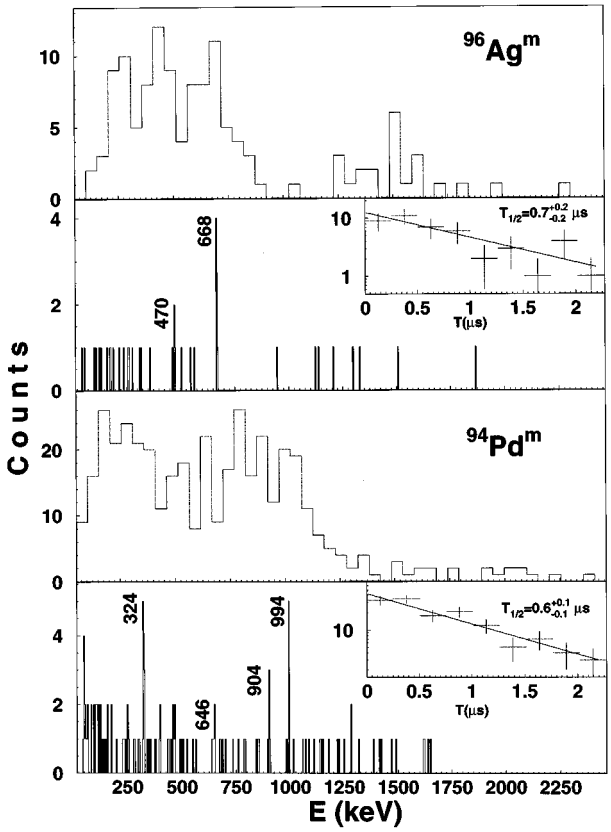

FIG. 4. Gamma radiation observed in correlation with ^{96}Ag and ^{94}Pd in BGO and germanium detectors. In the inset the time spectra for Ge events together with a fitted one-component exponential decay curve are given.

The isomeric state in ^{94}Pd was recently found also in the data recorded during an ''in-beam'' experiment [18], where the high-resolution gamma spectrum with better statistics was obtained and the half-life of $T_{1/2}=0.8(2)$ μs was determined. This isomer was interpreted as due to the 14^+ state decaying to the 0^+ ground state via a cascade of seven $E2$ gamma transitions [18].

The information about ^{96m}Ag obtained in this work is rather limited. In addition to the $T_{1/2}$ value of 0.7 ± 0.2 μs, a gamma transition of 470 and 668 keV following the isomer decay can be assigned. A measurement with much better statistics is necessary to test the shell-model predictions in the proton-neutron $(p_{1/2},g_{9/2})$ model space using an empirical interaction [19], suggesting the decay of the 15^+ or 13^- isomers followed by five or four transitions.

The few photons correlated with ^{98}Cd and ^{102}Sn ions were registered in the BGO detector which has high efficiency but low energy resolution. Those few counts may therefore give only a first experimental estimate for the half-life of the observed isomers, i.e., $T_{1/2}=0.2(+0.3,-0.17)$ μs for ^{98}Cd and $T_{1/2}=0.3(+0.5,-0.2)$ μs for ^{102}Sn. According to spherical shell-model predictions with ^{100}Sn as a core, the nature of the high-spin isomer in ^{98m}Cd is similar to the known isomers in the even-even cadmium nuclei (^{102m}Cd, ^{100m}Cd) [20] and in the $N=50$ isotones [21]. The isomer in ^{98}Cd is expected to be an 8^+ state with a pure two-proton-hole $\pi g_{9/2}^{-2}$ configuration. The estimated half-life of ^{98m}Cd is longer than for the two

heavier ones, and amounts to 0.5 μs [20]. Our observation was very recently confirmed and extended by an in-beam experiment by the PEX-NORDBALL collaboration, where ^{98m}Cd has been found and studied [22].

The interpretation for the possible existence of a relatively long-lived state in ^{102m}Sn is not as straightforward as for the ^{98m}Cd case. A shell-model calculation predicts a two-neutron-particle 6^+ state to be an isomer, however, with a much shorter half-life of 3.5 ns [20]. There is, however, an uncertainty in predicting the energy of the isomeric $6^+ \rightarrow 4^+$ transition [23,24] and in the effective $E2$ operator to be used [25], which permits the half-life to be in the order of more than 100 ns, as suggested by our data.

The observed isomeric ratio for ^{96m}Pd is estimated to be 40(10)%, which is compatible with the value measured in the previous experiment [3]. For the ^{94m}Pd and ^{96m}Ag nuclei, assuming the energy of the primary γ transition of 100 keV and multipolarity of $E2$, the isomeric ratio amounts to 30(10) and 20(10) %, correspondingly.

There is also clear evidence for an isomer in the $T_Z=1$ ^{80}Y nucleus, a single gamma line at about 80 keV detected in correlation with ^{80}Y ions. A more detailed study of the ^{80m}Y decay seems to be possible with the described method, however, the ^{80}Y production rate should be increased, e.g., by using the primary beam of ^{92}Mo or ^{106}Cd ions instead of ^{112}Sn.

The spectroscopic measurements very far from beta stability have to overcome the problems related to very low production rates. The results presented above represent the first step towards identification and study of new isomers in the region of ^{100}Sn by using a combination of fragment separator and gamma ray detectors. The use of more efficient cluster or clover Ge detectors for recording of gamma radiation together with an increase of the beam intensity should result in more complete information on the reported isomers. It will make possible the spectroscopic studies of excited states in very exotic nuclei not accessible with other methods, and may complement in the future the in-beam studies based on fusion reactions with radioactive beams.

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