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Energy levels in $^{251}_{98}$Cf populated in the α decay of $^{255}_{100}$Fm

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Gamma-ray spectra of a 20-h ^{255}Fm source containing $\sim$1 mCi activity were measured with a 25% Ge detector and a low-energy photon spectrometer (LEPS). Gamma lines with intensities as low as 1.0×10^{-6}% per ^{255}Fm α decay were observed. Gamma-gamma coincidence spectra of a ^{255}Fm sample were measured with the GAMMASPHERE array. A comparison of the γ-ray spectrum gated by the Cf K_α x-ray peak with the γ-singles spectrum provided spins of the excited states in ^{251}Cf. The γ-ray data, in conjunction with previously measured ^{250}Cf(d,p) reaction data, allowed us to characterize several single-particle and vibrational states above the $N=152$ subshell gap.

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I. INTRODUCTION

One of the important goals of nuclear research has been the search for superheavy elements and the understanding of their structure and stability. Spectacular progress has been achieved with the recent syntheses of elements $Z=112$, 114, and 118 [1–5]. The half-lives of these nuclei are largely determined by the single-particle orbitals near the Fermi surface. Theoretical calculations involving single-particle states have been carried out [6–8] to explain the observed properties of these nuclei. One way to gain some insight into the structure of superheavy nuclei is to characterize the single-particle valence orbitals in these nuclei by measuring their decay properties. However, the production of only a few atoms precludes such measurements. Another approach to exploring these orbitals is the study of the excited states in the heaviest nuclides available in larger quantities. The nuclide with the largest number of neutrons produced in microCurie quantity is ^{255}Fm, which decays by α-particle emission with a half-life of 20.1 h. Its decay scheme has been studied previously by γ-ray spectroscopy [9] with Ge spectrometers and α spectroscopy [10] with a magnetic spectrometer. In addition, ^{250}Cf(d,p) reaction spectra were measured with high-resolution [11]. The particle states $1/2^+[620]$, $7/2^+[613]$, $3/2^+[622]$, and $11/2^-[725]$ in ^{251}Cf were identified both in the decay scheme [9] and in the (d,p) reaction spectrum [11]. The $1/2^-[750]$ and $9/2^+[615]$ orbitals were observed in reaction spectra only [11].

In Ref. [9], ^{255}Fm γ-ray spectra were measured with a small Ge(Li) detector and the source strength was only $\sim$25 μCi. The recent use of high-efficiency Compton-suppressed Ge detectors in large arrays and the availability of an order of magnitude more ^{255}Fm activity prompted us to reexamine the decay scheme of ^{255}Fm. Preliminary results of this study have been reported elsewhere [12]. The present article describes the results of this investigation in more detail. We have confirmed the previous single-particle assignments and have identifed octupole and pair vibrational bands built on the $7/2^+[613]$ single-particle state in ^{251}Cf.

II. EXPERIMENTAL METHODS AND RESULTS

The nuclide ^{255}Fm, which is the daughter product of the 38.3-*d* ^{255}Es nucleus, was separated from $\sim$1 mg of Es (isotopic composition 99.5% ^{253}Es, $\sim$0.4% ^{254}Es, $\sim$0.04% ^{255}Es) produced in the high-flux isotope reactor (HFIR) at Oak Ridge National Laboratory. The chemically purified samples of Fm, $\sim$2 mCi each, were shipped to Argonne National Laboratory in three different weeks. The first two samples were used for the measurement of γ-singles spectra with a 25% Ge detector and a 2 cm$^2\times$10-mm low-energy photon spectrometer (LEPS) system. Each spectrum was measured for 17 h and its decay was followed for only three half-lives because after that time the decrease in the peak heights made identification of weak transitions difficult. The three spectra gave half-lives for the peaks which were used for the identification of ^{255}Fm γ rays. Gamma rays with intensities as low as 1.0×10^{-6}% per ^{255}Fm α decay were identified. We observed all γ rays reported in the previous work [9] and many new transitions. The γ rays below $\sim$570 keV observed in the present work can be placed in the level scheme established in earlier studies. A portion of the γ-ray spectrum showing new γ rays in the range of $\sim$570– $\sim$1120 keV is displayed in Fig. 1(b). The strong γ rays with the energies 774.0, 836.1 and 870.9 keV decayed with a half-life of 22.5 ± 0.5 h which is longer than the half-life of ^{255}Fm. This, as well as the fact that these γ rays are not in coincidence with Cf *K* x rays, strongly suggests that these γ rays belong to a fission product.

In order to place the γ rays observed in the singles spectrum in a level scheme, a γ-γ coincidence measurement was performed with the GAMMASPHERE array [13] which consisted of 101 Compton-suppressed Ge detectors. Most of the levels in ^{251}Cf populated by α decay deexcite to the ground state band or to the $7/2^+[613]$ band at 106.3 keV which decays by highly converted low-energy transitions and, hence, there are very few γ-γ coincidences. For this reason, only twofold coincidence events were collected. Coincidence relationships deduced from the data confirmed the previous

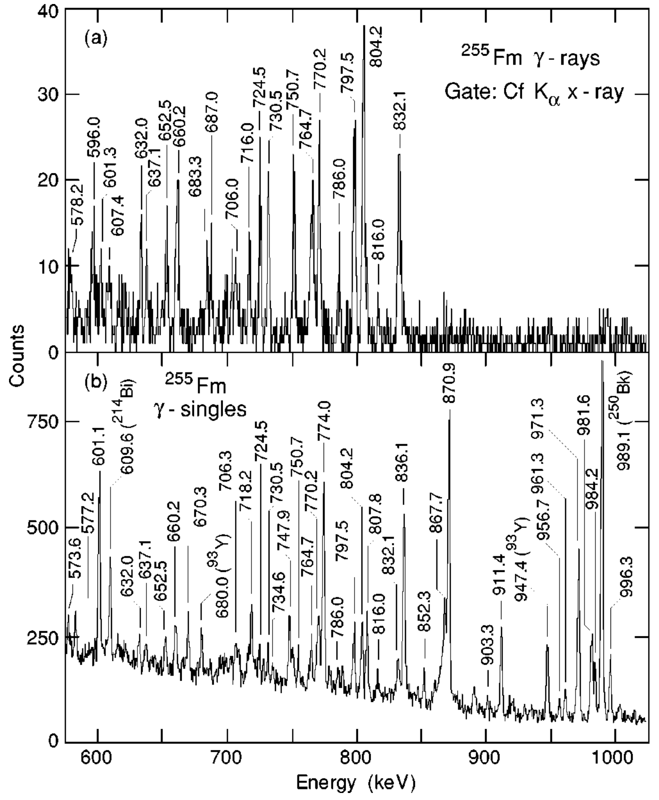

FIG. 1. (a) ^{255}Fm γ-ray spectrum measured with the GAMMASPHERE array and gated by Cf $K\alpha_1$ peak. (b) γ-singles spectrum of a 1 mCi ^{255}Fm source measured with a 25% Ge detector. The sensitivity of the measurement can be judged from the counts in the 632.0-keV peak which has an intensity of $\sim 2.0 \times 10^{-6}\%$ per ^{255}Fm α decay.

assignments of the low-lying levels of ^{251}Cf. Gamma rays connecting to the ground band and the $7/2^+[613]$ band have no γ ray in coincidence. In contrast, the γ rays deexciting to the $3/2^+[622]$ band at 177.6 keV have Cf K x rays in coincidence because this band decays by $M1$ transitions with large K conversion coefficients. The γ-ray spectrum gated by the Cf $K\alpha_1$ peak is shown in Fig. 1(a). The two spectra in Fig. 1 clearly distinguish the γ rays which decay to the $3/2^+[622]$ band from those decaying to the ground and the $7/2^+[613]$ bands.

III. DISCUSSION

Results of the ^{250}Cf(d,p) reaction experiment have been discussed in Ref. [11]. In Fig. 2 we display the portion of the (d,p) spectrum relevant to the levels discussed in this article. The γ rays from the deexcitation of some of the levels identified in Fig. 2 are shown in Fig. 1. In Ref. [11] the 600-626-, 633-, 683-, and 708-keV levels were assigned to the 3/2, 7/2, 1/2, 11/2, and 5/2 members of the $1/2^-[750]$ band on the basis of the expected cross sections. The transitions resulting from the decay of the 600.8-, 625.7-, 632.0-, and 708.0-keV levels are shown in the partial level scheme of Fig. 3. No transitions were observed from the decay of the 683-keV level because of its expected low alpha intensity. The level spins and parity deduced from the γ decay are consistent with the previous assignments. Alpha intensities to these levels are not shown because it is difficult to determine the feeding to these levels. The outgoing γ-ray intensities indicate a maximum of $\sim 5\times 10^{-6}\%$ α intensity for each level.

A partial level scheme constructed on the basis of the present work and previous studies is displayed in Fig. 4. The hindrance factors, shown on the right side of the levels, are defined as the ratio of the experimental partial half-life to the value calculated with the spin-independent theory of Preston [14]. Since $M1$ and $E1$ transitions dominate the interband deexcitations, excited bands with $K=1/2$ and 3/2 will decay to the ground band and the $3/2^+[622]$ band at 177.6 keV. Rotational bands with $K\geqslant 7/2$ will decay to the $7/2^+[613]$ band at 106.3 keV. Transitions observed in coincidence with Cf K x rays were, therefore, interpreted as deexcitation of levels to the members of the $3/2^+$ band at 177.6 keV and provided the energies of the excited states. These energies were further confirmed by the placement of γ rays between

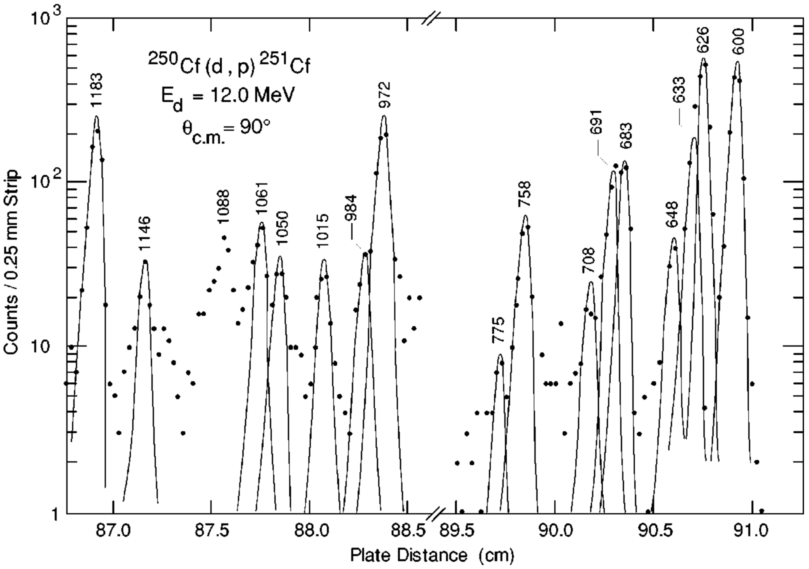

FIG. 2. A ^{250}Cf(d,p) spectrum measured with an Enge split-pole magnetic spectrometer. See Ref. [11] for detail.

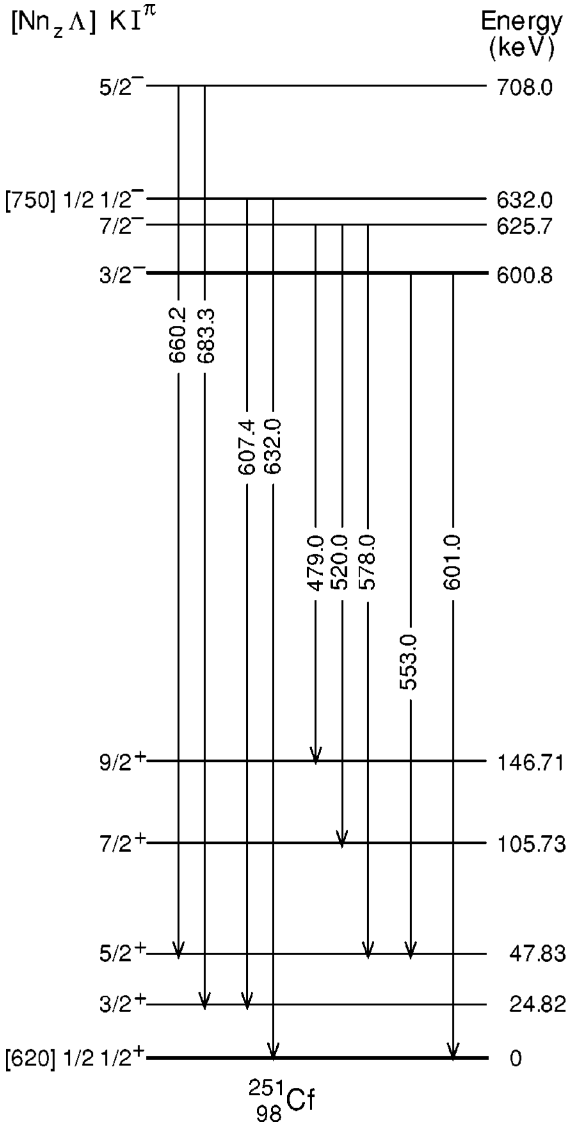

FIG. 3. A partial level diagram showing the decay of the 1/2$^-$[750] band previously identified in the ^{250}Cf(d,p) reaction [11]. Alpha intensities are not shown because of the γ-ray feeding uncertainties to these levels.

the excited states and the members of the ground band.

The decay pattern of the levels fixes their spins to within one unit of angular momentum. The single-particle assignments of these levels were made on the basis of the (d,p) reaction cross sections, the α-decay rates, and the calculated level energies [15,16]. In the (d,p) reaction, large cross sections are associated with particle states because of large values of u^2, the probabilty that the level is not occupied by a pair of neutrons. The large cross section to the 972-keV level (Fig. 2) clearly indicates that it is a particle state. The decay of this level to the members of the 7/2$^+$[613] band restricts its spin to 7/2, 9/2, or 11/2. Of the available single-particle levels with these spins in ^{251}Cf at this excitation energy, only 9/2$^+$[604] is expected to have a large cross section because of its large c_j^2, where c_j is the expansion coefficient of the wave function in terms of spherical basis. We, therefore, conclude that the 974.0-keV level has a substantial component of the 9/2$^+$[604] orbital.

We have calculated the cross section to the 9/2$^+$ level with the DWBA code DWUCK4 [17] using the potential parameters listed in previous studies [18]. By normalizing to the cross section of the well characterized 9/2$^+$ level at 166 keV, and using values of c_j^2 from Ref. [11] and values of u^2 from Ref. [19], we calculate the cross section for the 9/2$^+$[604] state. The measured cross section is only 60% of the theoretical cross section. Although theoretical calculations typically do not reproduce cross sections exactly, the lower cross section suggests that the state is not of pure single-particle character. Calculations of intrinsic states involving phonon degrees of freedom indicate that most states in ^{251}Cf with excitation energies of $\sim$1 MeV are only $\sim$50% pure [20,21]. The decrease in cross section and excitation energy from the predicted values could be due to vibrational phonon mixing in the state. It should be pointed out that without the knowledge of the spin deduced from the γ-decay data, it would be difficult to decide whether the 9/2$^+$[604] level is at 972 keV (as assigned in this work) or at 1183 keV (Fig. 2), both of which have almost equal cross section. In Ref. [11], the 9/2$^+$[604] orbital was assigned to the 1183-keV state because of the better agreement with the theoretical prediction of its energy [15,16].

The alpha-decay hindrance factor is also consistent with the assignment. The α-decay hindrance factors between states having their intrinsic spins parallel are between 10 and 100. Also the particle states have additional hindrance relative to the hole states because of the lower values of v^2, the pair occupation probability, of that state in the parent nucleus. Thus the hindrance factor of 500 for the 974-keV level is reasonable for the 9/2$^+$[604] state.

The 981.6-, 1009.1-, and 1044.1-keV levels fit as members of a $K=3/2$ band. We observe transitions from the 1/2$^-$[750] band in coincidence with Cf K x rays [Fig. 1(a)]. This indicates the presence of K-converted transitions from higher lying states to the members of the 1/2$^-$[750] band. In the γ-γ coincidence spectrum gated by the 632.0-keV peak, we identified a 349.6-keV γ ray and Cf K x rays (Fig. 5). The ratio of the K x-ray intensity to that of the 349.6-keV γ ray was found to be $\sim$1, which indicates $M1$ multipolarity for the 349.6-keV transition. This clearly demonstrates that the 3/2 level decays to the 1/2$^-$ level by an $M1$ transition and, hence, the 3/2 level should have negative parity. A coincidence gate on the 553-keV peak produced 381.0- and 408.2-keV γ rays and the gate on the 660.2-keV peak produced a 301.0-keV γ ray. These coincidence relationships are shown in Figs. 3 and 4. The 3/2$^-$ state at 981.6 keV could be the single-particle state 3/2$^-$[752]. However, the smaller than calculated cross sections measured for the members of the 981.6-keV band and the small α-decay hindrance factors rule out this assignment. We interpret this band as a vibrational state with the configuration 7/2$^+$[613]$\times 2^-$. The $K^\pi=2^-$ octupole band is known to lie at 870 keV in ^{250}Cf [22].

The deexcitation of the 1077.6-keV level to the members of the 7/2$^+$[613] band restricts its spin to 7/2 or 9/2. The low

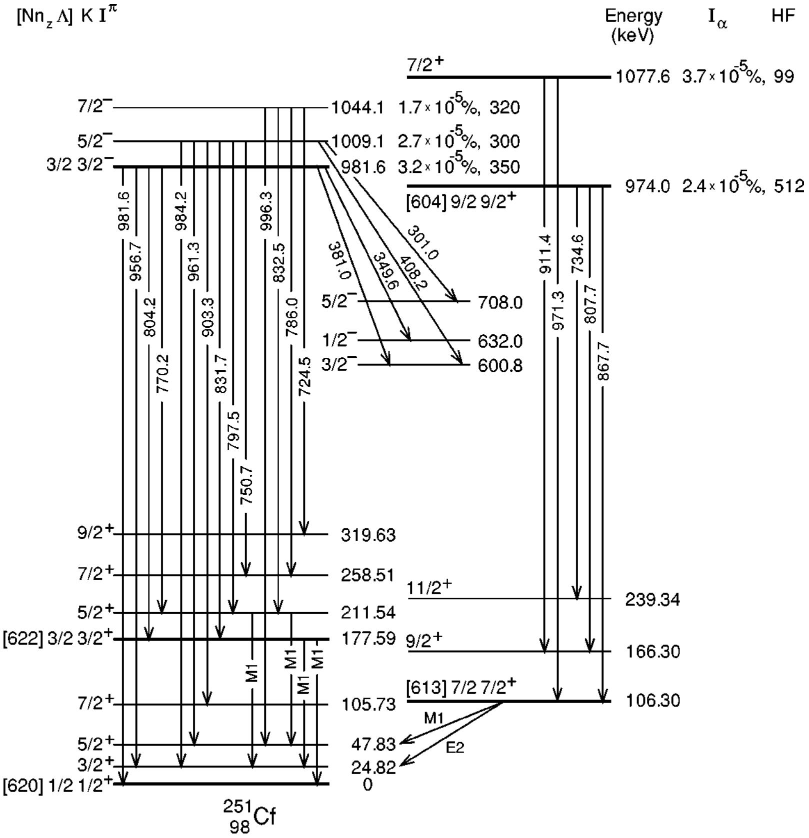

FIG. 4. A partial level scheme showing the decay of excited bands in ^{251}Cf. Excited bands at 974.0, 981.6, and 1077.6 keV have been identified in the present work for the first time. The 981.6- and 1077.6-keV bands are interpreted as the 7/2$^+$[613] state coupled to the 2$^-$ octupole and 0$^+$ pair vibrations, respectively. The decay of the 1/2$^-$ band at 632.0 keV is shown in Fig. 3. The hindrance factors shown on the right side of levels were calculated with the spin-independent theory of Preston [14].

hindrance factor suggests that this might be a pairing vibration built on the state 7/2$^+$[613]. In ^{250}Cf there is a 0$^+$ excitation at 1.15 MeV [23]. If this interpretation is correct, we might expect a 9/2$^+$ state at roughly 1.6 MeV which is a pairing vibration built on the 9/2$^+$[615] state. An admixture of such a state with the 9/2$^+$[604] single-particle state would account for the observed lowering of the 9/2$^+$ energy relative to the theoretical single-particle energy and the smaller than expected cross section in the (*d,p*) reaction (see discussion above).

The excited states that we have identified in ^{251}Cf are displayed in Fig. 6 and compared with the calculation [15] of single-particle states with a Woods-Saxon potential. The extracted energies represent the experimental single-particle

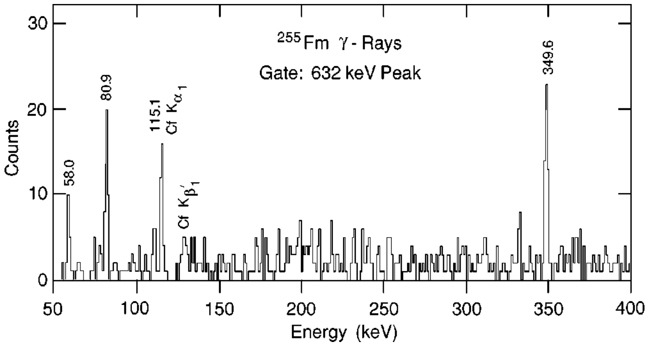

FIG. 5. γ-ray spectrum of a ^{255}Fm sample measured with the GAMMASPHERE array and gated on the 632.0-keV photopeak. The intensity of the 349.6-keV γ ray is $\sim 1.0 \times 10^{-6}$% per ^{255}Fm α decay.

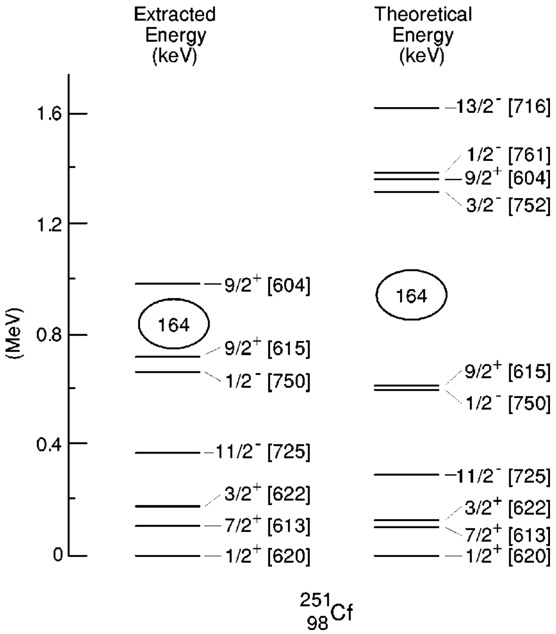

FIG. 6. A comparison of the experimental and theoretical energies of single-particle states above the subshell at $N = 152$. Experimental energies are taken from Refs. [9–11] and the present work. The extracted energy represents single-particle energy corrected for pairing. The experimental energy of the 9/2$^+$[604] state is lower than the calculated energy because this state is not of pure single-particle character.

energies and were obtained from the measured energies by removing contributions from pairing [15]. Our study shows that excited states up to $\sim$1 MeV can be observed in α-decay measurements of short-lived nuclides and their spins and parities can be deduced from γ-ray spectroscopy. However, for such states it is difficult to make single-particle assignments because of the mixing between various configurations, particularly with phonon excitations. It also points out the need for spectroscopic studies of even heavier nuclides for characterization of single-particle states beyond the 164 gap. We note that known nuclei through $Z=112$ have 165 or fewer neutrons.

In summary, γ-ray spectroscopy of ^{255}Fm samples has enabled us to confirm the previous assignment of the 632.0-keV band in ^{251}Cf to the $1/2^{-}[750]$ single-paticle configuration. In addition, octupole and pair vibrations built on the $7/2^{+}[613]$ state were also identified. A $9/2^{+}$ state was identified at 974.0 keV which was interpreted as a mixture of the $9/2^{+}[604]$ single-particle state and the pair vibration built on the $9/2^{+}[615]$ state. The identification of γ rays with intensities of $\sim 1.0\times 10^{-6}$% per α decay clearly demonstrates the sensitivity and power of the GAMMASPHERE array.

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