Phys. Scr. **T125** (2006) 78–81 doi:10.1088/0031-8949/2006/T125/017

Identification of Nilsson states in transcurium nuclei

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Received 15 July 2005
Accepted for publication 1 September 2005
Published 28 June 2006
Online at stacks.iop.org/PhysScr/T125/78

Abstract
In recent years, we have studied the structure of transcurium nuclei using the best available actinide sources and state-of-the-art instruments. These include the largest amount of high-purity samples produced in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory and the GAMMASPHERE spectrometer located at Argonne. Proton single-particle states in ^{249}Bk were investigated by measuring the γ-ray spectra of an extremely pure ^{253}Es sample and reactor-produced ^{249}Cm sources. Neutron single-particle states were identified in ^{251}Cf by measuring γ-ray spectra of ^{255}Fm sources and a cyclotron-produced ^{251}Es source. By combining the results of these measurements with the results of one-nucleon transfer reactions, we were able to identify almost all the single-particle states up to 1 MeV excitation in ^{249}Bk and ^{251}Cf. The level energies in these nuclei are in good agreement with energies calculated with a Woods–Saxon potential and pairing interactions.

PACS numbers: 21.10.Pc, 25.45.Hi, 27.90.+b

1. Introduction

In order to test theoretical models which predict gaps in proton and neutron single-particle spectra of superheavy nuclei, experimental energies of single-particle states in the heaviest nuclei are needed. The nuclides $^{253}_{99}$Es ($t_{1/2} =$ 20.47 d) and $^{255}_{100}$Fm ($t_{1/2} = 20.07$ h) are the heaviest odd-proton and odd-neutron nuclides which are available in milliCurie quantities, sufficient for detailed spectroscopy. These nuclides are produced in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. Three samples of ^{253}Es and five ^{255}Fm samples, produced in different irradiation cycles, were obtained from Oak Ridge National Laboratory for spectroscopic studies.

The level structure of $^{249}_{97}$Bk has recently been studied by measuring the γ rays associated with the α decay of ^{253}Es and β^- decay of $^{249}_{96}$Cm ($t_{1/2} = 65.3$ min) [1]. Neutron states in $^{251}_{98}$ Cf were investigated by measuring the γ-ray spectra of ^{255}Fm sources and γ-ray and electron spectra of cyclotron-produced ^{251}Es ($t_{1/2} = 30$ h) [2, 3]. Several single-particle and vibrational states in these nuclei were identified.

2. Experimental methods and results

2.1. ^{253}Es α decay and ^{249}Cm β^- decay

Gamma-ray singles spectra of the three ^{253}Es samples and several ^{249}Cm sources were measured with Ge detectors. The low-energy γ-ray spectra were measured with a $2\,\text{cm}^2 \times 10$ mm low-energy photon spectrometer (LEPS). The LEPS detector had better resolution than the larger Ge detector and was helpful in resolving close-lying gamma lines. The high-energy portion of the ^{253}Es spectrum was measured with a 25% Ge detector and it is displayed in figure 1. The energies of γ rays were measured using internal standards, i.e., the spectra of ^{253}Es and calibration sources were measured simultaneously. Absolute γ-ray intensities were determined by measuring the α-particle rate of a thin ^{253}Es source with an Si detector of known solid angle and its γ-ray spectrum with a Ge spectrometer whose efficiency was determined with a calibrated source.

In order to obtain further information on coincidence relationships of weak γ rays, a 6-day long γ–γ coincidence measurement was performed at Argonne National Laboratory.

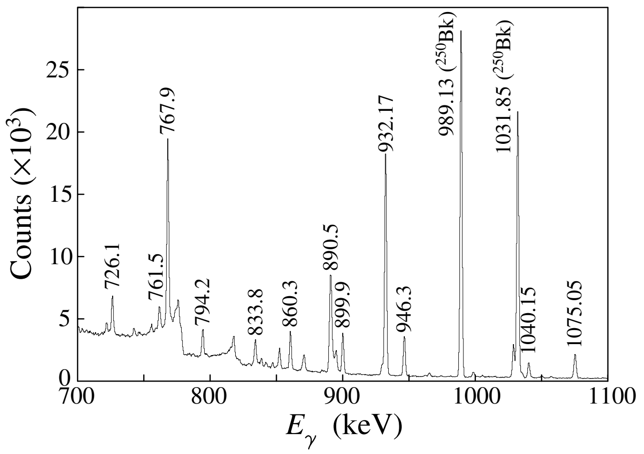

Figure 1. High-energy portion of the ^{253}Es γ-ray spectrum measured with a 25% Ge detector. The source strength was ∼4 mCi.

A ∼16 mCi ^{253}Es source was placed in the centre of the GAMMASPHERE spectrometer [4] that comprised 99 Compton-suppressed Ge detectors for this experiment. The data were sorted off-line into two-dimensional γ–γ coincidence matrices and γ-ray spectra were generated by placing gates on various γ-ray peaks. An example of a coincidence spectrum is shown in figure 2. The sensitivity of GAMMASPHERE was sufficient to identify γ rays with intensity as low as 1.0×10^{-6}% per ^{253}Es α decay in the gated spectra.

2.2. ^{255}Fm α ^{251}Es EC decay

Gamma-singles spectra of ^{255}Fm and ^{251}Es sources were measured with Ge detectors and analysed in the same way as the ^{253}Es spectra. Gamma–gamma coincidence measurements were performed with the GAMMASPHERE array at Argonne and analysed in the same way as the ^{253}Es coincidence data. Conversion-electron spectrum of a mass-separated ^{251}Es source was measured with a cooled Si(Li) detector which provided the conversion coefficients of low-energy transitions in ^{251}Cf. A gamma-ray spectrum measured with a 25% Ge detector is displayed in figure 3.

3. Discussion

3.1. Levels in ^{249}Bk

Energies of most of the levels in ^{249}Bk below 700 keV were directly obtained from high-resolution α-particle spectra [5]. The spins of high-lying levels were deduced from the deexcitation patterns of these levels to the members of lower rotational bands. The arguments for the single-particle assignments have been discussed in detail in [1].

The ground-state spin of ^{249}Bk has been measured [6] to be 7/2. The measured magnetic moment [6] of the ^{249}Bk ground state agrees with the value calculated for the 7/2$^+$[633] configuration [7]. Its rotational members up to $I = 17/2$ were identified in [1].

The ground state of ^{249}Cm has been assigned to the 1/2$^+$[620] Nilsson state [8] from the neutron-capture studies [9] and the ^{248}Cm(d,p) reaction cross-sections [10]. In ^{249}Bk, the only levels expected to receive measurable β^- population are those with spin 1/2 and 3/2 because $\Delta I = 0$ or 1 transitions are strongly favoured. These low-spin levels are easily identified in an analysis of the ^{249}Cm γ-ray spectrum.

The levels at 377.55, 569.20 and 643.0 keV were populated in the β^- decay of ^{249}Cm and hence have low

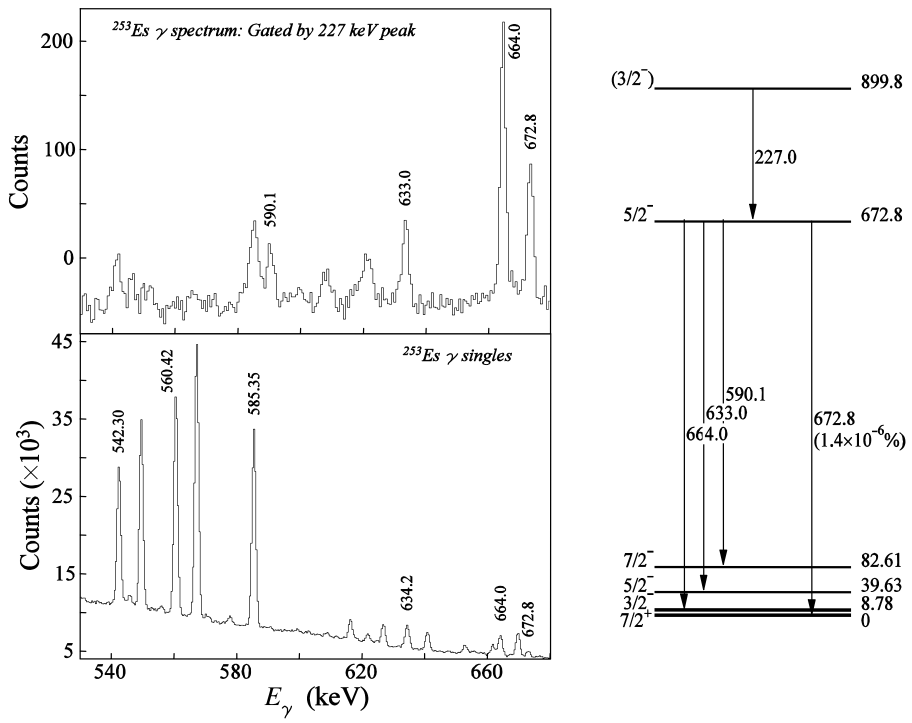

Figure 2. γ-Ray spectrum measured with GAMMASPHERE in coincidence with the 227.0 keV γ ray. A γ singles spectrum is also included for comparison. On the right-hand side, a partial level scheme containing the gate and coincident transitions is shown. The intensity of the 672.8 keV γ ray is 1.4×10^{-6}% per ^{253}Es α decay.

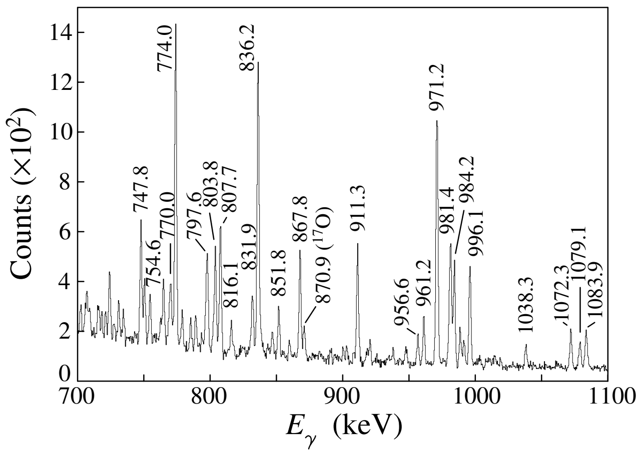

Figure 3. High-energy portion of the ^{255}Fm γ-ray spectrum measured with a 25% Ge detector. The source strength was ~1 mCi.

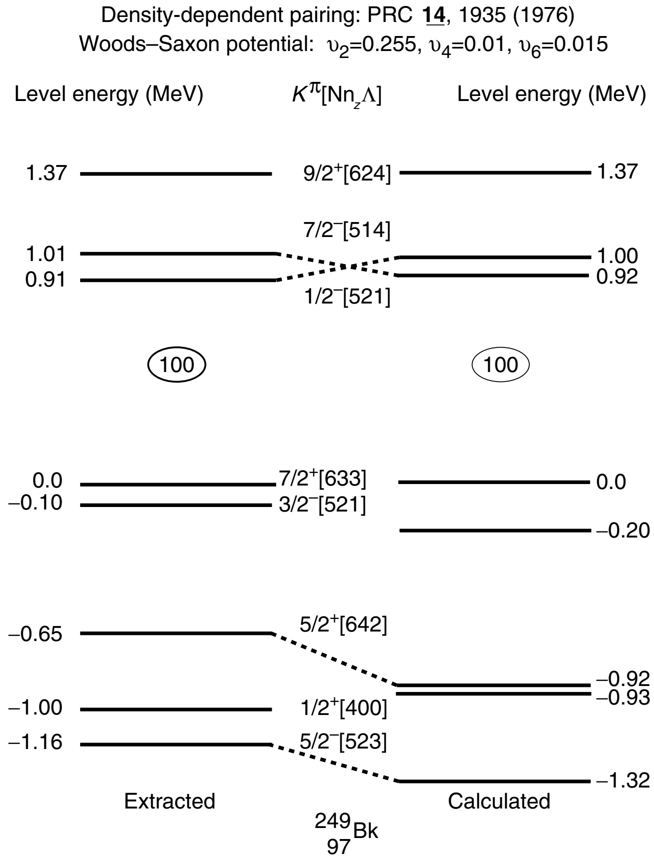

Figure 4. Comparison of extracted level energies of ^{249}Bk with the energies calculated with a Woods–Saxon potential.

spins. These states were assigned to the $1/2^+[400]$, $1/2^-[530]$ and $1/2^-[521]$ Nilsson states, respectively. The levels at 8.78, 389.17, 672.9 and 1075.1 keV were populated in the α decay of ^{253}Es and γ rays deexciting these levels were observed. These states were given assignments of $3/2^-[521]$, $5/2^+[642]$, $5/2^-[523]$ and $9/2^+[624]$, respectively. The single-particle states $7/2^+[633]$, $3/2^-[521]$, $1/2^-[530]$, $7/2^-[514]$ and $9/2^+[624]$ were also populated in the ^{248}Cm(α,t) reaction [11].

In figure 4, the extracted single-particle energies are compared with calculated energies [1]. The extracted energies were obtained by removing the contributions of the pairing

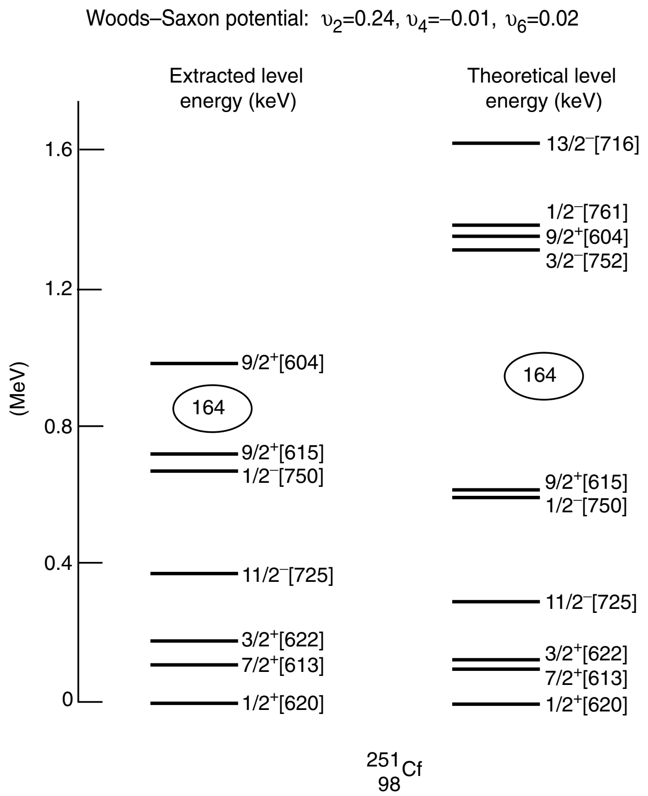

Figure 5. Comparison of extracted level energies of ^{251}Cf with the energies calculated with a Woods–Saxon potential. Only particle states are shown. Hole states, identified in ^{247}Cm, are compared with theory in [16].

interactions from the measured level energies. The calculated energies were determined from a Woods–Saxon potential. The position of the $7/2^+[633]$ level is taken as the zero of the energy scale. With the exception of the $5/2^+[642]$ level, the agreement between the extracted spacings and the Woods–Saxon level spacings is extremely good.

Energies of single-particle states in ^{249}Bk were also calculated by Gareev *et al* [12] using a quasi-particle–phonon interaction. Recently, proton one-quasi-particle energies were calculated by Parkhomenko and Sobiczewski [13] using the macroscopic–microscopic method without correcting for blocking effects.

3.2. Levels in ^{251}Cf

Energies of most of the levels in ^{251}Cf were obtained directly from the ^{255}Fm α spectrum [5] and the ^{250}Cf(d,p) reaction data [14]. However, more precise level energies were obtained from the γ-ray energies. Alpha–gamma coincidence data [15] show γ rays deexciting levels populated in the α decay. Also, multipolarities of most of the low-energy transitions were determined by the measurement of subshell ratios and conversion coefficients [15]. The γ–γ coincidence measurement with GAMMASPHERE, described in [2], was extremely useful in the identification of several rotational bands.

The ground state of ^{251}Cf is established as $1/2^+[620]$ on the basis of its α decay [16] to ^{247}Cm. Additional confirmation comes from the excellent agreement of the decoupling parameter, a, deduced from the observed level energies [15] with that calculated with the single-particle wavefunction [7]. Rotational members up to spin 13/2 were identified.

A $3/2^+$ spin-parity for the 177.59 keV level is established from the M1 multipolarity of transitions to the $1/2^+$, $3/2^+$ and $5/2^+$ members of the ground-state band. This level is given $3/2^+[622]$ Nilsson state assignment [8] and its rotational members up to $I = 11/2$ have been identified.

The levels at 106.30, 370.47, 433.91, 543.98, 632.0 and 974.0 keV were populated in the α decay of ^{255}Fm and γ rays from the decay of these levels were measured. On the basis of their decay pattern, these states were given the assignments of $7/2^+[613]$, $11/2^-[725]$, $9/2^-[734]$, $5/2^+[622]$, $1/2^-[750]$ and $9/2^+[604]$ Nilsson states, respectively, [2, 15]. The $1/2^+[620]$, $7/2^+[613]$, $3/2^+[622]$, $5/2^+[622]$, $1/2^-[750]$, $9/2^+[615]$ and $9/2^+[604]$ bands were also observed in the ^{250}Cf(d,p) spectrum [14]. Experimental energies are compared with theoretical values in figure 5 [2].

Acknowledgments

This work was supported by the US Department of Energy, Office of Nuclear Physics, under contract no W-31-109-ENG-38. The author is indebted for the use of ^{248}Cm, ^{253}Es and ^{255}Fm to the Office of Basic Energy Sciences, US Department of Energy, through the transplutonium element production facilities at Oak Ridge National Laboratory.

References

[1] Ahmad I *et al* 2005 *Phys. Rev.* C **71** 054305
[2] Ahmad I *et al* 2000 *Phys. Rev.* C **62** 064302
[3] Ahmad I *et al* 2005 *Phys. Rev.* C **72** 054308
[4] Lee I Y 1990 *Nucl. Phys.* A **520** 641c
[5] Ahmad I and Milsted J 1975 *Nucl. Phys.* A **239** 1
[6] Boatner L A, Reynolds R W, Finch C B and Abraham M M 1972 *Phys. Lett.* A **42** 93
[7] Chasman R R, Ahmad I, Friedman A M and Erskine J R 1977 *Rev. Mod. Phys.* **49** 833
[8] Nilsson S G 1955 *K. Dan. Vidensk. Selsk. Mat.-Fys. Medd.* **29** 16
[9] Hoff R W, Davidson W F, Warner D D, Börner H G and von Egidy T 1982 *Phys. Rev.* C **25** 2232
[10] Braid T H, Chasman R R, Erskine J R and Friedman A M 1971 *Phys. Rev.* C **4** 247
[11] Erskine J R, Kyle G, Chasman R R and Friedman A M 1975 *Phys. Rev.* C **11** 561
[12] Gareev F A, Ivanova S P, Malov L A and Soloviev V G 1971 *Nucl. Phys.* A **171** 134
[13] Parkhomenko A and Sobiczewski A 2004 *Acta Phys. Pol.* B **35** 2447
[14] Ahmad I, Chasman R R, Friedman A M and Yates S W 1990 *Phys. Lett.* B **251** 338
[15] Ahmad I *et al* 1971 *Phys. Rev.* C **1** 390
[16] Ahmad I *et al* 2003 *Phys. Rev.* C **68** 044306