Proton states in ^{247}Bk excited by ^{246}Cm(α,t) reaction and ^{247}Cf (electron capture) and ^{251}Es (α) decays

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Proton states in ^{247}Bk have been investigated by measuring the γ rays and conversion electrons associated with the electron capture decay of the 3.11-h ^{247}Cf, ^{251}Es α spectrum, and triton spectrum produced in the ^{246}Cm(α,t)^{247}Bk reaction. The γ-ray spectra were measured with a 25-cm^3 coaxial Ge(Li) diode and the electron spectrum was measured with a cooled Si(Li) spectrometer. Multipolarities of the intense transitions in ^{247}Bk were deduced and the logft values were derived from measured electron capture intensities. Triton spectra from the ^{246}Cm(α,t) reaction at bombarding energies of 28.0 and 29.0 MeV were momentum analyzed with an Enge split-pole magnetic spectrograph. Spectroscopic factors were derived from the measured cross sections and were found to be in good agreement with respective values calculated with single-particle wave functions. The ^{251}Es α spectrum was measured with the Argonne double-focussing magnetic spectrometer; five α groups were observed. On the basis of the results of the present investigation the following proton orbitals were identified in ^{247}Bk: 3/2 − [521], 0; 7/2 + [633], 40.8; 5/2 + [642], 334.9; 5/2 − [523], 447.8; 1/2 + [400], 487; 1/2 − [521], 704; I = 9/2,7/2 − [514], 904; and I = 13/2,9/2 + [624], 1166 keV.

RADIOACTIVITY ^{247}Cf [from ^{246}Cm (α, 3n)]; measured E_γ, I_γ, E_{ce}, I_{ce}, ^{251}Es [from ^{249}Cf (α, 2n), ^{251}Fm$\xrightarrow{EC}{}^{251}$Es]; measured E_α, I_α; deduced hindrance factors.

NUCLEAR REACTIONS ^{246}Cm(α, t), E = 28.0, 29.0 MeV; measured E (excitation), σ. ^{247}Bk deduced levels, logft (EC), γ multipolarity, I, π, eight single-particle states. Mass-separated ^{247}Cf, ^{251}Es, and ^{246}Cm.

I. INTRODUCTION

Information about proton orbitals in high-Z elements is needed for a better understanding of the single-particle potential and also to make a reasonable extrapolation about the stability of superheavy elements. Only two nuclides with $Z > 95$, ^{249}Bk and ^{251}Es, have been studied[1,2] in detail. The study of ^{247}Bk levels provides additional information about single-particle states in these heavy nuclei.

The levels in ^{247}Bk have been investigated by measuring γ-ray and conversion electron spectra of ^{247}Cf, ^{251}Es α spectrum, and triton spectrum from ^{246}Cm(α,t) reaction. Using the results of these experiments we have identified eight proton orbitals in the Z = 97 nucleus ^{247}Bk. The preliminary results of this investigation and its significance for the possible existence of superheavy elements have been discussed earlier.[3,4] In the present paper we describe these measurements in detail and discuss the single-particle orbital assignments to the observed levels in ^{247}Bk.

II. SOURCE PREPARATION

Approximately one milligram of ^{246}Cm (99.8% by mass) was irradiated with 40-MeV α particles in the Argonne 60-inch cyclotron. The irradiation time varied between 4 and 6 h and the average beam current density was ~30 μA/cm^2. The irradiated Cm was dissolved in concentrated HCl, evaporated to dryness, and redissolved in 0.05 M HCl. The activity was loaded on a cation-exchange resin column and eluted with ammonium α-hydroxy isobutyrate solution.[5] This procedure separated Cf from Cm and other actinide elements. Fission products were removed from the californium fraction by a liquid-liquid extraction chromatographic procedure.[6] The chemically purified Cf was either placed on a 1-mm thick quartz disk or run through the Argonne electromagnetic isotope separator[7] to produce thin ^{247}Cf sources.

The ^{251}Es sources were obtained from the decay of the parent ^{251}Fm (5.30 h). The procedure for the preparation and purification of ^{251}Fm samples is described elsewhere.[8]

The ^{246}Cm target for the (α,t) reaction was prepared by the deposition of 200-eV ^{246}Cm ions on a 40-μg/cm^2 carbon foil from the decelerated beam of the isotope separator.[7] The target thus prepared was isotopically pure (>99.99% by mass) ^{246}Cm, and its thickness as determined from elastically scattered α particles was 30 μg/cm^2.

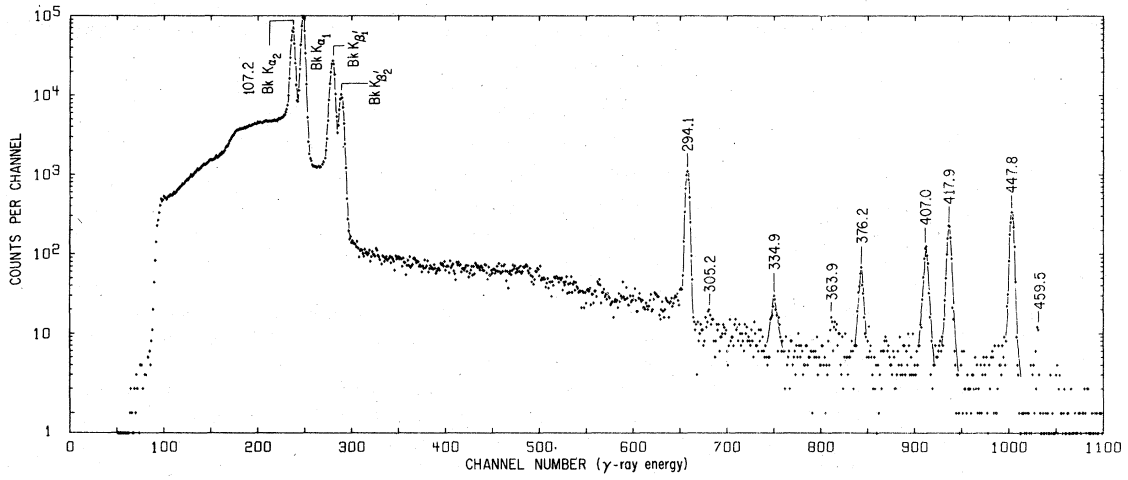

FIG. 1. γ-ray spectrum of a ^{247}Cf sample (not mass-separated) measured through a 220-mg/cm^2 Al absorber with a 25-cm^3 coaxial Ge(Li) spectrometer. Source-to-detector distance was 2 cm. Energy scale is 0.44 keV per channel.

III. EXPERIMENTAL PROCEDURES AND RESULTS

A. γ-ray spectroscopy

Several γ-ray spectra of ^{247}Cf samples were measured with a 25-cm^3 coaxial Ge(Li) spectrometer using mass-separated sources as well as samples which were not run through the isotope separator. Figure 1 shows a spectrum obtained by placing a ^{247}Cf sample 2 cm away from the detector end cap. A γ-ray spectrum measured with a set of Cd, Cu, and Al absorbers interposed between the source and the detector is displayed in Fig. 2. The absorbers were used to reduce summing-effect interference from intense Bk K x rays. Energies of intense γ rays were measured by counting the ^{247}Cf sample and the standard simultaneously and maintaining the gain of the counting system constant with a digital-gain stabilizer.

Energies and intensities of γ rays and K x rays were determined from hand-plotted graphs and also with the computer code SAMPO,[9] and these are given in Table I. The errors in Table I denote one standard deviation, σ. γ rays were assigned to ^{247}Cf decay on the basis of their decay with the characteristic half-life of ^{247}Cf (3.11 h) and the fact that they were observed in mass-separated samples. Intensities in Table I are expressed in photons per 100 ^{247}Cf EC decays, and these were obtained by equating the total γ, electron, and direct EC intensities feeding the $\frac{7}{2}^+$ [633] band to 100%.

B. Electron spectroscopy

The conversion-electron spectrum of a mass-separated ^{247}Cf sample was measured with a cooled Si(Li) spectrometer.[10] The spectrometer

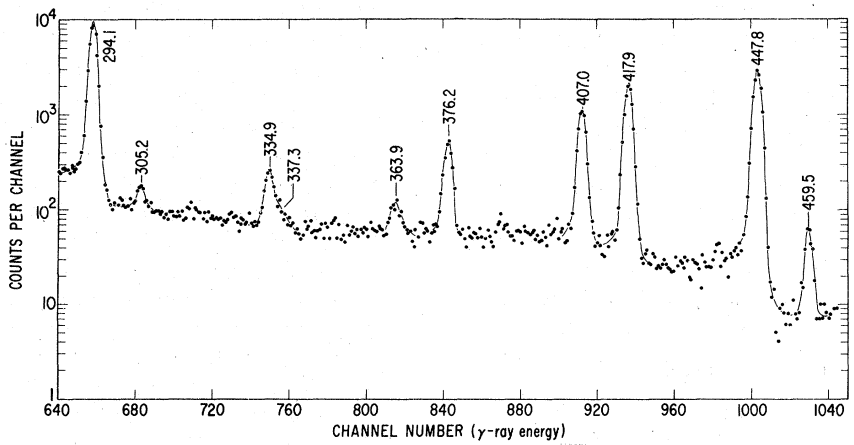

FIG. 2. ^{247}Cf γ-ray spectrum measured with a 25-cm^3 Ge(Li) spectrometer through a set of Cd, Cu, and Al absorbers. The sample was not mass-separated. Energy scale is 0.44 keV per channel.

TABLE I. ^{247}Cf γ rays and Bk K x rays.

Energy (keV)	Photon intensity (% per ^{247}Cf EC decay)	Transition (initial → final)
107.2 ± 0.1	21.3 ± 1.5	Bk K_{α_2}
112.1 ± 0.1	33.7 ± 2.4	Bk K_{α_1}
126.2 ± 0.2	12.6 ± 0.9 total = 72.3 ± 5.2	Bk $K_{\beta_1'}$
130.3 ± 0.2	4.7 ± 0.4	Bk $K_{\beta_2'}$
294.1 ± 0.1	0.98 ± 0.07	334.9 → 40.8
305.2 ± 0.3	$(8.9 \pm 1.4) \times 10^{-3}$	334.9 → 29.9
334.9 ± 0.2	0.028 ± 0.003	334.9 → 0
337.3 ± 0.5	$\sim 6 \times 10^{-3}$	378.1 → 40.8?
363.9 ± 0.2	0.011 ± 0.002	489.4 → 125.5
376.2 ± 0.1	0.071 ± 0.007	447.8 → 71.6
407.0 ± 0.1	0.19 ± 0.02	447.8 → 40.8
417.9 ± 0.1	0.34 ± 0.03	447.8 → 29.9
447.8 ± 0.1	0.55 ± 0.04	447.8 → 0
459.5 ± 0.3	0.011 ± 0.0016	489.4 → 29.9

consists of an 80-mm^2 × 3-mm lithium-drifted silicon detector and has a resolution [full width at half-maximum (FWHM)] of 1.0 keV at 100-keV electron energy. Energy calibration of the spectrometer was made with ^{239}Np electron lines and a reference pulser. Electron energies thus determined had errors of <0.3 keV. Transition energies obtained by adding these electron energies and appropriate electron binding energies[11] agreed with γ-ray energies within 0.4 keV.

Efficiency-geometry product of the detector was measured with a ^{203}Hg standard. Absolute conversion coefficients of transitions in ^{247}Bk were determined by measuring γ ray (electron) spectra of a ^{247}Cf source and a ^{203}Hg standard at identical geometries. Since the γ-ray and electron spectra were measured at different times, relative decay corrections were applied to these spectra. Transition energies, electron intensities, conversion coefficients, and derived multipolarities are given in Table II. The transition multipolarities in Table II were deduced by comparing experimental conversion coefficients with respective theoretical values.[12]

C. α spectroscopy of ^{251}Es

The α-particle spectrum of a mass-separated ^{251}Es source measured with the Argonne double-focussing magnetic spectrometer[13] is displayed in Fig. 3. The peaks observed in this spectrum were also seen in a spectrum measured with a 6-mm-diam Au-Si surface barrier detector, but because of poorer resolution (FWHM ~ 13 keV) α_{41} and α_{83} groups could not be resolved from α_{30} and α_{72} groups, respectively. Energies and intensities of ^{251}Es α groups determined with the magnetic spectrometer are given in Table III, and these agreed (within statistical uncertainties) with respective values obtained with the solid state detector. The hindrance factors in Table III were calculated from the spin-independent theory of Preston[14]; the half-life, α branching, and radius parameters used were 33.0 h, 0.50%, and 9.30 fm, respectively. The errors denote one standard deviation, σ.

D. ^{246}Cm(α,t) reaction spectroscopy

Proton transfer reaction was used to obtain additional information about ^{247}Bk levels. A thin ^{246}Cm target was bombarded with α particles from the Argonne FN tandem Van de Graaff accelerator and the reaction products were momentum analyzed with an Enge split-pole magnetic spectrograph.[15] The tritons arriving at the focal plane of the spectrograph were detected with Kodak NTB-50 photographic emulsion plates. Foils of cellulose triacetate (8 μm thick) were placed in front of emulsion plates to eliminate unwanted background tracks. A 1 × 3 mm slit was used to define the beam size, and the solid angle of acceptance of the spectrograph was 3.28 msr. A Au-Si surface barrier detector was placed at 60° to the incident beam to register elastically scattered α particles which were used to determine absolute differential cross sections.

Triton spectra were recorded at bombarding α-

TABLE II. ^{247}Cf conversion-electron lines.

Electron energy (keV)	Shell	Transition energy[a] (keV)	Electron intensity (% per EC decay)	Conversion coefficient	Theoretical $E1$	Theoretical $E2$	Theoretical $M1$	Multipolarity
23.4 ± 0.2	M	29.9 ± 0.2	16.5 ± 2.0		0.65	1390	53	
28.2 ± 0.2	$N+O$		6.2 ± 0.6					
34.3 ± 0.3	M	40.8 ± 0.3	2.5 ± 0.5			1450 for $M2$		
39.0 ± 0.3	$N+O$		1.0 ± 0.2					
35.4 ± 0.2	M	42.0 ± 0.2	3.7 ± 0.4		0.27	266	19	
40.2 ± 0.2	$N+O$		1.4 ± 0.2					
162.4 ± 0.2	K	294.0 ± 0.2	1.37 ± 0.12	1.40	0.037	0.085	1.40	$M1$
268.8 ± 0.2	L		0.26 ± 0.03	0.27	7.7(−3)	0.14	0.29	
287.4 ± 0.4	M		0.08 ± 0.02	0.08	1.9(−3)	0.04	0.07	
	K	407.0	<0.02	<0.11	0.019	0.05	0.57	$E1$ or $E2$
	L		<0.02	<0.11	3.8(−3)	0.04	0.12	
286.1 ± 0.4	K	417.7 ± 0.4	0.13 ± 0.02	0.38	0.018	0.047	0.53	$M1+31\%$ $E2$
392.1 ± 0.8	L		0.028 ± 0.009	0.08	3.6(−3)	0.038	0.11	
316.0 ± 0.4	K	447.6 ± 0.4	0.13 ± 0.02	0.24	0.016	0.042	0.44	$M1+50\%$ $E2$
422.0 ± 0.8	L		0.031 ± 0.009	0.06	3.1(−3)	0.03	0.09	

[a]Transition energies were obtained by adding the measured electron energies and appropriate binding energies from Ref. 11.

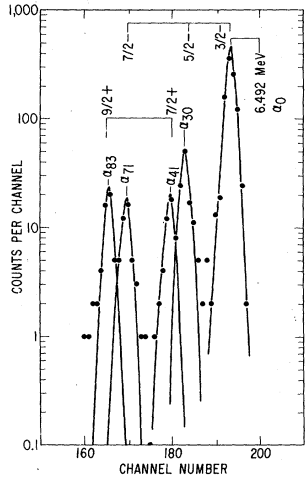

FIG. 3. ^{251}Es α-particle spectrum measured with the Argonne double-focussing magnetic spectrometer. The resolution (FWHM) is 5.0 keV. Zero events are plotted at 0.1.

particle energies of 28.0 and 29.0 MeV and at angles of 90° and 80°, respectively. The emulsion plates were developed and scanned manually in $\frac{1}{4}$-mm-wide strips. Energies and intensities of triton groups were determined from hand-plotted graphs. Absolute differential cross sections were calculated with the computer code AUTOPLOT[16]; the target thickness was determined from the elastically scattered α counts in the monitor detector. The triton spectrum measured at 90° with respect to the incident beam is shown in Fig. 4 and data obtained from its analysis are given in Table IV.

IV. DISCUSSION

A. Electron capture transition probabilities

Intensities of γ rays and conversion electron lines were measured in relative units normalized at the 294.1-keV γ intensity as 100. Transition intensities were then obtained by summing γ-ray

TABLE III. ^{251}Es α groups.

Energy (MeV)	Excited state energy (keV)	Intensity (%)	Hindrance factor
6.492 ± 0.003[a]	0	81.0 ± 1.6	3.9
6.462 ± 0.003	30	9.4 ± 1.0	24
6.452 ± 0.003	41	3.3 ± 0.7	62
6.422 ± 0.003	71	3.0 ± 0.6	49
6.410 ± 0.003	83	3.3 ± 0.6	39

[a]Errors in α-particle energies, given above, come primarily from uncertainties in spectrometer calibration. The errors in level spacings, which come from the uncertainties in peak locations only, are ~1 keV.

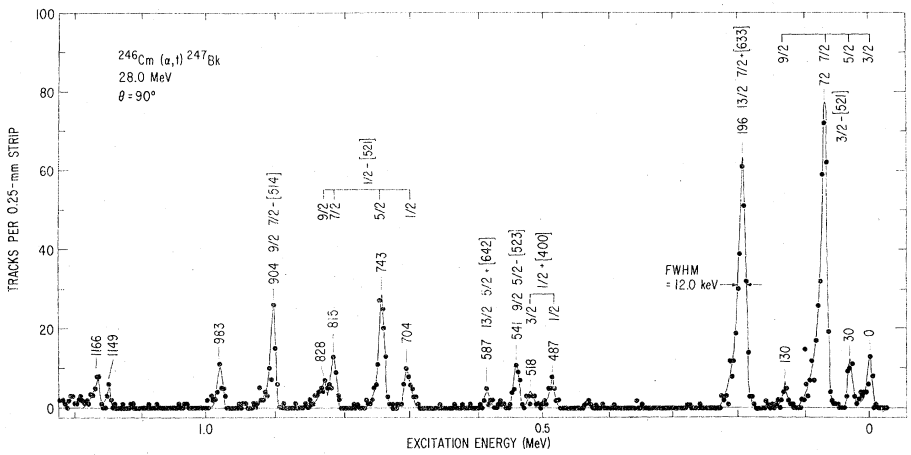

FIG. 4. Triton spectrum from the ^{246}Cm (α, t) reaction measured with an Enge split-pole magnetic spectrograph. The incident α-particle energy was 28.0 MeV, and the spectrograph angle with respect to the beam was 90°.

intensities and corresponding electron intensities; for transitions whose electron intensities were not measured, theoretical[12] values for assumed pure multipolarities were used. The EC population at each ^{247}Bk level was determined from the difference between γ plus electron outfeed and infeed. Using the EC intensity and the theoretical[17] K/total capture ratio, we obtained the number of K-shell holes created at each level. The K-shell vacancies produced by internal conversion were determined by summing the intensities of all K electron lines. The difference between the K-shell vacancies obtained from the experimental BK K x-ray intensity and those created by internal conversion and EC decay to excited states of ^{247}Bk gave the K capture intensity at the $\frac{7}{2}^+$ (633) state, which after correction for capture from higher shells gave the EC population at this level. The EC population to the $\frac{3}{2}^-$ (521) band was assumed to

TABLE IV. Levels in ^{247}Bk excited by ^{246}Cm (α, t) reaction.

Excitation energy (keV)	$(d\sigma/d\Omega)$ at 90° (μb/sr) [a]	I	Assignment $K\pi[Nn_z\Lambda]$
0	4.3 ± 0.7	$\frac{3}{2}$	$\frac{3}{2}^-$ [521]
30 ± 3	4.2 ± 0.7	$\frac{5}{2}$	$\frac{3}{2}^-$ [521]
72 ± 3	33.5 ± 1.9	$\frac{7}{2}$	$\frac{3}{2}^-$ [521]
130 ± 3	1.7 ± 0.5	$\frac{9}{2}$	$\frac{3}{2}^-$ [521]
196 ± 3	29.3 ± 2.0	$\frac{13}{2}$	$\frac{7}{2}^+$ [633]
487 ± 3	3.0 ± 0.6	$\frac{1}{2}$	$\frac{1}{2}^+$ [400]
518 ± 5	1.4 ± 0.5	$\frac{3}{2}$	$\frac{1}{2}^+$ [400]
541 ± 3	4.1 ± 0.7	$\frac{9}{2}$	$\frac{5}{2}^-$ [523]
587 ± 4	1.3 ± 0.4	$\frac{13}{2}$	$\frac{5}{2}^+$ [642]
704 ± 4	4.4 ± 0.8	$\frac{1}{2}$	$\frac{1}{2}^-$ [521]
743 ± 3	12.0 ± 1.2	$\frac{5}{2}$	$\frac{1}{2}^-$ [521]
815 ± 4	4.5 ± 0.8	$\frac{7}{2}$	$\frac{1}{2}^-$ [521]
828 ± 5	2.4 ± 0.7	$\frac{9}{2}$	$\frac{1}{2}^-$ [521]
904 ± 3	8.0 ± 1.3	$\frac{9}{2}$	$\frac{7}{2}^-$ [514]
983 ± 3	3.4 ± 0.7		
1149 ± 4	1.4 ± 0.6		
1166 ± 4	3.0 ± 0.6	$\frac{13}{2}$	$\frac{9}{2}^+$ [624]?

[a] The errors contain statistical uncertainties only.

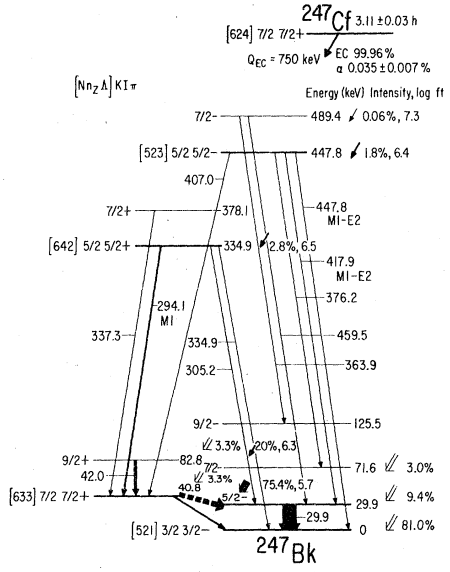

FIG. 5. Level structure of ^{247}Bk constructed from the results of the ^{247}Cf EC and ^{251}Es α-decay studies. States excited in the ^{246}Cm (α, t) reaction are not shown here.

be zero because this transition involves $|\Delta K| = 2$ and such transitions are strongly hindered (logft > 8).

The photon, electron, and EC intensities in per cent per ^{247}Cf EC decay were obtained by normalizing the total EC population to all the ^{247}Bk levels to 100%. The logft values were calculated by the procedure described by Major and Biedenharn[18] using an EC decay energy[19] of 750 keV, and these along with EC intensities are given in Fig. 5.

B. Spectroscopic factors

According to the theory[20] of direct reactions the differential cross section $d\sigma/d\Omega$ for the population of a state with spin J and quantum numbers α is given by

$$\left(\frac{d\sigma}{d\Omega}\right)_{0\to J} = N(2J+1)S_J^{\alpha}\,\theta_J^{\mathrm{DW}}\,. \qquad (1)$$

In the above equation θ_J^{DW} is the intrinsic single-particle transfer cross section for the excitation of a state with orbital angular momentum l and total angular momentum J, and N is a normalization constant. The quantity θ_J^{DW} contains the entire angular and energy dependence of the cross section, and the spectroscopic factor S_J^{α} contains all the spectroscopic information on the state excited by the reaction. The values of θ_J^{DW} were calculated with the distorted-wave Born approximation (DWBA) computer code DWUCK [21] using the optical-model parameters given by Elze and Huizenga.[22] Values of $(2J+1)S_J^{\alpha}$ calculated from the measured cross sections and with a normalization constant of 120 are given in Table V. This value of N was chosen to optimize the agreement between the experimental and theoretical spectroscopic factors.

Theoretical spectroscopic factors were calculated with the single-particle wave functions using the equation[1]

$$S_J^{\alpha} = \frac{2}{2J+1}(C_J^{\alpha})^2 U_{\alpha}{}^2\,,$$

where C_J^{α} is an amplitude in the expansion of the deformed wave function, and $U_{\alpha}{}^2$ is the probability that the orbital to be entered by the proton is empty. Values of $(2J+1)S_J^{\alpha}$ calculated with $(C_J^{\alpha})^2$ given in Ref. 1 and $U_{\alpha}{}^2$ given in Ref. 23 are included in Table V. The overall agreement between the experimental and theoretical spectroscopic factors supports the single-particle assignments in Table IV.

It should be noted that for several states the experimental and theoretical spectroscopic factors in Table IV do not agree. This disagreement could be attributed to the limitations of the DWBA code as suggested by Erskine *et al.*[1] For this reason we find it more useful to compare the ratio of

TABLE V. Spectroscopic factors for levels in ^{247}Bk.

State	Spin I	Excitation energy (keV)	Spectroscopic factor, $(2J+1)S$ Observed[a]	Calculated[b]
$\frac{3}{2}^-$ [521]	$\frac{3}{2}$	0	0.14 ± 0.03	0.15
	$\frac{5}{2}$	30	0.18	0.02
	$\frac{7}{2}$	72	1.40 ± 0.13	0.93
$\frac{7}{2}^+$ [633]	$\frac{13}{2}$	196	3.82 ± 0.28	1.28
$\frac{1}{2}^+$ [400]	$\frac{1}{2}$	487	0.21 ± 0.05	0.20
	$\frac{3}{2}$	518	0.09 ± 0.03	0.05
$\frac{5}{2}^-$ [523]	$\frac{9}{2}$	541	0.6 ± 0.12	0.27
$\frac{5}{2}^+$ [642]	$\frac{13}{2}$	587	0.22 ± 0.07	0.36
$\frac{1}{2}^-$ [521]	$\frac{1}{2}$	704	0.23 ± 0.05	0.48
	$\frac{5}{2}$	743	0.83 ± 0.09	0.61
	$\frac{7}{2}$	815	0.35 ± 0.07	0.37
	$\frac{9}{2}$	828	0.35 ± 0.10	0.33
$\frac{7}{2}^-$ [514]	$\frac{9}{2}$	904	1.36 ± 0.20	1.81
$\frac{9}{2}^+$ [624]	$\frac{13}{2}$	1166	0.77 ± 0.16	1.8

[a] These were obtained from the equation $(2J+1)S = (d\sigma/d\Omega)/(N\theta_J^{\mathrm{DW}})$, with $N = 120$.
[b] These were calculated with equation $(2J+1)S = 2C_J{}^2 U_{\alpha}{}^2$.

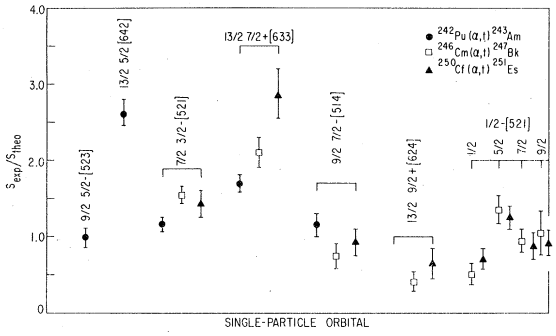

FIG. 6. A plot of the ratio of observed and theoretical spectroscopic factors for the ^{242}Pu (α,t) ^{243}Am, ^{246}Cm (α,t) ^{247}Bk, and ^{250}Cf (α,t) ^{251}Es reactions. Values of N used in the derivation of the spectroscopic factors were 71, 120, and 150, respectively.

the experimental and theoretical spectroscopic factors for the same state in several nuclei. The values of S_{exp}/S_{theo} are plotted for the ^{242}Pu(α,t) ^{243}Am, ^{246}Cm (α,t) ^{247}Bk, and ^{250}Cf(α,t) ^{251}Es reactions in Fig. 6. As can be seen the ratios for most states are very similar in these reactions giving support to the present assignments.

C. Single-particle orbital assignments

1. $\frac{3}{2}^-[521]$ and $\frac{7}{2}^+[633]$ bands

The ground state of ^{247}Bk has been assigned[24] to the $\frac{3}{2}^-[521]$ proton orbital on the basis of its α-decay properties. This assignment is further supported by the low hindrance factor of the ^{251}Es α group feeding this state (which suggests it is a favored α transition), and the large cross section to the $I=\frac{7}{2}$ member of this band in the (α,t) reaction. A level at 41 ± 1 keV is established from the ^{251}Es α spectrum. A more precise energy $(40.8\pm0.3$ keV) for this level is obtained from the M and N conversion electron lines of the 40.8-keV transition. This state is assigned to the $\frac{7}{2}^+[633]$ orbital because its $\frac{13}{2}$ member has been identified in the (α,t) reaction (see Sec. III D). The hindrance factor of the ^{251}Es α group and the logft value of the EC transition to this state are consistent with the $\frac{7}{2}^+[633]$ assignment. The level energies in Fig. 5 yield the values of the rotational constant, $\hbar^2/2\mathcal{I}$, as 5.98 ± 0.05 and 4.67 ± 0.04 keV for the $K\pi=\frac{3}{2}^-$ and $\frac{7}{2}^+$ bands, respectively.

In the conversion-electron spectrum we observe strong M and $N+0$ lines which give the total 29.9 transition intensity of (73 ± 9)% and a comparatively weaker 40.8-keV transition [transition intensity (12 ± 3)%]. This observation suggests that the 40.8-keV level deexcites predominantly by the 40.8 $\rightarrow$ 29.9 transition. Although we have not measured the multipolarity of the 10.9-keV transition, it is most likely an $E1$ transition. Thus the K-forbidden $E1$ transition is faster than the allowed $M2$ transition.

2. $\frac{5}{2}^+[642]$ state

The 334.9, 305.2, and 294.1 keV γ rays establish a level at 334.9 keV. The $M1$ multipolarity of the 294.1 (334.9 $\rightarrow$ 40.8) keV transition restricts the spin-parity of the 334.9-keV state to $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{9}{2}^+$. The fact that we observe a transition to the $\frac{5}{2}^-$ level, but do not see the 334.9 $\rightarrow$ 82.8 γ ray favors the $K\pi=\frac{5}{2}^+$ assignment. We, therefore, assign the 334.9-keV state to the $\frac{5}{2}^+$ [642] orbital because this is the only $\frac{5}{2}^+$ single-particle state expected in this energy region. The 378.1-keV level could be the $\frac{7}{2}$ member of this band.

3. $\frac{5}{2}^-[523]$ band

The multipolarities of the 447.8- and 417.9-keV transitions have been determined to be $M1$-$E2$. Thus the spin-parity of the 447.8-keV level can only be $\frac{3}{2}^-$ or $\frac{5}{2}^-$. The fact that the multipolarity of the 407.0-keV transition is not $M2$ rules out the $\frac{3}{2}^-$ assignment. We, therefore, assign the 447.8-keV state to the $\frac{5}{2}^-$ [523] hole state. The 489.4-keV level fits well as the $\frac{7}{2}^-$ member of this band and gives a rotational constant of 5.94 ± 0.05 keV for the $\frac{5}{2}^-$ [523] band. The 541-keV state observed in the (α,t) reaction has been assigned to the $\frac{9}{2}^-$ member of this band.

4. ^{247}Cf ground state

The ground state of ^{247}Cf has been established[8] to be the $\frac{7}{2}^+$ [624] neutron state from the α-decay studies of ^{251}Fm. The observed logft values of EC transitions to the $I=\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ states clearly show that the ^{247}Cf ground state spin is $\frac{7}{2}$. The logft values of ^{247}Cf EC transitions to the $\frac{7}{2}^+$ [633], $\frac{5}{2}^+$ [642], and $\frac{5}{2}^-$ [523] single-particle states in ^{247}Bk are very similar to the respective values observed in the ^{243}Pu β^- decay[24] to ^{243}Am. This excellent agreement further supports the above single-particle state assignments.

5. $\frac{1}{2}^-[521]$ band

The large (α,t) reaction cross sections to the 704, 743, 815, and 828 keV levels clearly indicate that these are particle states with large values of U^2. The only particle states available in the 0.5 to 1.0 MeV excitation energy of ^{247}Bk are the $\frac{1}{2}^-$ [521], $\frac{7}{2}^-$ [514], and $\frac{9}{2}^+$ [624] orbitals. We assign the above levels to the $\frac{1}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ members of the $\frac{1}{2}^-$ [521] band because of the good agreement (see Sec. IV B) between the experimental and theoretical spectroscopic factors for these states. The

energies of these levels give a rotational constant of 6.0 ± 0.3 keV and a decoupling parameter of 0.7 ± 0.1, which is in good agreement with the theoretical value of +1.0 for the $\frac{1}{2}^-$ [521] orbital.

The $\frac{1}{2}^-$ [521] proton orbital has also been observed[25] in ^{249}Bk and ^{251}Bk using radioactive decay data. Although the excitation energies of this orbital in these nuclei are similar to those in ^{247}Bk and ^{251}Es, the decoupling parameters are ~0.0. This large reduction in the decoupling parameter could possibly arise from the admixtures of the $\frac{1}{2}^-$ [530] orbital and the $\{\frac{3}{2}^- [521] \otimes 2^+\}_{1/2^-}$ phonon state in the $\frac{1}{2}^-$ [521] state. In ^{247}Bk, like ^{251}Es, we find that the measured decoupling parameter and spectroscopic factors are in good agreement with the theoretical values, suggesting predominantly pure single-particle character to the $\frac{1}{2}^-$ [521] state. Detailed calculations are necessary to explain the above differences in these Bk and Es nuclei.

6. $\frac{7}{2}^-$[514], $\frac{9}{2}^+$[624], and $\frac{1}{2}^+$[400] states

The $\frac{7}{2}^-$ [514] proton orbital has large C_J^2 for $J = \frac{9}{2}$ and the $\frac{9}{2}^+$ [624] state has $C_J^2 = 0.97$ for $J = \frac{13}{2}$; and U^2 for both states in ^{247}Bk are ~1.0. Thus one expects large cross sections to these two states. The strong peak at 904 keV in Fig. 4 is assigned to the $I = \frac{9}{2}$ member of the $\frac{7}{2}^-$ [514] band because this orbital is expected[23] to lie lower than the $\frac{9}{2}^+$ [624] orbital. The good agreement between the experimental and theoretical spectroscopic factors further supports this assignment.

The 1166-keV state is tentatively assigned to the $I = \frac{13}{2}$ member of the $\frac{9}{2}^+$ [624] state because this state is expected to lie in this energy region. The value of S_{exp}/S_{theo} for this state is similar to the value for the 942 keV state in ^{251}Es, which has been assigned[2] to the $\frac{13}{2}$ member of the $\frac{9}{2}^+$ [624] band.

The weak triton groups at 487 and 518 keV are assigned to the $\frac{1}{2}$ and $\frac{3}{2}$ members of the $\frac{1}{2}^+$ [400] band because this orbital is expected around this excitation energy. The good agreement between experimental and theoretical spectroscopic factors gives additional support for this assignment.

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[1] J. R. Erskine, G. Kyle, R. R. Chasman, and A. M. Friedman, Phys. Rev. C 11, 561 (1975).
[2] I. Ahmad, R. K. Sjoblom, A. M. Friedman, and S. W. Yates, Phys. Rev. C 17, 2163 (1978).
[3] I. Ahmad, A. M. Friedman, R. R. Chasman, and S. W. Yates, Phys. Rev. Lett. 39, 12 (1977).
[4] I. Ahmad, S. W. Yates, and A. M. Friedman, Bull. Am. Phys. Soc. 23, 614 (1978).
[5] G. R. Choppin, B. G. Harvey, and S. G. Thompson, J. Inorg. Nucl. Chem. 2, 66 (1956).
[6] I. Ahmad, R. F. Barnes, R. K. Sjoblom, and P. R. Fields, J. Inorg. Nucl. Chem. 34, 3335 (1972).
[7] J. Lerner, Nucl. Instrum. Methods 102, 373 (1972).
[8] I. Ahmad, J. Milsted, R. K. Sjoblom, J. Lerner, and P. R. Fields, Phys. Rev. C 8, 737 (1973).
[9] J. T. Routti and S. G. Prussian, Nucl. Instrum. Methods 72, 125 (1969); Lawrence Radiation Laboratory Report No. UCRL-19452 (unpublished).
[10] I. Ahmad and F. Wagner, Nucl. Instrum. Methods 116, 465 (1974).
[11] F. T. Porter and M. S. Freedman, J. Phys. Chem. Ref. Data 7, 1267 (1978).
[12] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968), for K, L, and M shells; O. Dragoun, Z. Plajner, and F. Schmutzler, *ibid.* A9, 119 (1971), for $(N+O+\cdots)$ shells.
[13] I. Ahmad and J. Milsted, Nucl. Phys. A239, 1 (1975).
[14] M. A. Preston, Phys. Rev. 71, 865 (1947).
[15] J. E. Spenser and H. A. Enge, Nucl. Instrum. Methods 49, 181 (1967).
[16] J. R. Erskine, Argonne National Laboratory report (unpublished).
[17] C. M. Lederer and V. S. Shirley, *Table of Isotopes* (Wiley, New York, 1978) Appendix. V.
[18] J. K. Major and L. C. Biedenharn, Rev. Mod. Phys. 26, 361 (1954).
[19] Nuclear Data Group, *Nuclear Level Scheme A = 45 through A = 257* (Academic, New York, 1973).
[20] G. R. Satchler, Ann. Phys. (N.Y.) 3, 275 (1958).
[21] P. D. Kunz, University of Colorado (unpublished).
[22] Th. W. Elze and J. R. Huizenga, Nucl. Phys. A149, 585 (1970).
[23] R. R. Chasman, I. Ahmad, A. M. Friedman, and J. R. Erskine, Rev. Mod. Phys. 49, 833 (1977).
[24] A. M. Friedman, I. Ahmad, J. Milsted, and D. W. Engelkemeir, Nucl. Phys. A127, 33 (1969).
[25] R. W. Lougheed, J. F. Wild, E. K. Hulet, R. W. Hoff, and J. H. Landrum, J. Inorg. Nucl. Chem. 40, 1865 (1978).