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SINGLE PARTICLE STATES IN THE HEAVIEST KNOWN NUCLEI

I. Ahmad, R.R. Chasman and A.M. Friedman*

Argonne National Laboratory, Argonne, Illinois 60439

S.W. Yates

University of Kentucky, Lexington, Kentucky 40506

ABSTRACT

Neutron single-particle states above the N=152 subshell have been studied by high-resolution (d,p) reaction on a ^{250}Cf target. All of the orbitals between N=152 and N=164 subshells have been identified. A tentative assignment has been made for the 1/2-[750] Nilsson state.

INTRODUCTION

Theoretical calculations[1], about twenty years ago, predicted long half-lives for superheavy elements with atomic number 114 and neutron number 184. Attempts to identify such elements in nature and in nuclear reactions have been unsuccessful, but neutron-deficient isotopes of elements up to 109 have been discovered[2]. The estimates of half-lives for superheavy elements are based on calculations of nuclear energies as a function of deformation. An essential ingredient in these Strutinsky type calculations is the magnitude of the shell correction, which is extremely sensitive to the single-particle energy gap at Z=114 and N=184, and to the level spacings near these gaps. For this reason any experimental measurements of energies of orbitals near these gaps is extremely important. In the case of protons, the gap at Z=114 is determined by the splitting of the $f_{7/2}$ and $f_{5/2}$ orbitals, and this was deduced from the spectroscopy of odd-proton nuclei[3,4] and used to derive the parameters of a single-particle potential as illustrated in Fig. 1. The shell correction near N=184 is largely determined by the position of the $h_{11/2}$, $k_{17/2}$ and $j_{13/2}$ spherical states[5]. It is therefore important to determine the energies of single-particle states in the heaviest nuclei.

The best way to identify orbitals above the N=152 subshell is to perform single neutron transfer reactions on a target with neutron number 152 or greater. In such a stripping reaction, the 153rd neutron will occupy orbitals above the N=152 gap. The advantage of a target with N=152 is that the population of hole state orbitals is strongly suppressed because of the large values of V^2 (V^2 is the pair occupation probability). Thus a clean (d,p)

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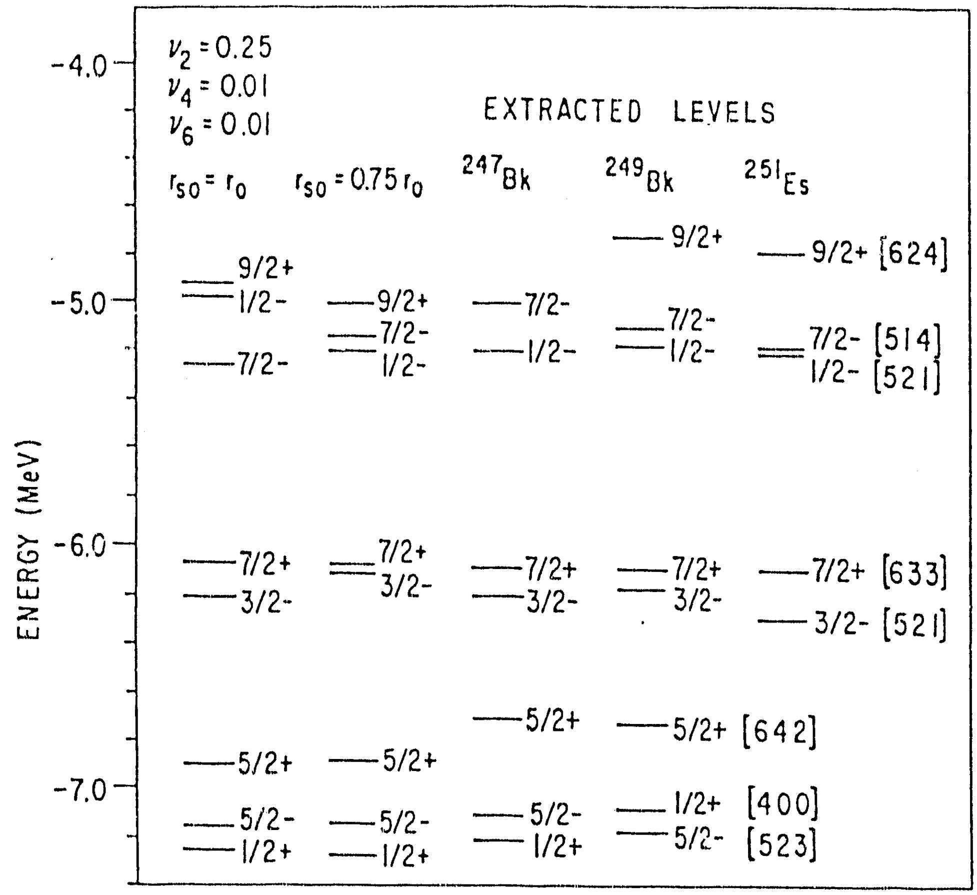

Fig. 1. Theoretical (two left columns) and extracted energies of proton single-particle states. Theoretical energies were calculated with a Woods-Saxon potential using the parameters shown in the figure. The extracted energies were obtained by removing the contribution of the pair correlation effects from the experimental level energies.

spectrum is expected. The only target with N≳152, with a reasonable half-life, is ^{248}Cm ($T_{1/2}$ = 3.5 x 10^5 y). Neutron transfer reaction[6] and neutron capture gamma[7] experiments have been performed with ^{248}Cm targets which give information on states in ^{249}Cm. However, these experiments did not have sufficient sensitivity to observe weakly populated levels. Another possible target with N≳152 is ^{250}Cf ($T_{1/2}$ = 13.1 y), which is much more radioactive than ^{248}Cm, but has the advantage that many single particle states in ^{251}Cf have been well characterized[8] in the alpha decay of ^{255}Fm.

EXPERIMENTAL PROCEDURE

The ^{250}Cf(d,p)spectra were measured with the Argonne Tandem Van de Graaf accelerator using a 12.0-MeV deuteron beam and an 8-μg/cm^2 ^{250}Cf target on a 40-μg/cm^2 carbon film which was prepared in the Argonne electromagnetic isotope separator. The emerging protons were momentum analyzed with an Enge split-pole spectrograph and were detected with photographic emulsion plates in the focal plane. Spectra were recorded at 90° and 120° with respect to the beam direction. Portions of the proton spectra showing the regions of interest are displayed in Figs. 2 and 3. The resolution (FWHM) of the peaks in these spectra is 7 keV and these are among the cleanest spectra measured in the heavy-element region.

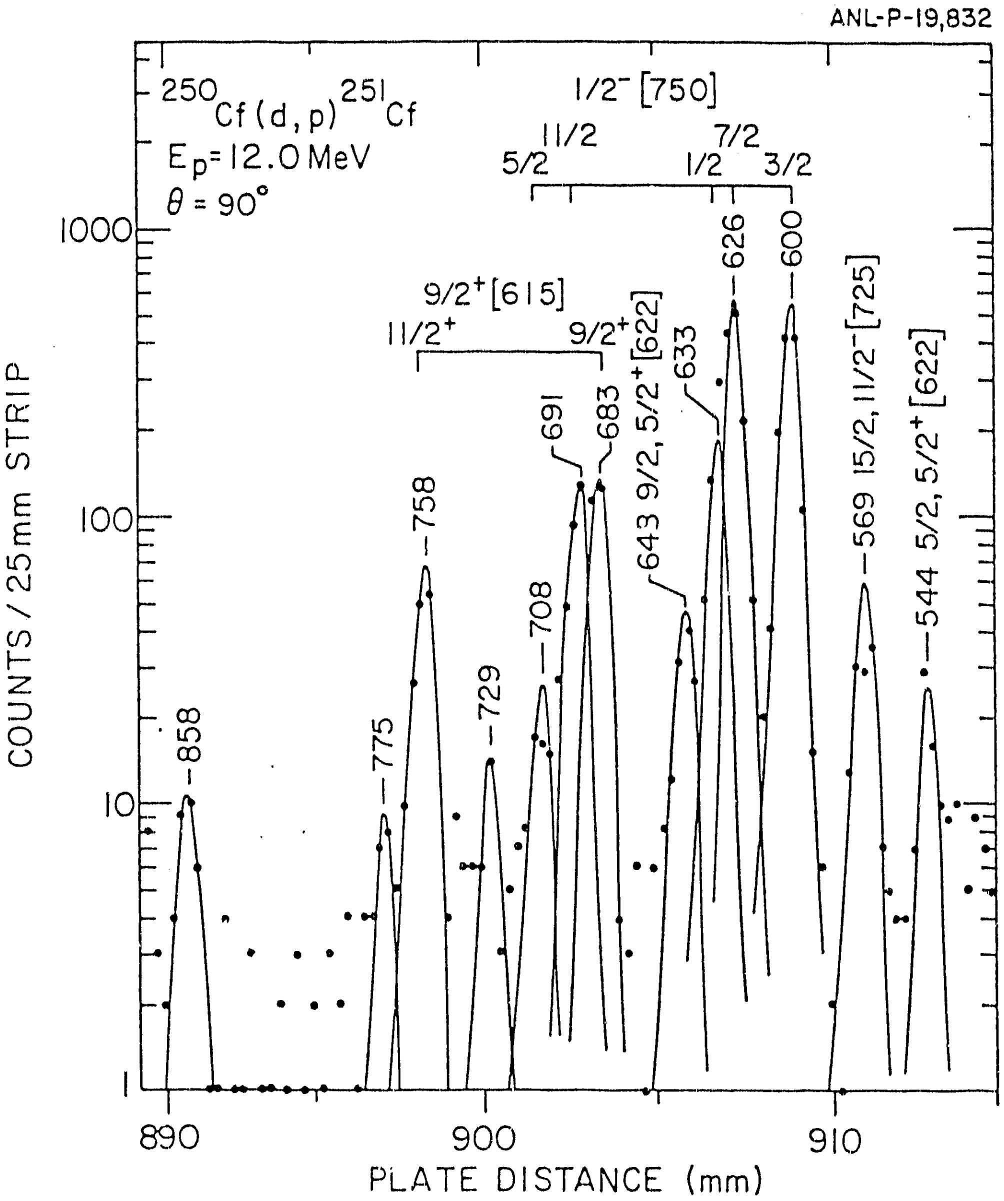

Fig. 2. Proton spectrum from the ^{250}Cf(d,p) reaction measured with the Argonne Enge split-pole spectrograph showing the population of the 1/2-[750] and 9/2+[615] bands. Energy scale is ~3.5 keV per 0.25-mm strip.

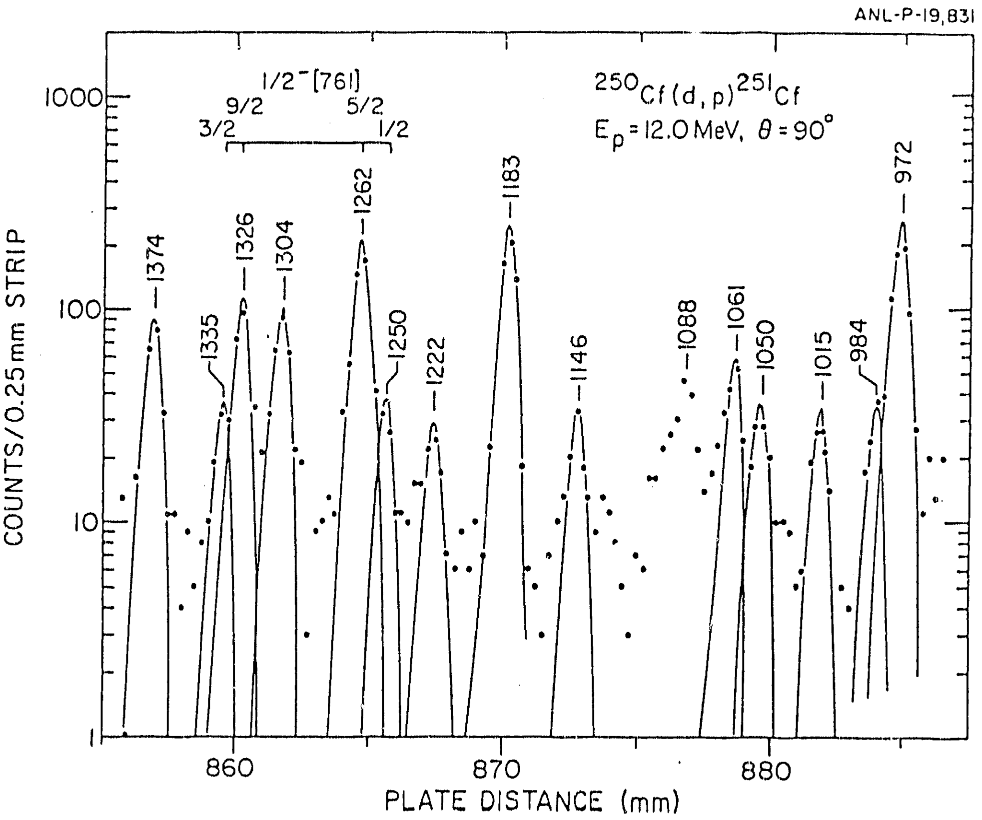

Fig. 3. A portion of the proton spectrum from the ^{250}Cf(d,p) reaction showing peaks above 1 MeV excitation. The spectrum was measured with the Argonne Enge split-pole spectrograph. Energy scale is ~3.5 keV per 0.25-mm strip.

DISCUSSION

The rotational bands 1/2+[620], 7/2+[613], 3/2+[622], 5/2+[622], 11/2-[725] and 9/2-[734] were well characterized[8] in the ^{255}Fm alpha decay. The present (d,p) reaction data (Fig. 2) fully support these assignments and enable us to compare calculated cross sections with the measured ones. All observed levels below 600 keV excitation fit extremely well as members of known bands, leaving no level unassigned. According to our calculations the remaining intense peaks below 1 MeV should be associated with the 1/2-[750] and 9/2+[615] bands. Using the calculated[9] signature of the 1/2-[750] band we have made the following assignment: 1/2 (633 keV); 3/2 (600 keV); 5/2 (708 keV); 7/2 (626 keV); 11/2 (691 keV). These level energies give a rotational constant of 4.8 keV and a decoupling parameter of -3.29, in very good agreement with the theoretical value of -3.8. The peaks at 683 and 758 keV are assigned to the 9/2 and 11/2 members of the 9/2+[615] band, respectively, which yield a reasonable rotational constant of 6.9 keV. The observed energy of the 9/2+[615] orbital in ^{251}Cf is considerably higher than the assignment made in ^{249}Cm at 209 keV[6].

The experimental level energies, after correction for pairing effects, are shown on the right hand side in Fig. 4. These are compared with the energies calculated with a momentum-dependent Woods-Saxon single particle potential using $\nu_2 = 0.25$, $\nu_4 = -0.01$ and $\nu_6 = +0.02$ (left column). The deformation parameters were chosen to give a good fit to the energies of the well characterized levels in ^{251}Cf. The agreement between the theoretical and extracted energies is good. This gives us some confidence in the predicted energies of the higher lying states. The values of C_j^2 obtained in these calculations are given in Table 1. Values of C_j^2 for the lower-lying orbitals are given in Ref. 10.

Although there are many peaks in the spectrum above 1 MeV (Fig. 3), only tentative assignments have been possible for some levels. We have made a tentative assignment of I=1/2, 5/2, 9/2 and 3/2 members of the 1/2-[761] rotational band to the 1250, 1262, 1326 and 1335 keV levels. These assignments give a rotational constant of 6.9 keV, and a decoupling parameter of +3.1, which is in good agreement with the theoretical value of +3.9 for this band. We also assign the 1183 keV level to the 9/2 member of the 9/2+[604] band because it is the strongest peak in the spectrum above 1 MeV excitation.

The energy of the 1/2+[880] orbital, which is largely determined by the position of the $k_{17/2}$ spherical shell state, is calculated to be 1376 keV. The decoupling parameter of +8.3 makes this a very unusual band. In addition, this band has a very strong interaction with the 3/2+[871] band. Using appropriate Coriolis matrix elements we have made a mixing calculation which brings down the 9/2+, 13/2+, 5/2+ and 17/2+ levels below the energy of the 1/2+ level to 1218, 1224, 1267 and 1286 keV, respectively. Also, the 9/2, 13/2, 17/2, and 1/2 members of the band are expected to receive populations of 10-30 μb/sr. We do not have any unassigned peak in the spectrum below 1 MeV with the predicted cross section, indicating that the 1/2+[880] band lies above 1 MeV excitation. One important thing worth noting is the lowering of the 17/2 member of the 1/2+[880] band to ~1 MeV. Thus heavy-ion reactions, which preferentially populate high angular momentum states, could be used to identify the 1/2+[880] band.

In summary, we have identified all of the single-particle states in the subshell between N=152 and N=164 in ^{251}Cf. We have also calculated the levels above the N=164 gap and have tentatively identified the 1/2-[761] and 9/2+[604] orbitals. The position of the 1/2-[761] orbital provides information about the $j_{13/2}$ spherical shell orbital which lies above the N=184 neutron gap. If the excitation energy of the 1/2+[880] orbital can be determined, we will then have some experimental information on all of the spherical orbitals between N=184 and N=224. These constraints should help us to determine the feasibility of making superheavy elements.

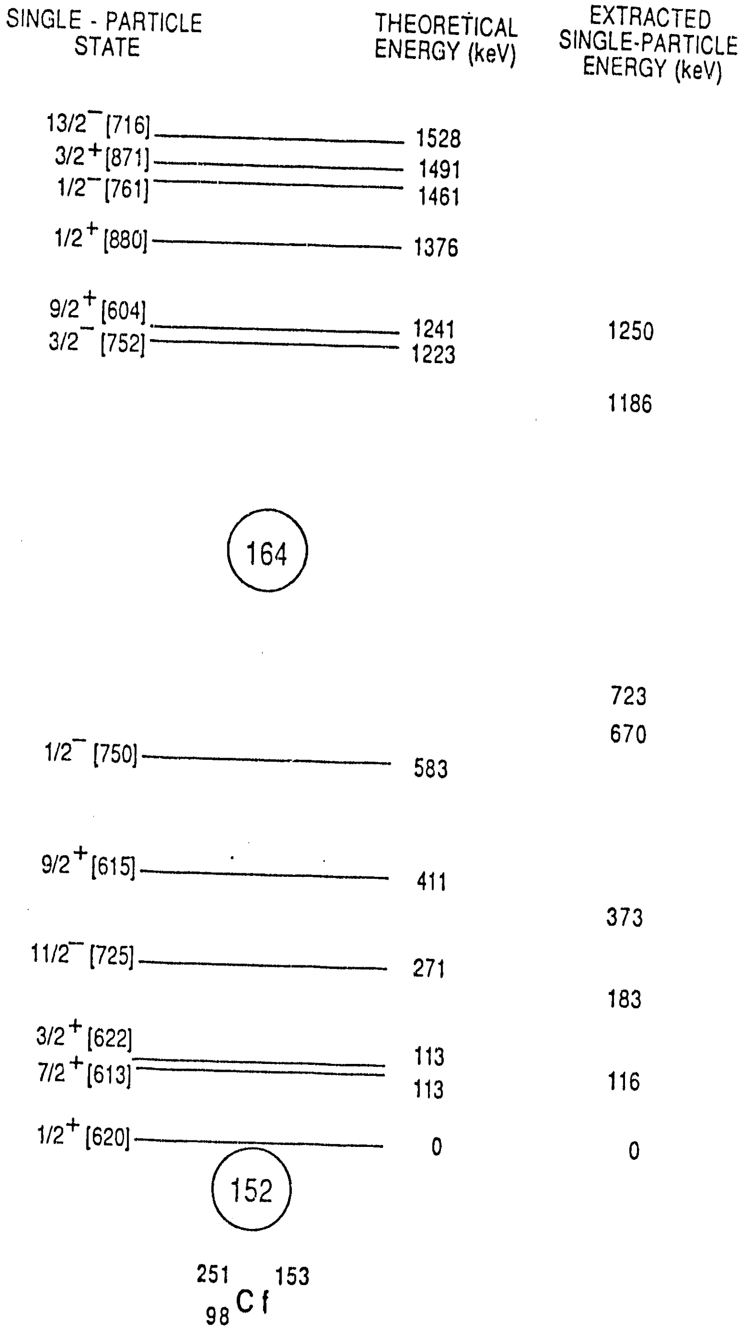

Fig. 4. Theoretical (left column) and extracted (right column) energies of neutron single-particle states. Theoretical energies were calculated with a Woods-Saxon potential, using ν_2=0.25, ν_4=-0.01 and ν_6=+0.02. The extracted energies were obtained by removing the contribution of pair correlation effects from the experimental level energies. A constant matrix element (G=21/A MeV) was used for the pairing calculations.

Table I C_j^2 for Neutron Single-Particle States Above N=152

State	a	1/2	3/2	5/2	7/2	9/2	11/2	13/2	15/2	17/2
$1/2^+[620]$	+0.402	0.131	0.041	0.209	0.216	0.238	0.133	0.030	-	-
$7/2^+[613]$		0.0	0.0	0.0	0.003	0.843	0.102	0.049	0.0	0.003
$3/2^+[622]$		0.0	0.168	0.091	0.358	0.161	0.196	0.024	0.0	0.002
$11/2^-[725]$		0.0	0.0	0.0	0.0	0.0	0.010	0.004	0.981	0.0
$9/2^+[615]$		0.0	0.0	0.0	0.0	0.069	0.914	0.016	0.0	0.0
$1/2^-[750]$	-3.8	0.031	0.183	0.039	0.383	0.025	0.207	0.011	0.120	0.0
$3/2^-[752]$		0.0	0.048	0.055	0.309	0.094	0.291	0.063	0.137	0.0
$9/2^+[604]$		0.0	0.0	0.0	0.0	0.910	0.076	0.009	0.0	0.005
$1/2^+[880]$	+8.3	0.006	0.001	0.002	0.004	0.029	0.001	0.209	0.0	0.743
$1/2^-[761]$	+3.9	0.031	0.0	0.186	0.034	0.347	0.049	0.332	0.019	0.0
$3/2^+[871]$		0.0	0.001	0.042	0.030	0.022	0.008	0.191	0.0	0.701
$13/2^-[716]$		0.0	0.0	0.0	0.0	0.0	0.0	0.001	0.997	0.0
$11/2^+[606]$		0.0	0.0	0.0	0.0	0.0	0.996	0.003	0.0	0.0
$3/2^+[611]$		0.0	0.0	0.516	0.202	0.158	0.050	0.017	0.0	0.056
$5/2^+[862]$		0.0	0.0	0.030	0.067	0.014	0.013	0.165	0.001	0.702

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