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Configuration Mixing of Two-Quasiparticle States in ^{250}Cf†

S. W. Yates
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439, and Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506

and

I. Ahmad, A. M. Friedman, and K. Katori*
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439

and

C. Castaneda and T. E. Ward
Cyclotron Laboratory, Indiana University, Bloomington, Indiana 47401
(Received 23 February 1976)

The interaction of a $K^\pi = 5^-$ two-quasiproton band with a $K^\pi = 5^-$ two-quasineutron band in ^{250}Cf has been observed using proton and neutron transfer reactions and radioactive-decay measurements. Configuration-mixing calculations using a two-body neutron-proton force give an interaction matrix element in good agreement with the value derived from our measurements.

In recent years the interaction of two-quasineutron states with two-quasiproton states has been observed[1-5] between high K states in the hafnium region. Massmann *et al.*[6] have developed a theoretical treatment of configuration mixing due to a two-body neutron-proton force which reproduces the experimental mixing quite well. In this Letter we report the observation of this configuration mixing in a different region of deformation and, in particular, between two $K^\pi = 5^-$ bands of ^{250}Cf.

From an initial investigation[7] of the electron capture decay of 8.6-h ^{250}Es, $K^\pi = 5^-$ bands based at 1396 and 1478 keV were identified. Although definite spin-parity assignments were possible in this study,[7] the configurations of these states could not be uniquely determined. A portion of the decay scheme showing primarily the high K states of ^{250}Cf is given in Fig. 1. From single-particle-level systematics the only probable two-quasiparticle configurations for these states are $\{\frac{1}{2}^+[620]n;\frac{9}{2}^-[734]n\}_{5^-}$, $\{\frac{1}{2}^+[631]n;\frac{9}{2}^-[734]n\}_{5^-}$, and $\{\frac{3}{2}^-[521]p;\frac{7}{2}^+[633]p\}_{5^-}$. Since $\frac{9}{2}^-[734]n$ is the ground-state configuration of ^{249}Cf and the $\frac{7}{2}^+[633]$ proton orbital is the ground state of ^{249}Bk, the neutron and proton transfer reactions into the ^{250}Cf final nucleus should aid in delineating the correct Nilsson orbital assignments. The reactions ^{249}Cf$(d,p)^{250}$Cf and ^{249}Bk$(\alpha,t)^{250}$Cf were therefore studied to deduce the configurations of these $K^\pi = 5^-$ bands.

The charged-particle transfer experiments were performed using 12-MeV deuteron and 28-MeV α-particle beams from the Argonne FN tandem Van de Graaff accelerator. Reaction products were analyzed with an Enge split-pole magnetic spectrograph, and the particles were recorded using nuclear emulsion plates. Targets

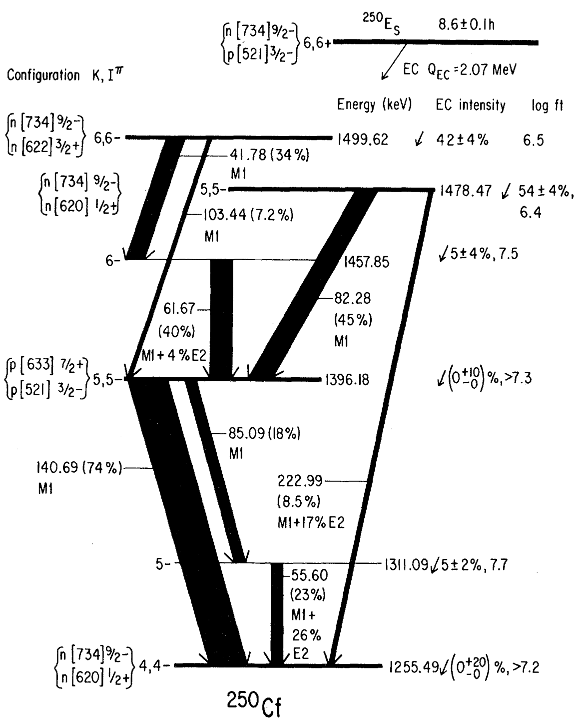

FIG. 1. Decay scheme of 8.6-h ^{250}Es showing high K states of ^{250}Cf. The level energies and spin parities are based on Ref. 7 and the two-quasiparticle configuration assignments are deduced from this work and Ref. 8. The labels for the $K^\pi = 5^-$ bands represent the dominant configurations.

were prepared using the Argonne electromagnetic isotope separator by deposition of the actinide ions on 40-μg/cm^2 carbon foils. Spectra from the reactions ^{249}Cf(d,p) and ^{249}Bk(α,t) are shown in Fig. 2. It is evident from these spectra that the $K^\pi = 5^-$ bands at 1396 and 1478 keV are populated in both reactions. Since the (α, t) reaction can only populate two-quasiproton states in an even-even nucleus and the (d,p) reaction will populate only two-quasineutron states, it is also apparent that these bands must be of mixed character. Additional evidence for configuration mixing between these states is adduced from the γ-ray branching observed following the 8.6-h ^{250}Es decay.[7] The intense transition between the 5^- states can occur only if these states have a particle common to both or if there is strong configuration mixing between them.

The ground state of ^{249}Bk has been established[9] to be the $\frac{7}{2}^+[633]$ Nilsson state. Hence one component of the two-quasiproton states populated in the reaction ^{249}Bk$(\alpha,t)^{250}$Cf must be the $\frac{7}{2}^+[633]$ orbital. As pointed out earlier, the spins and parities of all the states shown in Fig. 1 have been deduced from radioactive-decay data.[7] The composition of the $K^\pi = 5^-$ state at 1396 keV must be $\{\frac{7}{2}^+[633]p;\frac{3}{2}^-[521]p\}_{5^-}$, because no other proton orbital can combine with the $\frac{7}{2}^+[633]$ state to produce a $K^\pi = 5^-$ band at this low excitation energy.

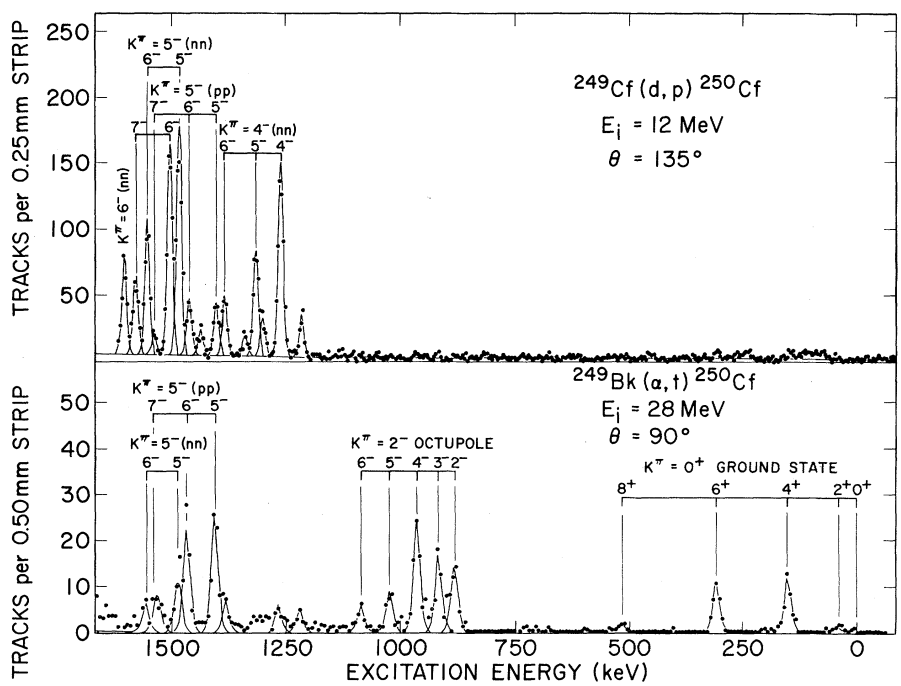

FIG. 2. Spectra from the reactions ^{249}Cf$(d,p)^{250}$Cf and ^{249}Bk$(\alpha,t)^{250}$Cf.

The $K^\pi = 2^-$ octupole band at 872 keV, known from radioactive-decay studies,[7] is also populated in the (α, t) reaction, since this band contains a large $\{\frac{7}{2}^+[633]p; \frac{3}{2}^-[521]p\}_{2^-}$ two-quasiproton component.

From α-decay studies[10] the ^{249}Cf ground state is known to be the $\frac{9}{2}^-[734]$ single-particle orbital. Thus any two-quasineutron state excited in the neutron transfer reaction must contain the $\frac{9}{2}^-[734]$ orbital as one component. The $K^\pi = 4^-$ and 5^- bands at 1255 and 1478 keV which are populated strongly in the reaction ^{249}Cf$(d,p)^{250}$Cf must have one neutron in the $\frac{9}{2}^-[734]$ orbital and the other in a $K^\pi = \frac{1}{2}^+$ orbital. Only two $K^\pi = \frac{1}{2}^+$ single-particle states are available at low excitation energy: the $\frac{1}{2}^+[620]$ particle state ($U^2 \sim 0.97$) and the $\frac{1}{2}^+[631]$ hole state ($U^2 \sim 0.03$). Since the (d,p) reaction cross section is directly proportional to U^2, the orbital to which the neutron is transferred must be the $\frac{1}{2}^+[620]$ state, and the configurations of the 1255- and 1478-keV states can only be $\{\frac{9}{2}^-[734]n; \frac{1}{2}^+[620]n\}_{4^-}$ and $\{\frac{9}{2}^-[734]n; \frac{1}{2}^+[620]n\}_{5^-}$, respectively. Additional support for the above assignments of the two-quasiproton and two-quasineutron states comes from the excellent agreement between the experimental and calculated relative cross sections to various members of the rotational bands. The detailed analysis of two-quasiparticle states of ^{250}Cf will be published elsewhere.[8]

For the case of only two interacting configurations the unperturbed energies, E_1 and E_2, of the pure two-quasiproton and two-quasineutron states and the interaction matrix element, $\mathfrak{M}$, may be obtained from the following expressions[11]:

$$E_{H,L} = \tfrac{1}{2}[E_1 + E_2] \pm \tfrac{1}{2}[(E_1 - E_2)^2 + 4\mathfrak{M}^2]^{1/2} \qquad (1)$$

and

$$a_L^2/a_H^2 = (E_1 - E_L)/(E_2 - E_L). \qquad (2)$$

In the above equations a_L and a_H are the mixing amplitudes of the lower and higher states, and E_L and E_H are quasiparticle energies. From the ^{249}Cf$(d,p)^{250}$Cf reaction data the cross section ratio $[d\sigma(1396)/d\Omega]/[d\sigma(1478)/d\Omega]$ was measured to be 0.234 ± 0.016. No excitation energy corrections were made to the experimental cross sections, since distorted-wave Born-approximation calculations indicate that any Q dependence of the reaction for these states would be small. The mixing ratio (a_L^2/a_H^2) given above, which is identical with the parameter χ of Massmann *et al.*,[6] was observed to be independent of angle and the above value represents an average over the three angles of measurements. The unperturbed energy of the pure two-quasiproton state was calculated to be 1411 keV, while the unperturbed two-quasineutron state would be at 1463 keV. The measured interaction matrix element is 32 ± 2 keV. As noted by Massmann *et al.*,[6] this matrix element is not very sensitive to changes in the mixing ratio when the ratio is large but is more dependent on the energy differences of the like-spin members of the two bands. The value of the mixing ratio derived from the (α, t) reaction is 0.19 ± 0.08, in good agreement with the value obtained from the neutron transfer reaction.

It is important to compare the experimentally determined mixing matrix element to that obtained using the theoretical approach of Massmann *et al.*.[6] For the case of parallel angular momentum projections (i.e., $\Omega = \Omega_{n_1} + \Omega_{n_2}$ and $\Omega_{p_1} + \Omega_{p_2}$) the interaction matrix element is given by

$$\mathfrak{M} = |(U_{n_1}V_{n_2}U_{p_1}V_{p_2} + V_{n_1}U_{n_2}V_{p_1}U_{p_2})\langle n_1\bar{p}_2|V_{np}|\bar{n}_2p_1\rangle - (U_{n_1}V_{n_2}V_{p_1}U_{p_2} + V_{n_1}U_{n_2}U_{p_1}V_{p_2})\langle n_1\bar{p}_1|V_{np}|\bar{n}_2p_2\rangle|, \qquad (3)$$

where U_i and V_i are the BCS amplitudes, a bar denotes a time-reversed state, and V_{np} is the effective neutron-proton potential. In the present study Ω_{n_1}, Ω_{n_2}, Ω_{p_1}, and Ω_{p_2} denote the $\frac{9}{2}^-[734]n$, $\frac{1}{2}^+[620]n$, $\frac{7}{2}^+[633]p$, and $\frac{3}{2}^-[521]p$ orbitals, respectively. The pairing factors were calculated using the gap parameters ($\Delta_{n,p} = 650$ keV), which are in good agreement with values obtained from the two-quasineutron and two-quasiproton energies of ^{250}Cf, and the one-quasiparticle energies for this mass region as given by Ellis and Schmorak.[12] The pairing-strength parameters $G_n(G_p)$ were adjusted so that the BCS calculations reproduced the experimental pairing-gap parameters. The off-diagonal V_{np} matrix elements calculated with Force I ($r_0 = 1.5$ fm) and Force II ($r_0 = 1.0$ fm) of Ref. 6 are $\langle\frac{9}{2}\frac{\bar{3}}{2}|V_{np}|\frac{\bar{1}}{2}\frac{7}{2}\rangle_{3^-} = -131.8$ and -70.0 keV and $\langle\frac{9}{2}\frac{\bar{7}}{2}|V_{np}|\frac{\bar{1}}{2}\frac{3}{2}\rangle_{1^-} = -60.0$ and 16.4 keV, respectively. These matrix elements yield $\mathfrak{M} = 27.3$ keV (Force I) and $\mathfrak{M} = 21.7$ keV (Force II). In the present calculation, Coriolis effects were also considered. The inclusion of Coriolis coupling of the $K_{nn}{}^{\pi} = 4^-$ (1255 keV) and 5^- (1478 keV) bands in the calculation increased the mixing matrix elements by 1.4 and 1.1 keV. The total mixing matrix elements, including Coriolis effects, are 28.7 keV and 22.8 keV for Forces I and II, respectively. The experimental value of 32 ± 2 keV is in better agreement with the value calculated with Force I. However, in the case of the rare-earth nuclei[6] Forces I and II enjoyed nearly equal success in reproducing the experimental mixing ratios. Thus the experimental data presently available do not allow one to decide which force defines the residual neutron-proton interaction in a more realistic way.

In summary, the present study shows that the phenomenon of configuration mixing through the off-diagonal V_{np} interaction occurs in actinide as well as rare-earth nuclei. Hence, an understanding of this residual interaction is important in explaining the level structure of deformed nuclei. By examining more nuclei, it should be possible to establish the nature of the effective neutron-proton force.

We acknowledge the help of J. Lerner for fabrication of the actinide targets and R. K. Sjoblum for performing the chemical separations. We are indebted to Professor J. O. Rasmussen for providing the off-diagonal V_{np} code and Dr. T. L. Khoo for helpful discussions.

†Work performed under auspices of the U. S. Energy Research and Development Administration.

*Present address: Tokyo University of Education, Tokyo, Japan.

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High-Spin Isomeric States in $^{202,204,206}Po$†

H. Beuscher
Cyclotron Institute, Texas A&M University, College Station, Texas 77843, and Institut für Kernphysik, Kernforchungsanlage Jülich, 517 Jülich, West Germany*

and

D. R. Zolnowski, D. R. Haenni, and T. T. Sugihara
Cyclotron Institute, Texas A&M University, College Station, Texas 77843
(Received 17 February 1976)

Several new isomeric states above the well-known $(h_{9/2})^2$ 8^+ level have been observed in $^{202,204,206}Po$. They can be accounted for by simple weak coupling between two-particle or two-quasiparticle states found in the closed-shell nuclei ^{210}Po and $^{200,202,204}Pb$.

Even-mass Po isotopes from mass number 200 to 210 have an isomeric 8^+ state which is believed to result from the $\pi(h_{9/2})^2$ configuration.[1-3] However, no higher spin states were known in the lighter Po isotopes analogous to the high-spin particle states in the closed-neutron-shell nucleus ^{210}Po [1,4] or the neutron quasiparticle states in nearby Pb isotopes with the closed proton shell.[5-7]

In this work the nuclei $^{202,204,206}Po$ have been studied by in-beam spectroscopy. With Ge(Li) detectors, γ-γ-t coincidence spectra, γ-ray angular distributions, and γ spectra time-related to the cyclotron beam bursts were obtained. Conversion electrons were measured with a broad-range electron spectrometer consisting of a steering magnet and a cooled Si(Li) detector.[8]