cussed in Ref. 4. In this calculation, $D/4\pi = 3.87 \times 10^{-12}$ cm^2 was used to give a good fit to the data. This was necessary because of the previously discussed nonquadratic behavior for the lower order branches. From Fig. 3 the agreement between theory and experiment is seen to be quite good. The initial slope of the dispersion relation obtained by numerical evaluation is still 0.02 for the $n = 3$ branch, but the linear portion of the dispersion extends only out to $k_\rho S < 0.01$. Thus the data for the higher order branches do not really represent a measurement of the initial slope. Just as in the case of the $n = 1$ branch of film C-5, the measurements are being made on a portion of the dispersion curve that is nonlinear because of repulsion between branches.

The present study demonstrates several important aspects of spin waves in finite films whose thickness is less than 1.2 μm. (1) Films having a magnetostatic branch do not indicate a strong repulsion between branches and have initial slopes of about 0.25. These data agree with the predictions of the theory for films having unpinned surface spins.[4] (2) In the case of unpinned surface spins, the discrepancy between experiment and theory for $k_\rho S > 0.1$ is not understood at present. (3) Inhomogeneities in the demagnetizing fields are small. (4) Films that have several strong magnetoexchange branches obey a quadratic dispersion relation, show strong repulsion between even branches, and have initial slopes for the first branch of about 0.20. All of these data are in agreement with the theory of Wolfram and De Wames and verify their contention that branch repulsion cannot be neglected.

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[9] More recent data confirm this contention. Modes are observed after the $n = 3$ branch passes through the $n = 4$ branch.

0^+ Excited States in the Actinides*

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We present a calculation of 0^+ excited states in the actinides for a pairing-force theory of the type suggested by Griffin, Jackson, and Volkov. Contrary to previous results, we find that such a theory does not explain low-lying 0^+ excited states in the actinides any better than does a conventional pairing-force theory.

It has recently been proposed[1,2] that the low-lying 0^+ excited states seen in the actinides can be explained in terms of a modified pairing-force theory. The basic idea of this modified theory is to label single-particle states as oblate or prolate and to assume that the pairing-force matrix elements between an oblate and prolate state are considerably weaker than the matrix elements between two prolate states or two oblate states. The purpose of this Letter is to point out some serious objections to such an explanation for the low-lying 0^+ excited states in the actinides.

There are two distinct issues involved in the notion of prolate-oblate pairing, and we should distinguish between them at the outset. (1) Should the constant-G pairing-force model be replaced by a model in which the pairing-interaction matrix elements G_{ij} depend on the oblateness or prolateness of levels i and j? (2) If this replacement is made, does it explain the low-lying 0^+ excited states in the actinides? In this Letter, we assume that this replacement should be made, and carry out calculations in the framework of the modified theory in order to answer the second question.

Before describing the results of any calculations, we must first make our model somewhat more specific. The Hamiltonian that we use is

$$H = \sum_{r>0} 2\epsilon_r a_r^\dagger a_r - \sum_{r>0,\, s>0} G_{rs} a_r^\dagger a_{-r}^\dagger a_{-s} a_s, \quad (1)$$

where ϵ_r denotes a single-particle energy; $a_r^\dagger$ (a_r) denotes a fermion creation (annihilation) operator; G_{rs}, the pairing-interaction matrix element; and the index $-r$, the time-reversal partner of r. A single-particle state r is considered oblate if the single-particle energy ϵ_r increases with increasing quadrupole deformation of the single-particle potential. We denote the quadrupole deformation parameter as β_2. If the single-particle energy ϵ_r decreases as a function of β_2, the level r is considered prolate. We have plotted the energies of the neutron single-particle states, relevant to the actinides, as a function of β_2 using a Woods-Saxon single-particle potential. We find that many of these states show little change in energy as β_2 is varied from 0.2 to 0.3. Specifically, we note that the states $\frac{5}{2}^+[622]$, $\frac{7}{2}^+[624]$, $\frac{9}{2}^-[734]$, $\frac{1}{2}^+[620]$, and $\frac{3}{2}^+[622]$ cannot be meaningfully designated as either prolate or oblate. Nevertheless, a two-body δ-force interaction does suggest that the pairing-force matrix elements are larger for states that have similar slopes than for states having widely different slopes. The same interaction also suggests that the diagonal matrix elements of the pairing force are considerably larger than the off-diagonal matrix elements.

We incorporate these observations into a pairing-force model by setting

$$G_{rs} = G_0(1 - 0.5|T_r - T_s|), \qquad G_{rr} = 2G_0, \quad (2)$$

where T_r is a measure of the oblateness of level r and varies from $+1$ to -1. We have fixed values of T_r by setting it equal to the change in single-particle energy (in MeV) as β_2 is varied from 0.2 to 0.3, using a Woods-Saxon central field. If the change is larger than 1 MeV, we set $T_r = +1$ or -1 as is appropriate. The matrix elements which we have defined in this way are of the type suggested by Griffin, Jackson, and Volkov.[1] The new feature in Eq. (2) is that we are no longer making the artificial division of orbitals into just two categories, as has been done[1,2] previously.

In Fig. 1, we display the relevant single-particle states plotted as a function of β_2 for a Woods-Saxon potential. The level orderings of this potential are in rough agreement with experiment for $\beta_2 = 0.23$. Higher-order deformations such as β_4 and β_6 improve the agreement with experiment considerably. In the calculations we report, however, we use the single-particle energies extracted from experimental data whenever such data are available.

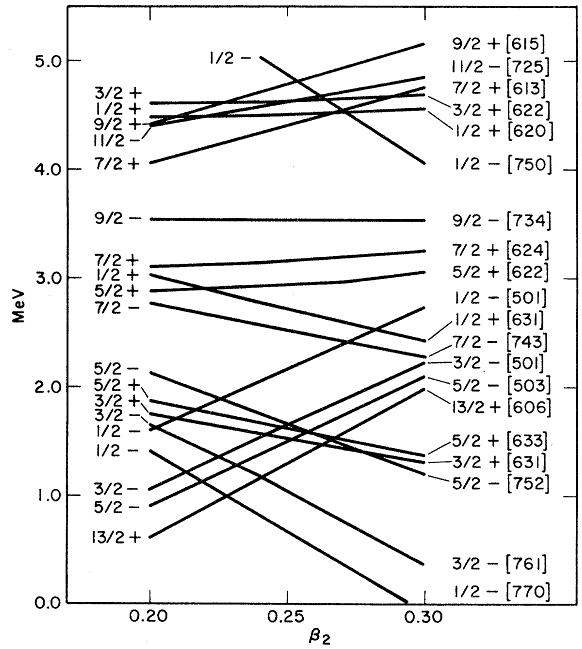

FIG. 1. Neutron single-particle states plotted as a function of quadrupole deformation in a Woods-Saxon single-particle potential.

The calculational technique that we use to determine the eigenvalues is a slightly improved version of the correlated quasiparticle method.[3] This method is used to compute the seniority-zero ($S=0$) ground state and the $S=2$ excited states in the even-neutron-number nuclides. We also use it to compute the $S=1$ states in adjacent odd-neutron-number nuclides. A separate calculation is made for each state, and the appropriate levels are blocked. The correlated quasiparticle method is combined with previously reported results[4] to compute the $S=0$, 0^+ pairing excited states conveniently and rapidly.

The inputs necessary to carry out the calculation are values of the single-particle energies ϵ_r and an overall pairing interaction strength G_0. Most of the relevant single-particle energies can be extracted from the experimental studies of single-neutron-transfer reactions. Such calculations have been carried out for the constant-G pairing-force model in studies[5] of ^{235}U and the odd-mass[6] Cm isotopes. As the state $\frac{1}{2}^-[501]$ plays such an important role in the explanation[2] of the 0^+ excited states, we emphasize that this is the most intensely populated state in (d, t) studies of the actinides and its energy is well known.

The excitation energies of the $S=2$ states in the even–neutron-number nuclides are quite sensitive to G_0, and we use these data to fix the magnitude of G_0. The value of G_0 and the single-particle energies ϵ_r are somewhat interdependent, but the dependence on G_0 is not very strong in the $S=1$ odd-mass spectra, and we can disentangle the various quantities.

When the quantities ϵ_r and G_0 are put into the Hamiltonian of Eq. (2), the output is the experimentally observed single-particle spectrum. Making use of the known data in ^{235}U, and the recent determination[7] of the $S=2$ states in ^{236}U, we obtain, using thirity levels in our computation,

$$G_0 = 0.137 \text{ Mev} \tag{3}$$

and an extracted single-particle spectrum that is essentially the same as obtained[5] for ^{235}U using the constant-G pairing-force model. The one noticeable difference is that the extracted energy of the state $\frac{1}{2}^-[501]$ is now 100 keV further from the Fermi level than was the case in the earlier calculations. Using the same values for G_0 and the single-particle energies, we calculated the energy of the 0^+ pairing excited state to be 1120 keV. The suggestion was made[2] that the configuration in which the $\frac{1}{2}^-[501]$ level is empty is an important component of the 0^+ excited state. Denoting the ground state as $|0\rangle$, we have

$$|\varphi_{1/2^-}\rangle = \frac{[(1-N_{1/2^-}) - \langle 1-N_{1/2^-}\rangle]|0\rangle}{[\langle N_{1/2^-}\rangle\langle 1-N_{1/2^-}\rangle]^{1/2}}, \tag{4}$$

as the configuration orthogonal to the ground state, in which the level $\frac{1}{2}^-[501]$ is essentially empty. The angular brackets denote ground-state expectation values. We have evaluated the quantity $\langle\varphi_{1/2^-}|H|\varphi_{1/2^-}\rangle$ and find that it is ~2.5 MeV; this configuration makes very little contribution to the low-lying 0^+ excited state, and we conclude that weak prolate-oblate pairing forces are not relevant to the 0^+ excited state in the 144-neutron system. An examination of the data for the Cm isotopes[6] indicates that the single-particle energy of the state $\frac{1}{2}^-[501]$ is ~1 MeV below the energy of the Fermi level, and the configuration $|\varphi_{1/2^-}\rangle$ does not contribute substantially to the low-lying 0^+ excited states of nuclides having more than 144 neutrons.

It appears somewhat more plausible to associate the configuration $|\varphi_{1/2^-}\rangle$ with low-lying 0^+ excited states in nuclides having 142 neutrons or fewer. There is a good deal of relevant data[8] on ^{234}U, and we have carried out some computations for this nuclide. Using the same value of G_0 as in ^{236}U, we obtain the $S=2$ state with unpaired particles in the levels $\frac{7}{2}^-[743]$ and $\frac{5}{2}^+[633]$ at 1380 keV, in good agreement with the experimental value[8] of 1428 keV. Making use of these data,[8] we also compute that the state $\frac{1}{2}^-[501]$ has an extracted single-particle energy 600 keV below the energy of the level $\frac{5}{2}^+[633]$ in U^{234}. The energy of the configuration $|\varphi_{1/2^-}\rangle$ is 2400 keV in this nuclide and it is not an important component of the lowest-pairing 0^+ excited state. We note that our calculation gives the energy of this 0^+ state as 1400 keV in ^{234}U, which is substantially above the experimentally observed 0^+ state at 810 keV. The nature of the state observed at 810 keV remains to be explained.

We have carried out the same series of computations reported above in the framework of the constant-G pairing-force model The excitation energies we obtain for the 0^+ excited states are about the same as given by the pairing-force model of Eq. (2). The energies are in fair agreement with experiment for nuclides having 144 neutrons or more, but in poor agreement with experiment for nuclides having 142 neutrons or fewer.

We emphasize that the results of this Letter should not be construed as evidence against the validity of a pairing-force model with small matrix elements between prolate and oblate states. However, we do conclude that such a model does not afford an improved explanation of low-lying 0^+ excited states in the actinides.

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