spin assignment for the 1.90-MeV state.

The evidence that a large anisotropy is associated with the excitation of zero-spin states suggests that compound elastic scattering should be strongly anisotropic for nuclei with zero-spin ground states. The Hauser-Feshbach calculation for excitation of the ground state of Pb^{206} at 2.5 MeV gives a value of 7 for the ratio of yields 0°/90°. This result is in contrast to the assumption usually made in the optical-model analysis of elastic neutron scattering that compound elastic scattering is isotropic. The agreement reported here between experiment and calculation for a zero-spin excited state suggests that the large anisotropy calculated for the ground state must be taken seriously.

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*Work done under the auspices of the U. S. Atomic Energy Commission.

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EVIDENCE FOR NUCLEAR PAIRING EFFECTS AT THE FISSION BARRIER*

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In order to acquire a complete understanding of the problem of the structure of finite nuclei, it would be useful to know the properties of nuclei as a function of nuclear deformation. Although such information is, in general, beyond present experimental capability, that particular deformation associated with the saddle point of a fissioning nucleus can be studied by means of the angular distribution of fission fragments.[1] This Letter reports the application of the (d,pf) reaction to this problem at excitation energies just above the fission threshold, where superfluidity effects[2] of the nuclear pairing are most in evidence, especially those effects which distinguish the finite, isolated nuclear superfluid[3] from the infinite systems usually considered.[4,5]

The results corroborate directly the expected[3] discontinuity in the spectrum at the onset of two-quasiparticle excitations, and the indicated[5] increase in the energy gap over that occuring at stable deformations for Pu^{240}. They also evidence certain more detailed structure which is consistent with the existence of low-lying collective excitations at the fission barrier analogous to those observed at the stable shape.

The experiment involves measuring the angular distribution of fission fragments emitted in coincidence with protons from the (d,p) process. The experimental method is similar to that used in a previous determination of fission thresholds.[6] Semiconductor fission detectors are situated in a plane defined by the incoming 14.9-MeV deuteron beam and the direction of the observed reaction protons. The proton detector consisted of a semiconductor transmission detector followed by a semiconductor detector in which the protons stop. Protons were identified by an analog computer.[7] A coincidence circuit with $\tau = 50$ nsec was used to select proton-fission events which originated from individual cyclotron beam bursts.

In a preliminary experiment, the angle of the proton detector was fixed and a movable fission detector was used to measure the shape of the coincident fission-fragment angular distribution. The fragment distribution was peaked fore and aft along an axis which lies near the recoil direction, φ_R, of the excited fissioning nucleus. The more accurate data reported here were taken with the proton detector at -140 deg to the deuteron beam, and simultaneously data were gathered with fission detectors at +20, +110, and +155 deg to the beam. The proton spectra were recorded in a 400-channel analyzer which was gated in 100-channel blocks according to which fission detector responded, and the fourth 100-channel block was used to monitor the chance coincidence rate associated with one fission detector. Chance rates were typically 5% of the true rates.

To analyze the experimental data, we consider a target of spin I_0 into which a neutron of angular momentum j and orbital angular momentum l is stripped to form a compound state of angular momentum J. This compound state then fissions through a barrier state described by a symmetric top wave function with projection, K, of angular momentum along the nuclear symmetry axis.

It is assumed that in any interval of excitation energy, stripping occurs into overlapping single-particle states whose distribution in j is identical with the distribution of j among all the levels of the relevant major oscillator shell ($N = 7$), and whose distribution in J is obtained from this distribution by Clebsch-Gordan addition of the (isotropically distributed) target spin I_0 to each value of j. It is further assumed that all interference terms among various stripping processes, j, vanish. This allows the total angular correlation to be calculated by adding the angular correlation functions corresponding to various (j, J) values, weighted by their respective distorted-wave Born approximation (DWBA)[8] cross sections.

These assumptions are considered justifiable first approximations because of the high density of single-particle neutron states in such heavy nuclei and because of their strong deformation, which effects a mixture of various j values into each single-particle eigenstate.

Then the angular distribution of the fragments is given by

$$W(\theta) = \sum_K \rho(K) \sum_{jJ} \sigma(j, J) \sum_{L=\text{even}} \bar{g}_L(K, j, J; I_0) \times P_L(\cos(\varphi - \varphi_R)), \quad (1)$$

where $\rho(K)$ is the probability of fission through a state with projection K, $\sigma(j, J)$ is the probability of a given neutron stripping process (proportional to the DWBA stripping cross section), and $\bar{g}_L$ is a geometrical weighting coefficient. Equation (1) involves a plane-wave approximation for the angular correlations. This approximation was found (by comparison with DWBA calculations[9]) to be appropriate for the proton angle (140 deg) used in this experiment. The nuclear recoil direction is defined by φ_R.

We assume the usual (second part of reference 1) Gaussian distribution of K values defined by one parameter, K_0^2. Then the angular distribution (1) reduces to

$$W(\varphi) = 1 + g_2(I_0, K_0^2) P_2(\cos(\varphi - \varphi_R)) + \cdots, \quad (2)$$

where

$$g_2 = \sum_K \rho(K) \sum_{jJ} \sigma(j, J) \bar{g}_2(K, j, J; I_0). \quad (3)$$

For each proton energy (which defines the excitation energy), data from the fission detectors were converted to the center-of-mass system for the fissioning nucleus and then fitted to a distribution of this form. The resulting values of g_2 are plotted in Fig. 1(b) as a function of the excitation energy above the fission threshold.

The P_4 term in (1) can be observed in principle, but its coefficient is too small for it to be extracted from the present data with sufficient precision. If its coefficient, g_4, could be measured, a two-parameter function could be used in place of the Gaussian to give more detailed information on the distribution of K values.

The calculated function, $g_2(K_0^2)$, is plotted in Fig. 2 for the two cases considered here. Note that the target spin has a large effect, and provides the essential difference between the two curves. From this curve the values of K_0^2 [Fig. 1(c)] were obtained as a function of $E^* - E_f$ from the measured values of g_2 [Fig. 1(b)].

The analysis is subject to verification at both extremes of the excitation energy realized in the present experiment. A well-defined upper limit is implied for g_2 when $K_0^2 = 0$, as in the case for $E^* - E_f = 0$ in an even-even nucleus. Comparison of Figs. 1(b) and 2 shows that this limit is approximately realized in both nuclei. The second test is the comparison with K_0^2 values obtained independently from neutron studies at the higher excitation energies.[5,10] It is seen that here again the agreement is satisfactory.

The experimental results and the theoretically

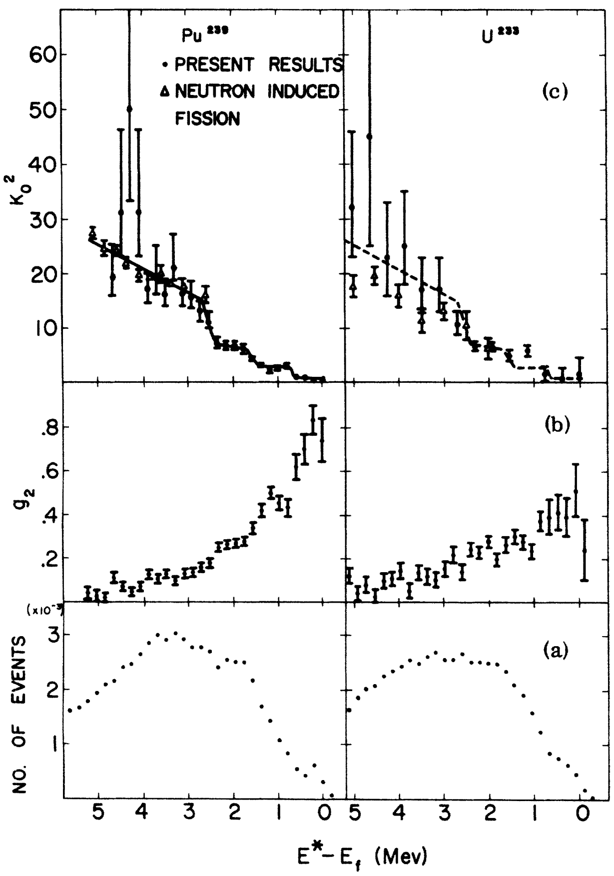

FIG. 1. (a) Coincident proton spectrum, (b) the values of g_2 extracted from the measured angular correlation function, and (c) K_0^2 as calculated from g_2 by methods explained in the text, are plotted against excitation energy in excess of the fission threshold. The neutron data and its analysis for Pu^{240} can be found in Griffin[5] and Simmons[10]; for U^{233}, see Simmons and Henkel[10] and Blumberg and Griffin.[10]

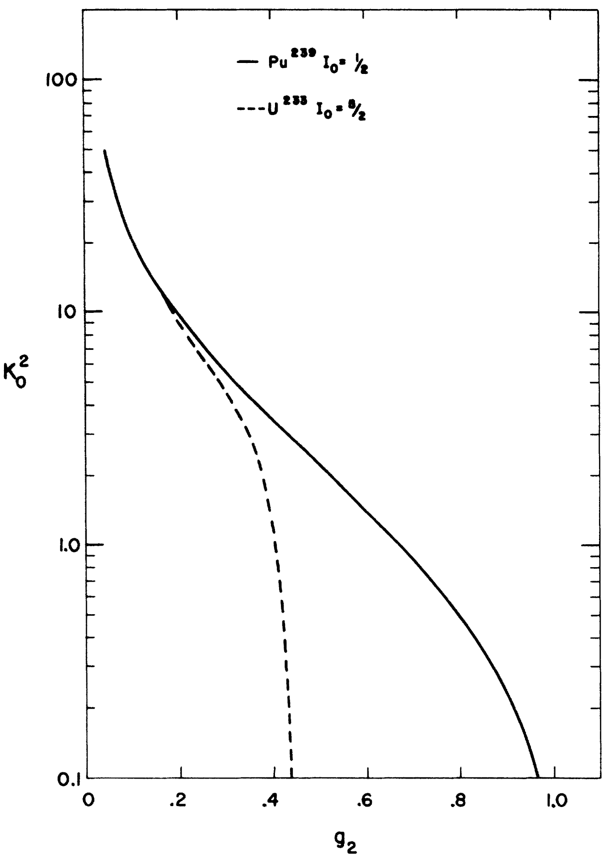

FIG. 2. Plot of $K_0^2(g_2)$ obtained from the calculated function $g_2(K_0^2)$.

inferred values of K_0^2 are plotted in Fig. 1. For Pu^{240} there is rather definite evidence for a steep increase in K_0^2 at $E^* - E_f \approx 2.7$ MeV (and smaller increases at 0.7 and 1.6 MeV). This energy is close to that expected from the saddle shape pairing gap ($\lesssim 2\Delta_0 = 2.7$ MeV) obtained indirectly for Pu^{240} from neutron and alpha-particle data at higher excitations[5]; the magnitude of K_0^2 after this rise is also consistent with the average value expected for two free quasiparticles in this nucleus ($K_0^2 = 2\langle k_p^2\rangle \approx 16$ to 20). The smaller steps are also interpretable as analogs of the γ vibrations of stable nuclei: a single γ excitation would contribute 4 (vs $K_0^2 = 3$ observed) to the average K_0^2 while a double-γ vibration would contribute $(2/3)\times 16 = 10.7$ (vs 6 to 7 observed). The value observed should, of course, be less than these values because of $K = 0$ contributions from the ground-state rotational band.

The U^{234} data are statistically inferior to those for Pu^{240} and could easily be described by a smooth curve lacking the structure evident in Pu^{240}. We have, therefore, superimposed on the U^{234} data the same structured curve drawn through the Pu^{240} data to indicate merely that there is no evidence of a statistically significant difference between the K_0^2 curves for the two nuclei.

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INVESTIGATION OF Y^* AND $\bar{Y}^*$ PRODUCTION IN REACTIONS OF THE TYPE $\bar{p}+p\rightarrow Y+\bar{Y}+\pi$†

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In a recent Letter[1] we reported the observation of $Y_1^*(1385)$ and $\bar{Y}_1^*(1385)$ in $\bar{p}$-p reactions leading to the final state $\Lambda+\bar{\Lambda}+\pi^++\pi^-$. A striking feature of these reactions was the predominance of Y_1^{*-} (and $\bar{Y}_1^{*+}$), a result inconsistent with the exchange of a particle [e.g., K or $K^*(885)$] with isotopic spin of one half. In the following we report the observation of $Y_0^*(1405)$, $Y_0^*(1520)$, as well as the $Y_1^*(1385)$, and their antiparticles in $\bar{p}$-p reactions leading to three-body final states of the form $Y+\bar{Y}+\pi$. We find that these reactions proceed primarily by resonance production: $\bar{p}+p\rightarrow Y^*+\bar{Y}$ (and $\bar{p}+p\rightarrow\bar{Y}^*+Y$). In contrast to the previous result,[1] the $Y^*+\bar{Y}$ ($\bar{Y}^*+Y$) reactions show excellent agreement with the single-K or -K^* exchange model. An analysis of the masses and widths of the Y_0^* and Y_1^* states produced in these reactions yields results consistent with previous determinations[2] for the $Y_0^*(1405)$ and $Y_0^*(1520)$ but yields a result of 26 ± 5 MeV for the full width of the $Y_1^*(1385)$. These data come from a study of 300 000 photographs obtained with a 20-in. liquid hydrogen bubble chamber in a separated antiproton beam at the AGS. The following reactions have been investigated:

$$\bar{p}+p\rightarrow\Sigma^++\bar{\Lambda}+\pi^-, \qquad (a)$$

$$\rightarrow\bar{\Sigma}^-+\Lambda+\pi^+, \qquad (\bar{a})$$

$$\rightarrow\Sigma^-+\bar{\Lambda}+\pi^+, \qquad (b)$$

$$\rightarrow\bar{\Sigma}^++\Lambda+\pi^-. \qquad (\bar{b})$$

The total cross sections for these reactions are found to be 54 ± 15 μb for 3.25 BeV/c and 89 ± 16 μb for 3.69 BeV/c incident momentum of the $\bar{p}$. Since statistics are small at 3.25 BeV/c, the following discussion is limited to the 3.69 BeV/c events only. In the events studied, both hyperon decays were seen so that four-constraint fits could be obtained for most production vertices by means of the IBM-7094 KICK and YACK programs. Thus events are well identified and quantities used for further analysis are well determined.

The general features of these reactions include a strong preponderance of a, $\bar{a}$ over b, $\bar{b}$, and a strong tendency of $\bar{Y}$ to travel forward and of Y to travel backward in the center-of-mass system. The $\pi^\pm$ show only slight tendencies to deviate from isotropy. It appears that these reactions are mostly "peripheral" in character, involving low momentum transfers. As will be discussed in detail, the resonant states $Y^*\rightarrow Y+\pi$ and $\bar{Y}^*\rightarrow\bar{Y}+\pi$ are produced copiously.

In Fig. 1 a Dalitz plot for the square of the