[11]J. C. Hardy, A. D. Bacher, G. R. Plattner, J. A. Macdonald, and R. G. Sextro, to be published.

[12]These L values are determined from independent spin and parity assignments for the final states. [See the reviews by F. Ajzenberg-Selove, Univ. of Calif., Los Angeles, Reports ("Lemon Aid Preprints") No. LAP-76 and No. LAP-82 (to be published).] The (2^+) assignment to the 9.72-MeV level in ^{14}O is from D. G. Fleming, J. C. Hardy, and J. Cerny, to be published; since it is a "normal" transition, its uncertainty does not affect any of the arguments given here.

[13]W. T. H. Van Oers and J. M. Cameron, Phys. Rev. 184, 1061 (1969), and private communication. In order to improve the details of the fits to our cross-section data we have increased the imaginary well depth in these parameters. This is not uncommon in such light nuclei [see, for example, L. A. Kull and E. Kashy, Phys. Rev. 167, 963 (1968)], and has little effect on the predicted analyzing powers.

[14]L. N. Blumberg, E. E. Gross, A. van der Woude, A. Zucker, and R. H. Bassel, Phys. Rev. 147, 812 (1966).

[15]Private communication from N. F. Mangelson quoted in Ref. 2. Recent polarization measurements of ^{3}He scattered from ^{12}C at 20 MeV [W. S. McEver et al., Phys. Rev. Lett. 24, 1123 (1970)] indicate the need for a spin-orbit potential of ≈4 MeV. No such potential was used in our analysis; however, its effects were checked and found not to influence our conclusions.

[16]J. C. Hiebert, E. Newman, and R. H. Bassel, Phys. Rev. 154, 899 (1967).

[17]All DWBA calculations reported here used the program DWUCK written by P. D. Kunz. The modifications to include the harmonic-oscillator form factor and coherent summation were made by us.

[18]N. K. Glendenning, Phys. Rev. 137, B102 (1965).
[19]B. F. Bayman and A. Kallio, Phys. Rev. 156, 1121 (1967).
[20]S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).

UNEXPECTED STRONG PAIR CORRELATIONS IN EXCITED 0^+ STATES OF ACTINIDE NUCLEI*

J. V. Maher, J. R. Erskine, A. M. Friedman, J. P. Schiffer,† and R. H. Siemssen
Argonne National Laboratory, Argonne, Illinois 60439
(Received 1 June 1970)

The (p,t) reaction has been studied with 17-MeV protons on targets of Th^{230}, $U^{234,236,238}$, and $Pu^{242,244}$. The results indicate unexpectedly strong $l=0$ transitions to states at about 900-keV excitation. Their cross sections are approximately 15% of the ground-state transitions; this percentage does not change appreciably with neutron number. This result, together with other available evidence, seems to suggest a simple and rather stable collective mode which has not yet emerged from any theoretical calculations.

Two-neutron–transfer reactions have proved to be especially sensitive in probing pair correlations in complex nuclei.[1] In our study of the (p,t) reaction on six even-even actinide targets, the yield of the $l=0$ transition to the first 0^+ state at $E_x \approx 900$ keV in each case was found to be approximately 15% of the yield of the ground-state transition. The observation of such uniformly strong $l=0$ transitions is not understood in terms of present models.

For most even-even target nuclei, two-neutron transfer with $l=0$ populates the ground state; excited 0^+ states have at most a few percent of the ground-state yield. Excited 0^+ states have been found previously to be strongly excited by two-neutron transfer in limited regions of the periodic table. These regions can be grouped into three categories.

(a) The vicinity of closed shells where the gap in single-particle states is larger than the pairing interaction. This can give rise to an excited 0^+ state for which pairing correlations produce a large two-neutron–transfer cross section much as they do for the ground state. Such $l=0$ transitions have been seen in the Pb isotopes and in Zr, Ni, and Ca isotopes. The concept of pairing vibrations[2] has been applied to such data with some degree of success.[3]

(b) Some deformed nuclei, for which there is a gap in the energy spacing of Nilsson orbits, can give rise to a similar situation and also show a splitting of the $l=0$ two-neutron–transfer cross sections.[2] Strong excited 0^+ states seen in the Yb isotopes[4] have been interpreted in this fashion.

(c) In regions of rapidly changing equilibrium shape such as is found near $N=90$, the $l=0$ strength seen in two-neutron–transfer reactions is also found to proceed strongly to excited states.[5]

In all these cases the fragmentation of the $l=0$ strength seen in the two-neutron–transfer reaction changes rapidly with neutron number. In cases (a) and (b) the excited 0^+ states appear strongly in the (p,t) reaction only when neutrons are present in the orbits above the gap. [Strong

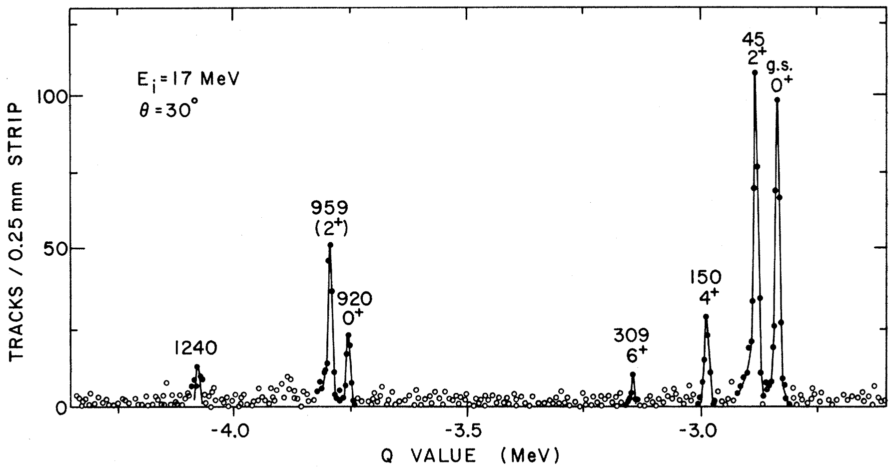

FIG. 1. Spectrum of tritons from the reaction $U^{238}(p,t)U^{236}$. The target was 35 $\mu g/cm^2$ of U^{238} evaporated onto a carbon foil. The peaks are labeled by the excitation energies (keV) and spins of the corresponding states in U^{236}.

excited 0^+ states were seen[6] in $Pb^{210}(p, t)Pb^{208}$ and in[4] $Yb^{176}(p, t)Yb^{174}$ but no such strong excitations were observed in $Pb^{208}(p, t)Pb^{206}$ or $Yb^{174}(p, t)Yb^{172}$.] Also, in the $N \approx 90$ region, the splitting in $l = 0$ strength occurs only at the transitional nuclei.

In an attempt to find further cases of split $l = 0$ strength, we have studied the (p, t) reaction on targets in the actinide region. Th, U, and Pu span the gap in Nilsson single-particle levels at 142 neutrons.[7] Effects similar to those seen in the Yb isotopes might then be expected in these nuclides. In this experiment the (p, t) reactions on targets of Th^{230}, $U^{234,236,238}$, and $Pu^{242,244}$ were studied with 17-MeV protons from the Argonne tandem Van de Graaff accelerator. The tritons were detected in photographic emulsions placed in the focal plane of a split-pole magnetic spectrograph. The plates were scanned with a computer-controlled automatic plate scanner.[8] A typical spectrum is shown in Fig. 1.

The angular distributions obtained were sufficient in each case to establish the sharp minimum at ~35° characteristic of $l = 0$ transitions. The most complete data were obtained for the reaction $U^{238}(p, t)U^{236}$, for which the angular distributions are displayed in Fig. 2, along with distorted-wave Born-approximation (DWBA) cal-

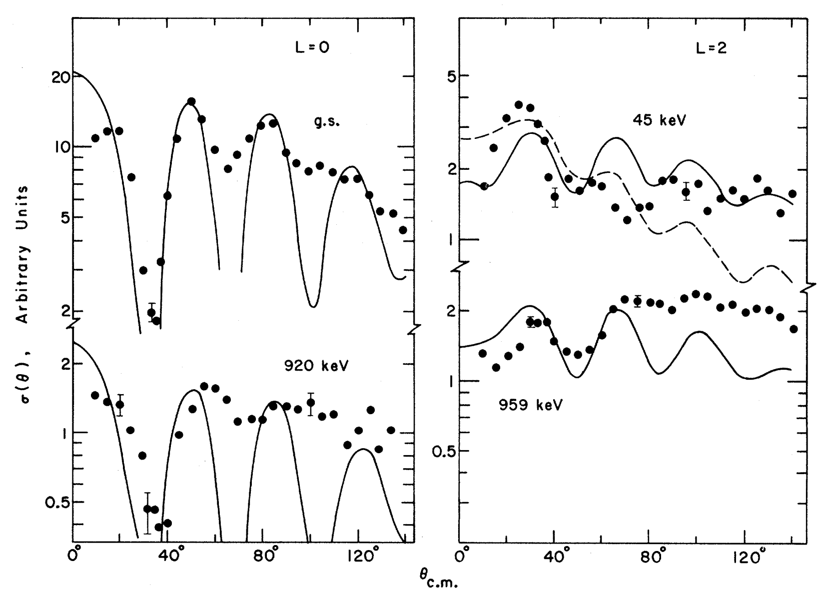

FIG. 2. Angular distributions for the reaction $U^{238}(p,t)U^{236}$. The relative yields for the various experimental data sets are correctly shown. The cross section at ~60° for the ground-state transition is 220 ± 80 μb/sr. The DWBA curves were calculated with a spherical $3d_{5/2}$ form factor for the solid curves and $1j_{15/2}$ for the dashed curve. Relative error bars are shown on a few representative points.

culations. We note a strong $l=0$ transition to a hitherto unknown 0^+ state at 920 keV and an $l=2$ transition to the known 2^+ state at 959 keV. The DWBA calculations fit the shapes of the angular distributions reasonably well. They were carried out with the computer code TWOPAR[9] which assumes spherical single-particle orbits. The shapes of the calculated angular distributions for $l=0$ transitions were not sensitive to the choice of form factor, while those of $l=2$ transitions are unstable in both the calculations and the data, as shown in the figure. The variation in $l=2$ shapes is a characteristic of all our data and has also been noted elsewhere.[10] This instability in shape may be caused by the sensitivity to form factors or by higher-order processes. In any case, empirical determinations of l transfer can be reliably made at present only for $l=0$; we have made no spin assignments on the basis of angular distributions for higher l transfers. One should note the slight difference in the positions of the minima in the two $l=0$ transitions in Fig. 1. This seems to be a real, structure-dependent difference; the ground-state Q values for the U targets studied span the range in Q values between the ground state and the excited 0^+ states and the corresponding angular distributions show no such shift in shape.

The 0^+, 2^+, and 4^+ members of the ground-state rotational band were seen in all the reactions studied here. Our results for all states are summarized in Table I. Absolute cross sections were also obtained for the three uranium isotopes with approximately 40% accuracy; the ground-state cross sections are constant within these limits. The most striking result shown in Table I is the fact that the ratio of the yield for the excited 0^+ state to that of the ground state does not vary sharply for the targets studied. This precludes an explanation in terms of the Nilsson-level gap at 142 neutrons because the U^{234} and Th^{230} targets have 142 and 140 neutrons, respectively, and should show no strong excited 0^+ state under such an explanation. The excited $l=0$ transition leading to Pu^{240} is in two fragments whose yields add up to about that of the one excited transition to Pu^{242}.

Excited 0^+ states, and rotational bands based on them, have long been known in several of these nuclei.[11] They have been characterized as β vibrations though they are not connected to the ground state by $E2$ transitions as strong as would be expected for such a collective shape vibration: The observed $B(E2)$ values are about twice the single-particle estimate. In U^{234}, for which careful one-nucleon transfer work has been done with both the $U^{235}(d,t)$ and $U^{233}(d,p)$ reactions, no sign of this excited 0^+ band was seen.[12] These bands show two additional characteristics. They exhibit $E0$ transitions (about one single-particle unit, $\rho\approx 0.2$) between members of this $K=0$ rotational band and the corresponding members of the ground-state band.[13] Rasmussen[14] has calculated the ratio of $E0$ to $E2$ transitions expected from β vibrations if the requirement for volume conservation is imposed. Bjornholm[11] has shown that the data for these nuclei are in qualitative agreement with Rasmussen's expectation. It is interesting to speculate whether the systematic shift noted in the (p,t) angular-distribution patterns reflects a difference in radius between the ground state and the excited 0^+ state and has its origin in the same features that lead to the $E0$ transitions. Strong alpha-particle decays to these excited 0^+ states (with hindrance factors of ~7 relative to the ground state) have been observed in the few cases in which alpha decay is possible. This property must clearly be related to the enhancement we see for these states in the (p,t) reaction. We also note that the separation between the excited 0^+ and 2^+ states is systematically less than the 0^+-2^+ spacing in the ground-state rotational band, and is also more nearly constant. The spacing for the excited band decreases from ~43 to ~40 keV in going from Th to U and Pu isotopes, while the ground-state value over the same isotopes decreases from ~55 to ~44 keV. The moment of inertia for the excited band would thus be 10-20% larger than that for the ground-state band, and is less sensitive to neutron number in this region.

There have been several published calculations of excited 0^+ states in which the pairing and the β vibration modes were allowed to mix. The numerical work in the rare-earth regions indicates large fluctuations in two-neutron transfer amplitudes for neighboring nuclides—in other words, it indicates great sensitivity to the underlying microscopic population of Nilsson orbits.[15] Calculations for actinide nuclei have also been carried out, though the two-neutron—transfer amplitudes are not available.[16] Every expectation is that such calculated wave functions would reflect fluctuations in two-neutron—transfer amplitudes similar to those found in the rare-earth region.

The interesting and surprising result of this

Table I. Properties of states observed in the present study. In addition to the states shown below, preliminary results indicate excited 0^+ states in Th^{230} and Cm^{246} at 633 and 1173 keV with 0.18 and 0.12 of the ground-state cross section.

Residual nucleus and g.s. Q value[a] (MeV)	Excitation energy[b] (keV)	J^{π} [c]	Cross section ratio[d]	Residual nucleus and g.s. Q value[a] (MeV)	Excitation energy[b] (keV)	J^{π} [c]	Cross section ratio[d]
Th^{228}	0	0^+		U^{236}	0	0^+	
-3.570	57	2^+		-2.785	45	2^+	
	185	4^+			150	4^+	
	830	0^+	0.18		309	6^+	
	874[e]	(2^+)	(0.2)		920[e]	0^+	0.13
	940[e]				959	2^+	(0.7)
	977	2^+	(0.3)		1240[e]		
	1160	$(3^-$ or $3^+)$			1810[e]		
U^{232}	0	0^+		Pu^{240}	0	0^+	
-4.119	46	2^+		-3.065	42	2^+	
	156	4^+			142	4^+	
	692	0^+	0.14		862	0^+	0.15
	736	2^+	(0.3)		902	2^+	(0.3)
	867	2^+	(0.4)		1005[e]		
					1091[e]	0^+	0.10
					1137[e]	(2^+)	(0.8)
					1227[e]		
					1580[e]		
U^{234}	0	0^+		Pu^{242}	0	0^+	
-3.350	44	2^+		-2.580	45	2^+	
	145	4^+			146	4^+	
	812	0^+	0.13		956[e]	0^+	0.24
	852	(2^+)	(0.3)		995[e]	(2^+)	(0.2)
	927	(2^+)	(0.5)		1107[e]		

[a]The estimated uncertainty is 10 keV.

[b]The estimated uncertainty is 2 keV for the U^{234} and U^{236} levels and 5 keV for levels in the other nuclei.

[c]Spin and parity assignments taken from Ref. 11, except for previously unobserved $l=0$ transitions, and the 2^+ states in parentheses whose spins are tentatively assigned from the fact that they are ~40 keV above a 0^+ state.

[d]For 0^+ states the ratio of the cross section of the excited state to that of the ground state is given. If we were to extract the Q dependence, as given by DWBA calculations, this would increase this ratio by 15-20%. The ratios are accurate to ~25%. Because the $l=2$ shapes fluctuate drastically, the ratio is that of the averages of the cross sections observed at two angles (30° and 60°). The angular distributions for $l=0$ shapes are sufficiently stable for the ratio to be nearly independent of angle.

[e]State previously unobserved.

study lies in the population of the first excited 0^+ state for each actinide target with substantial and approximately constant strength.[17] The properties of these 0^+ states—namely, the rather weak $E2$ transitions to the ground state, the $E0$ transitions, the strong α decays, and our large values for the (p, t) cross sections—do not seem consistent with the expected properties of either β vibrations or pairing vibrations. All the evidence seems to point to this 0^+ state being a simple and rather stable collective mode, closely related to the ground state and not included among the presently known collective excitations.

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†ANL and University of Chicago.

[1]S. Yoshida, Nucl. Phys. 33, 685 (1962).

[2]D. R. Bés and R. A. Broglia, Nucl. Phys. 80, 289 (1966).

[3]A. Bohr, in *Nuclear Structure, Dubna Symposium,*

1968 (International Atomic Energy Agency, Vienna, 1968), p. 179; O. Nathan, *ibid.*, p. 191, and references to experiments therein.

[4]M. Oothoudt, P. Vedelsby, and N. M. Hintz, Bull. Amer. Phys. Soc. 14, 509 (1969); John Williams Laboratory, University of Minnesota, Annual Report No. C00-1265-83, 1969 (unpublished), p. 71.

[5]J. R. Maxwell, G. M. Reynolds, and N. M. Hintz, Phys. Rev. 151, 1000 (1966); J. H. Bjerregaard, O. Hansen, O. Nathan, and S. Hinds, Nucl. Phys. 86, 145 (1966); W. McLatchie, J. E. Kitching, and W. Darcey, Phys. Lett. 30B, 529 (1969); K. Yagi, Y. Aoki, J. Kawa, and K. Sato, Phys. Lett. 29B, 647 (1969).

[6]G. J. Igo, P. D. Barnes, and E. R. Flynn, Phys. Rev. Lett. 24, 470 (1970).

[7]T. H. Braid, R. R. Chasman, J. R. Erskine, and A. Friedman, Phys. Rev. C 1, 275 (1970).

[8]J. R. Erskine and R. H. Vonderohe, to be published.

[9]We are indebted to Dr. B. Bayman for this computer program.

[10]Bjerregaard, Hansen, Nathan, and Hinds, Ref. 5.

[11]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.; E. K. Hyde, I. Perlman, and G. T. Seaborg, *The Nuclear Properties of the Heavy Elements* (Prentice-Hall, Englewood Cliffs, N. J., 1964); S. Bjornholm, thesis, Institute for Theoretical Physics, University of Copenhagen, 1965 (unpublished).

[12]S. Bjornholm, J. Dubois, and B. Elbek, Nucl. Phys. A118, 241 (1968).

[13]F. E. Durham, D. H. Rester, and C. M. Class, Phys. Rev. Lett. 5, 202 (1960); see also Bjornholm, Ref. 11.

[14]J. O. Rasmussen, Nucl. Phys. 19, 85 (1960).

[15]See, for instance, O. Mikoshiba, R. K. Sheline, T. Udagowa, and S. Yoshida, Nucl. Phys. A101, 202 (1967).

[16]V. G. Soloviev, At. Energy Rev. 3, 117 (1965); R. R. Chasman, Phys. Rev. 138, B326 (1965).

[17]It would be most interesting to study the (t,p) reaction in the actinides. Unfortunately, the one published result on $U^{238}(t,p)U^{240}$ [R. Middleton and H. Marchant, in *Proceedings of the Second International Conference on Nuclidic Masses, Vienna, Austria 1963* (Springer, Vienna, Austria, 1964)], gives angular distributions only for the ground state and first excited state. In the one spectrum shown, the excitation region of interest is obscured by impurities.

SEPARATION OF DIRECT-REACTION AND COMPOUND-NUCLEUS CONTRIBUTIONS TO (p,p') REACTIONS IN Sn ISOTOPES*

B. L. Cohen, G. R. Rao, C. L. Fink, J. C. Van der Weerd, and J. A. Penkrot
University of Pittsburgh, Pittsburgh, Pennsylvania 15213
(Received 30 March 1970)

By comparing energy spectra of protons from (p,p') reactions on various tin isotopes, a clean separation between direct-reaction and compound-nucleus contributions is made and the two processes are studied independently. The compound-nucleus results are in good agreement with predictions from the Gilbert-Cameron level densities. The direct-reaction angular distributions become quite isotropic for large $-Q$; the direct reaction cross section at 17 MeV is about one-third of the total reaction cross section.

Measurements were made of energy distributions of protons emitted at various angles following bombardment of various Sn-isotope targets with 17-MeV protons. Typical results are shown in Fig. 1. The cross lines on the curves there show the maximum proton energy for which subsequent neutron emission is energetically possible; the increased intensity to the left of these cross lines in the spectra from Sn^{112} and Sn^{114} are clearly due to (p,np) reactions, so we will temporarily ignore that part of the spectrum. The peaks in the spectra for $Q \leq -9$ MeV are due to $(p,n\tilde{p})$ reactions from excitation of isobaric analog states in direct (p,n) reactions, and the peaks in the spectra for $Q \gtrsim -6$ MeV are due to excitation of individual collective states by direct reactions, but these are of no concern here. The aspect of Fig. 1 we emphasize here is the difference between the spectra from light and heavy isotopes, and its regular progression with mass number in the region above and a short distance below the (p,np) threshold where there are no peaks or where these peaks can be averaged over.

There are two well-known processes leading to (p,p') reactions in this mass region, direct reaction (DR) and compound nucleus (CN). The DR process is controlled by the relationship between the nuclear structure of the ground and excited states, and this relationship is extremely similar for all even-A Sn isotopes; we therefore expect the DR contribution from these isotopes to be virtually identical. The cross section for the (p,p') CN process, on the other hand, is very sensitive to competition from (p,n), and hence is highly sensitive to the Q value for the latter reaction. In the heaviest isotopes where $Q(p,n)$ is near zero [the value for $Q(p,p')$], neutron