# Population of $0^+$ States in Actinide and $A \approx 190$ Nuclides by the $(p, t)$ Reaction*

J. V. Maher, J. R. Erskine, A. M. Friedman, and R. H. Siemssen
*Argonne National Laboratory, Argonne, Illinois 60439*

and

J. P. Schiffer
*Argonne National Laboratory, Argonne, Illinois 60439,*
*and University of Chicago, Chicago, Illinois 60637*
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The $(p,t)$ reaction has been studied for targets of $^{230,232}$Th, $^{234,236,238}$U, $^{242,244}$Pu, $^{248}$Cm, $^{182,184,186}$W, and $^{196}$Pt. Uniformly strong (~15% of ground-state cross section) transitions were found to populate excited $0^+$ states in all of the actinide nuclides. The observed $0^+$ states were previously known for five of the actinide nuclei, and in these cases the states were characterized by small $\alpha$-decay hindrance factors and large $E0$ matrix elements. They have been previously classified as $\beta$ vibrations. The strong excitation of the $0^+$ states in the $(p,t)$ reactions, combined with all other available evidence, suggests that throughout the actinide mass range these $0^+$ states represent a stable collective excitation different in character from both the $\beta$ vibration and the most common formulation of the pair vibration. No such excitations were seen in the W–Pt region.

## I. INTRODUCTION

Monopole pairing excitations have been the subject of continuing theoretical and experimental interest in nuclear structure.[1] Yoshida[2] was the first to point out that the two-neutron-transfer reactions $(p, t)$ and $(t, p)$ are particularly suited for the experimental investigation of pair correlations. The strong population of $0^+$ ground states in these reactions in certain regions of the Periodic Table can be regarded as a good indication for a BCS "superconducting" ground state.

Recent results of two-neutron-transfer studies in heavy nuclei have indicated the presence of enhanced transitions to excited $0^+$ states in several distinct mass regions. Since models of pairing vibrations allow such enhanced transitions for the two-neutron-transfer reaction only under certain conditions, it is of interest to search for any systematic trends connected with the appearance of these excited $0^+$ states. Nuclei in which enhanced transitions have been observed can be classified into three categories:

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

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

(3) In regions of rapid transition from spherical to deformed shape, the $l=0$ strength seen in two-neutron-transfer reactions can proceed strongly to excited states. Such a splitting has been seen[5-7] in $^{150}$Nd and $^{152}$Sm, which are such transitional nuclei.

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 (1) and (2), the excited $0^+$ states appear strongly in the $(p, t)$ reaction only when neutrons are present in the orbits above the gap. Also in the $N \approx 90$ region, the splitting of $l=0$ strength occurs only at the transitional nuclei.

In an attempt to find further cases of enhanced $l=0$ transitions to excited states, we have studied the $(p, t)$ reaction in two mass regions. Actinide nuclei spanning the $N=142$ gap[8] in Nilsson orbitals were investigated for possible states similar to those of category (2) above. As reported previously,[9] transitions to the first excited $0^+$ states were found to be ~15% as strong as the ground-state transitions throughout the mass region studied. None of the explanations discussed above seem to fit this new situation.

We have also studied the $(p, t)$ reaction in the transitional W–Pt region, searching for enhanced excited $0^+$ states similar to those described in (3). No such states were seen in this region, perhaps because the shape transition with changing neutron number is more gradual in this region than in the $N \approx 90$ region.

## II. EXPERIMENTAL PROCEDURES

The 17-MeV proton beam from the Argonne FN tandem accelerator was used to bombard targets of $^{182,184,186}W$, $^{196}Pt$, $^{230,232}Th$, $^{234,236,238}U$, $^{242,244}Pu$, and $^{248}Cm$. The Pu and Cm targets were prepared through the use of an electromagnetic isotope separator in the Argonne Chemistry Division. The isotopes in the beam from the separator were deposited onto thin carbon backings. The uranium, thorium, tungsten, and platinum targets were prepared by conventional evaporation techniques. The isotopic enrichment of these targets was in all cases better than 98%.

Tritons were detected in photographic emulsions placed in the focal plane of a split-pole magnetic spectrograph.[10] The solid angle of the spectrograph was 3.2 msr. Plates were scanned with a computer-controlled automatic plate scanner.[11] A typical spectrum is shown in Fig. 1. Most of the spectra were analyzed with the peak-fitting program AUTOFIT.[12]

A NaI detector was used to record elastically scattered protons at a laboratory angle of 60° during the $(p, t)$ exposures. Nonuniformities in the targets made it necessary to monitor the effective target thickness in this manner throughout each angular-distribution measurement. Absolute cross sections were determined by relating the $(p, t)$ data to proton elastic scattering, measured in the magnetic spectrograph at a laboratory angle of 40°. At this angle the ratio to Rutherford scattering (0.9) is insensitive to optical-model parameters. These elastic scattering measurements also provided a measure of the incident beam energy for use in determining ground-state $Q$ values.

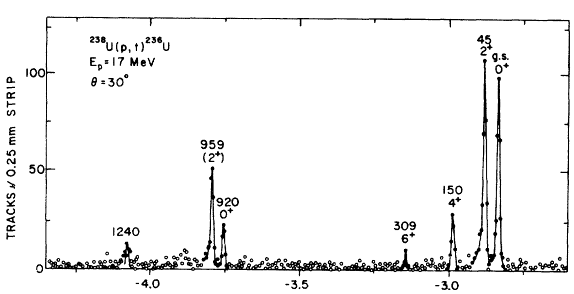


FIG. 1. Spectrum of tritons from the reaction $^{238}U(p,t)^{236}U$. The peaks are labeled by the excitation energies (keV) and spin-parities of the corresponding states in $^{236}U$.

## III. DATA PRESENTATION

The schematic spectra shown in Fig. 2 indicate which states are populated by the $(p, t)$ reaction on the various actinide targets and give their absolute differential cross sections at 20°. (The $^{244}Pu$ target was accidentally destroyed before complete angular distributions and absolute cross sections could be measured. However, measurements were made at enough angles to identify $l=0$ transitions and other previously known final states.) Also shown are the spins of states that can be confidently associated with previously known states. Of the previously unknown states populated in this experiment, spins can be assigned only to the $J^\pi = 0^+$ states, since only the $l=0$ angular distributions have an identifiable characteristic shape. Angular distributions of states populated by higher $l$ transfer are unstable in shape – perhaps as a result of both a strong form-factor dependence and higher-order processes. Table I summarizes our measurements of the levels observed with the actinide targets. The

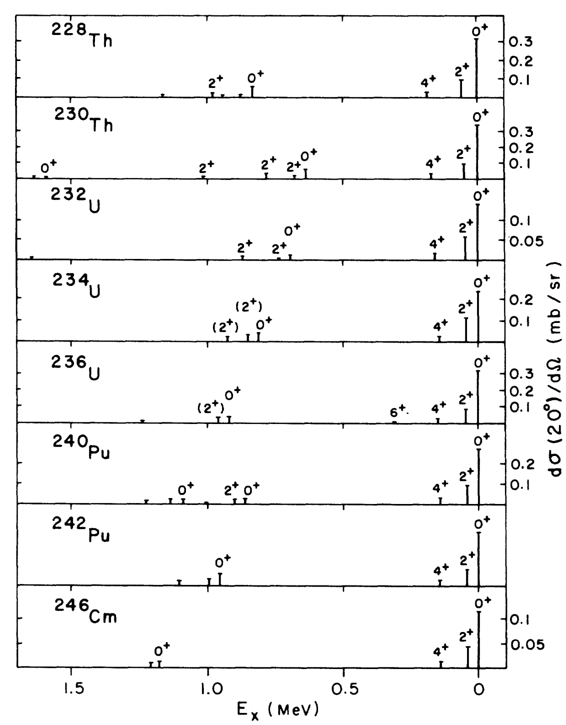


FIG. 2. Schematic spectra for the $(p,t)$ reaction at 20° on actinide targets. Each spectrum is labeled with the appropriate residual nucleus. At this angle, most states are at or near their peak cross sections. Spin-parity assignments (where known) are indicated. The length of line indicates the absolute cross section for each residual state except in $^{242}Pu$, for which this information is not available.

ground-state $Q$ values measured on the actinide targets are presented in Table II.

The $l=0$ angular distributions measured for all actinide targets are shown in Fig. 3. Figure 4 shows angular distributions for transitions to the $2^+$ members of the ground-state rotational band of each residual nucleus, while Fig. 5 shows angular distributions for the states whose excitation energy qualifies them as candidates for the $2^+$ states in rotational bands built on the first excited $0^+$ state. Angular distributions for transitions to the other known $2^+$ states that are not members of either the ground state or excited $K=0^+$ band are shown in Fig. 6. Transitions to several $4^+$ members and one $6^+$ member of the ground-state bands are shown in Fig. 7. In spite of the similarity of all $l=0$ angular distributions (Fig. 3), small shape differences are present in the $l=0$ angular distributions within a given nucleus.

The most prominent feature in the $l=0$ data is

TABLE I. Levels observed in the various actinide nuclides. Excitation energies measured in this work, spin and parity (where known), differential cross sections at selected angles, and cross-section ratios are given.

| Residual nucleus | $E_x$ [a] (keV) | $J^\pi$ [b] | $d\sigma/d\Omega$ [c] (mb/sr) | Cross-section ratio [d] |
|---|---|---|---|---|
| $^{228}$Th | 0 | $0^+$ | 0.21 (60°) | |
| | 57 | $2^+$ | 0.097 | |
| | 185 | $4^+$ | 0.028 | |
| | 830 | $0^+$ | 0.042 (60°) | 0.18 |
| | 874 [e] | $(2^+)$ | 0.012 | 0.20 |
| | 940 [e] | | 0.011 | |
| | 977 | $2^+$ | 0.021 | 0.3 |
| | 1160 | ($3^-$ or $3^+$) | 0.010 | |
| $^{230}$Th | 0 | | 0.30 (60°) | |
| | 51 | $2^+$ | 0.094 | |
| | 173 | $4^+$ | 0.030 | |
| | 636 | $0^+$ | 0.073 (60°) | 0.18 |
| | 678 | $(2^+)$ | 0.018 | 0.3 |
| | 782 | $(2^+)$ | 0.035 | |
| | 1013 | $(2^+)$ | 0.007 | |
| | 1590 | $0^+$ | 0.014 (60°) | 0.03 |
| | 1636 | $(2^+)$ | 0.009 | 0.1 |
| $^{232}$U | 0 | $0^+$ | 0.14 (60°) | |
| | 46 | $2^+$ | 0.062 | |
| | 156 | $4^+$ | 0.016 | |
| | 692 | $0^+$ | 0.021 (60°) | 0.14 |
| | 736 | $(2^+)$ | 0.004 | 0.3 |
| | 867 | $(2^+)$ | 0.010 | 0.4 |
| | 1646 | | 0.018 (30°) | |
| $^{234}$U | 0 | $0^+$ | 0.26 (60°) | |
| | 44 | $2^+$ | 0.11 (23°) | |
| | 145 | $4^+$ | 0.024 (23°) | |
| | 812 | $0^+$ | 0.027 (60°) | 0.13 |
| | 852 | $(2^+)$ | 0.031 (23°) | 0.3 |
| | 927 | $(2^+)$ | 0.023 (23°) | 0.5 |
| $^{236}$U | 0 | $0^+$ | 0.26 (60°) | |
| | 45 | $2^+$ | 0.087 | |
| | 150 | $4^+$ | 0.029 | |
| | 309 | $6^+$ | 0.006 | |
| | 920 [e] | $0^+$ | 0.037 | 0.13 |
| | 959 | $(2^+)$ | 0.035 | 0.7 |
| | 1240 [e] | | 0.013 | |
| | 1810 [e] | | 0.009 | |
| $^{240}$Pu | 0 | $0^+$ | 0.19 (60°) | |
| | 42 | $2^+$ | 0.095 | |
| | 142 | $4^+$ | 0.034 | |
| | 862 | $0^+$ | 0.052 (60°) | 0.15 |
| | 902 | $2^+$ | 0.024 | 0.3 |
| | 1005 [e] | | 0.006 | |
| | 1091 [e] | $0^+$ | 0.020 (60°) | 0.10 |
| | 1137 [e] | $(2^+)$ | 0.030 | 0.8 |
| | 1227 [e] | | 0.017 | |
| | 1580 [e] | | 0.003 | |
| $^{242}$Pu | 0 | $0^+$ | 1.0 [f] | |
| | 45 | $2^+$ | 0.20 [f] | |
| | 146 | $4^+$ | 0.07 [f] | |
| | 956 [e] | $0^+$ | 0.17 [f] | 0.24 |
| | 995 [e] | $(2^+)$ | 0.10 [f] | 0.2 |
| | 1107 [e] | | 0.05 [f] | |
| $^{246}$Cm | 0 | $0^+$ | 0.17 (60°) | |
| | 39 | $2^+$ | 0.060 | |
| | 140 | $4^+$ | 0.019 | |
| | 1176 [e] | $0^+$ | 0.016 | 0.11 |
| | 1208 [e] | $(2^+)$ | 0.013 | 0.2 |

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

[b] Spin and parity assignments taken from Ref. 18, except for previously unobserved $l=0$ transitions and $2^+$ states that are ~40 keV above the $0^+$ state.

[c] Measured at 20° center-of-mass angle unless otherwise stated. The estimated uncertainty of these numbers as absolute cross sections is 25%, and as relative cross sections is 15%.

[d] For $0^+$ states, the value given is the ratio of the excited-state cross section (averaged over several angles) to the ground-state cross section. Removal of the $Q$ dependence, as given by distorted-wave Born-approximation calculations, would increase this ratio by 15–20%. The ratios are accurate to ~10%. Because the $l=2$ shapes fluctuate drastically, the ratios for $l=2$ are those 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 (except for the minimum).

[e] State previously unobserved.

[f] Relative cross section.

TABLE II. Ground-state $Q$ values measured for the $(p, t)$ reaction on various actinide targets.

| Target nucleus | $Q_0$ (MeV) |
|---|---|
| $^{230}$Th | $-3.550 \pm 0.015$ |
| $^{232}$Th | $-3.070 \pm 0.015$ |
| $^{234}$U | $-4.099 \pm 0.015$ |
| $^{236}$U | $-3.330 \pm 0.015$ |
| $^{238}$U | $-2.765 \pm 0.015$ |
| $^{242}$Pu | $-3.045 \pm 0.015$ |
| $^{244}$Pu | $-2.560 \pm 0.015$ |
| $^{248}$Cm | $-2.894 \pm 0.015$ |

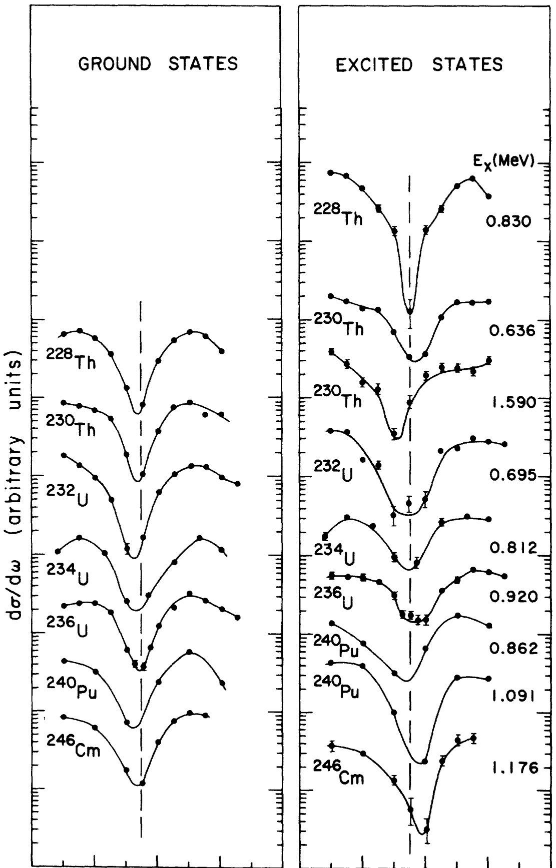


FIG. 3. Angular distributions for $l = 0$ transitions (labeled with the residual nuclei involved). Ground-state transitions are shown on the left-hand side, while excited-state transitions are shown on the right. Vertical lines at $\theta = 35°$ indicate that ground-state transitions have a minimum at or forward of 35°. Excited-state transitions have their corresponding minima at or behind 35° except for the weakly populated state at 1.590 MeV in $^{230}$Th. Curves through the angular distributions are drawn to guide the eye and have no further significance.

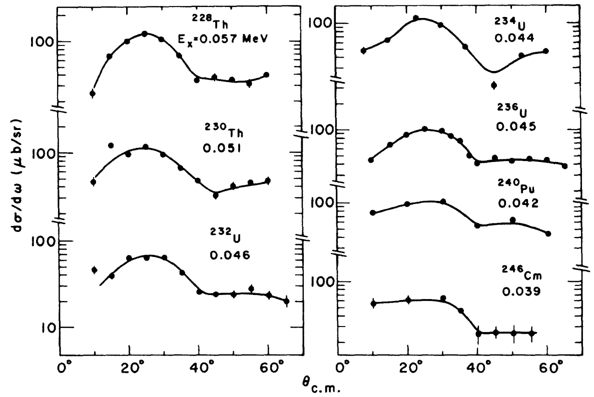


FIG. 4. Angular distributions populating $2^+$ members of ground-state rotational bands (labeled with the residual nuclei involved). Curves through the angular distributions are drawn to guide the eye and have no further significance.

the sharp minimum at ~35°. As can be seen in Fig. 3, this minimum occurs at angles slightly forward of 35° for ground-state transitions and, with one weak exception, at angles slightly backward of 35° for excited $0^+$ states.

In Fig. 8, more detailed angular distributions measured in smaller angular steps are shown for transitions to the strongly populated states in $^{236}$U. Distorted-wave Born-approximation calculations of the transfer cross sections were performed to look for $Q$ dependence and for a rough estimate of sensitivity to configuration. Calculations were performed with the code TWOPAR,[13] and several simple shell-model form factors using $(j)^2$ configurations were employed. The $l = 0$ transition shapes were not sensitive to choice of form factor. A small (15%/MeV) dependence

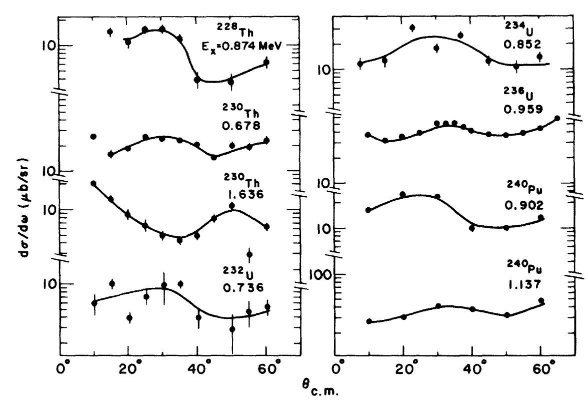


FIG. 5. Angular distributions populating states presumed to be $2^+$ members of rotational bands built on excited $0^+$ states. The curves are labeled with the residual nuclei involved. Curves through the angular distributions are drawn to guide the eye and have no further significance.

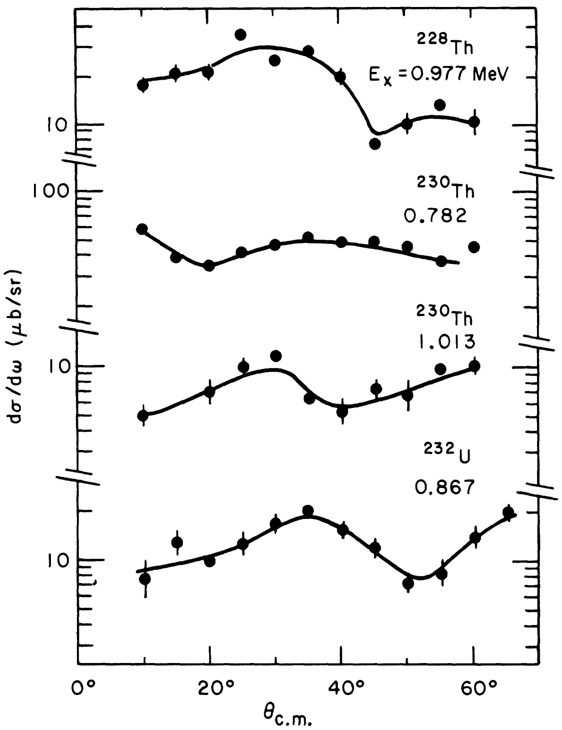


FIG. 6. Angular distributions populating known $2^+$ states not associated with rotational bands built on either the ground states or the excited $0^+$ states. The curves are labeled with the residual nuclei involved. Curves through the angular distributions are drawn to guide the eye and have no further significance.

of the absolute cross section on $Q$ value was found. As can be seen from Fig. 8, the shape differences between the angular distributions for the ground state and excited $0^+$ state are not reproduced exactly by the calculations. This effect, though small, probably represents a real dependence on the structure of the state.

The $l=2$ calculations in Fig. 8 (solid and dashed lines) are seen to be extremely sensitive to the choice of form factor. This may explain why the $l=2$ transitions fail to show a stable shape in this region. Another complication could be the importance of second-order processes in this reaction.[14] The angular distributions to the $2^+$ states in the ground-state band are all very similar in shape, while those for the higher known $2^+$ states vary greatly. No known $4^+$ states – other than those associated with the ground-state rotational band – were populated in any of the actinide targets studied. Angular distributions for these $4^+$ and $6^+$ states are shown in Fig. 7. Deformation parameters $\beta_4$ and possibly $\beta_6$ might be extracted from these data with the technique of Broglia *et al.*,[15] however, we did not attempt such an analysis.

Table III lists the data for states populated in the W and Pt isotopes. Absolute cross sections were not measured for these cases. The angular distributions for $l=0$ transitions are shown in Fig. 9, along with transitions to the known $2^+$ levels of the residual nuclei. Complete angular distributions were not measured for the $^{182}W(p,t)$-$^{180}W$ reaction.

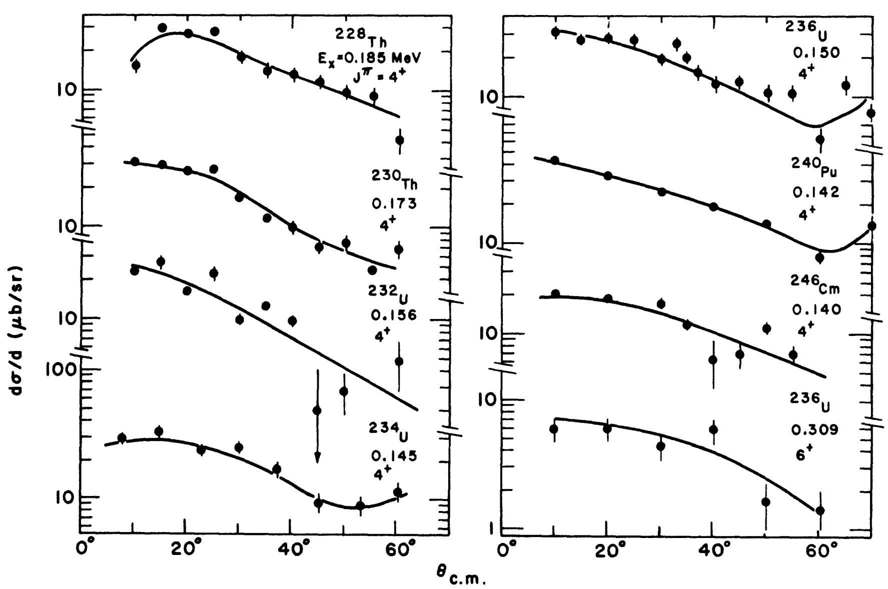


FIG. 7. Angular distributions populating several $4^+$ members and one $6^+$ member of ground-state rotational bands. The curves are labeled with the residual nuclei involved. Curves through the angular distributions are drawn to guide the eye and have no further significance.

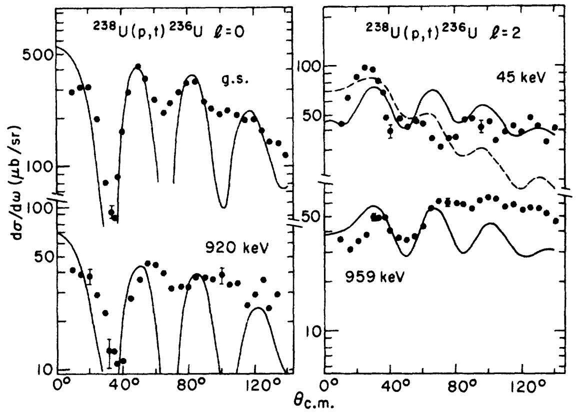


FIG. 8. Angular distributions for the reaction $^{238}$U-$(p,t)^{236}$U. The $l=2$ distorted-wave Born-approximation curves were calculated with a spherical $(3d_{5/2})^2$ form factor for the solid curves and a spherical $(1j_{15/2})^2$ form factor for the dashed curve, for $l=0$ the differences were less pronounced. Relative error bars are shown on a few representative points.

It should be noted that there are states of known spin-parity[16] at 1.14 MeV in $^{182}$W($8^+$) and at 1.007 MeV in $^{184}$W($3^+$). However, these probably are doublets, since the patterns of the $(p, t)$ angular distributions populating states at 1.137 MeV in $^{182}$W and 1.009 MeV in $^{184}$W are clearly $l=0$, as shown in Fig. 9. It is also noteworthy that the weak $l=0$ transition (~6% of ground-state strength)

TABLE III. Energies and spin-parities of excited states populated in W–Pt $(p, t)$ reactions. Ratio of cross sections for excited $0^+$ states to cross sections of the ground states are also shown.

| Residual nucleus | $E_x$ [a] (keV) | $J^\pi$ [b] | $d\sigma(\text{excited } 0^+)/d\sigma(\text{g.s. } 0^+)$ |
|---|---|---|---|
| $^{180}$W | 102 | $(2^+)$ | |
| | 336 | $(4^+)$ | |
| $^{182}$W | 100 | $2^+$ | |
| | 328 | $4^+$ | |
| | 1137 | $0^+$ | 0.06 |
| | 1225 | $2^+$ | |
| $^{184}$W | 113 | $2^+$ | |
| | 367 | $4^+$ | |
| | 905 | $2^+$ | |
| | 1009 | $0^+$ | 0.06 |
| $^{194}$Pt | 329 | $2^+$ | |
| | 626 | $2^+$ | |
| | 1435 | $3, (1, 2)^-$ | |
| | 1551 | $0^+$ | 0.04 |

[a] The estimated uncertainty is 3 keV.
[b] See Ref. 16.

shown for the reaction $^{196}$Pt$(p, t)^{194}$Pt populates the third excited $0^+$ state (previously tentative) in $^{194}$Pt at 1.551 MeV. The first two excited $0^+$ states (at 1.267 and 1.480 MeV) are not seen and so must be populated with less than 0.5% of the ground-state strength.

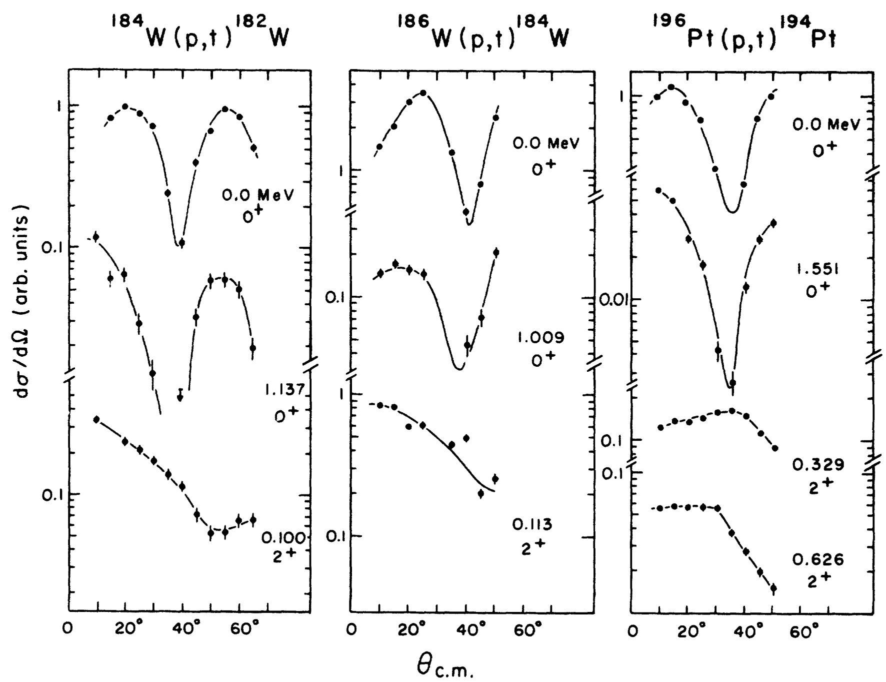


FIG. 9. Angular distributions for reactions populating $0^+$ and $2^+$ states in $^{182,184}$W and $^{194}$Pt. Curves through the angular distributions are drawn to guide the eye and have no further significance.

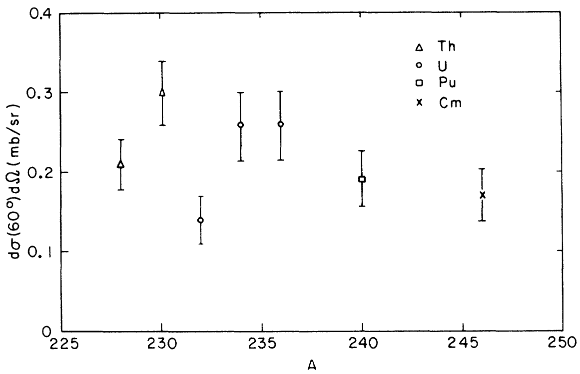


FIG. 10. Absolute cross sections for ground-state transitions at 60°. This angle lies on the broad second maximum of the $l=0$ angular distribution.

## IV. DISCUSSION

### A. Actinides

The most important finding of this experiment is the uniform population (~15% of ground-state strength) of excited $0^+$ states in all actinide targets studied. This precludes an explanation in terms of an energy gap at 142 neutrons because the $^{230,232}$Th and $^{234}$U targets have 142 or fewer neutrons and would show no strong $0^+$ state under such an explanation.

Figure 10 shows absolute cross sections at 60° for the ground-state transitions of the actinides studied. This angle represents the most stable maximum for all angular distributions, and the results figure indicate that the $(p,t)$ strength is roughly constant across the mass region. Table IV lists the excited $0^+$ states of the actinides and their strength relative to the ground states, along with the available information for the five of these states that were previously known. In a few cases more than one excited $0^+$ state is observed. In $^{230}$Th, the 1.590-MeV state is much weaker (~3% of the ground state) than the one at 0.636 MeV (18%) and also has a slightly different angular distribution. In $^{240}$Pu, two $0^+$ excited states are seen with similar large strengths. All five of the previously known $0^+$ states are characterized by large $E0$ transition rates and low $\alpha$-decay hindrance factors. These previously reported states all lie below ~900 keV in excitation, while the previously unobserved states all lie above 900 keV. Thus the previously unobserved states are probably no different in character from the others – their $\alpha$-decay rates are just inhibited by additional orders of magnitude by penetrability effects.

These excited $0^+$ levels, along with similar states in several neighboring even-even nuclei not studied in this experiment, have previously been called $\beta$ vibrations.[17] The properties of excited $0^+$ states in the actinides are summarized in Table IV, which includes $0^+$ states that were not studied in the $(p,t)$ reaction. The reciprocal of the $\alpha$-decay hindrance factors[18] are also given where

TABLE IV. Available information for excited $0^+$ states in actinide nuclei. Excitation energies and cross sections relative to ground-state cross sections are shown. Column 4 lists the reciprocals of the $\alpha$-decay hindrance factors $(HF_\alpha)^{-1}$ (ratio of excited-state reduced $\alpha$ matrix element to that for the ground state). And column 5 lists the ratio $X$ (Ref. 19) of reduced transition probabilities, where $X \equiv \rho^2 R^4/B(E2)$.

| Nucleus | Excitation[a] energy (keV) | $\sigma(\text{excited } 0^+)/\sigma(\text{g.s. } 0^+)$ | $(HF_\alpha)^{-1}$ [b] | $X$ [c] |
|---|---|---|---|---|
| $^{218}$Rn | 650 | ··· | (0.05) | |
| $^{220}$Rn | 534 | ··· | (0.06) | |
| $^{222}$Rn | 449 | ··· | (0.09) | |
| $^{228}$Th | 830 | 0.18 | 0.09 | (0.83) |
| $^{230}$Th | 636 | 0.18 | | $0.22 \pm 0.10$ |
| | 1590 | 0.03 | | |
| $^{232}$Th | 730 | ··· | | $0.12 \pm 0.01$ |
| $^{232}$U | 695 | 0.13 | 0.09 | $0.17 \pm 0.04$ |
| $^{234}$U | 812 | 0.13 | 0.24 | $0.50 \pm 0.08$ |
| $^{236}$U | 920 | 0.13 | | |
| $^{238}$U | 994 | ··· | | $0.20 \pm 0.06$ |
| $^{238}$Pu | 942 | ··· | 0.14 | $0.63 \pm 0.20$ |
| $^{240}$Pu | 862 | 0.15 | 0.26 | $0.05 \pm 0.01$ |
| | 1091 | 0.10 | | |
| $^{242}$Pu | 956 | 0.24 | | |
| $^{246}$Cm | 1176 | 0.11 | | |

[a] The energies of $0^+$ states in the Rn isotopes and in $^{232}$Th, $^{238}$U, and $^{238}$Pu are from Ref. 18.

[b] $\alpha$-decay hindrance factors are from Ref. 18.

[c] Values of $X$ are reproduced from Ref. 17 and attributed to B. Elbek except for $^{232}$Th and $^{238}$U, for which a more recent unpublished value of Wood (Ref. 20) is quoted.

available. These values are deduced from very weak decay branches and are clearly very sensitive to the method of calculating penetrabilities. It is interesting to note that even though there is quite a bit of fluctuation, the reciprocal hindrance factors average to about 0.12. In other words, the reduced transition probabilities for $\alpha$ decays to excited $0^+$ states and to the ground state are in roughly the same ratio as are the cross sections for $(p, t)$ reactions to these states. The ratio of reduced $E0$ to $E2$ matrix elements is also given, in the form of the parameter $X$ which was defined by Rasmussen.[19] It is interesting to speculate whether the low-lying $0^+$ states in the radon isotopes also belong to this same family, in view of their strong $\alpha$-decay hindrance factors. However, the $B(E2)$ values for transitions connecting the excited-state band to the ground-state band have been measured[20] for $^{238}$U and $^{232}$Th. The measured values are 0.9 and 3.0 single-particle units, respectively, and although this indicates some enhancement, these $B(E2)$ values are still an order of magnitude lower than would normally be expected of a quadrupole excitation such as a $\beta$ vibration. The strong population in the $(p, t)$ reaction is certainly not a feature of $\beta$ vibrations.

One may argue that the strong population in $(p, t)$ reactions automatically guarantees that these states are pairing vibrations. However, conventional models of pairing vibrations do not provide a satisfactory explanation for these states. Pairing vibrations should not show such strong $E0$ transitions. Further, two-neutron-transfer strengths in rare-earth nuclei have been predicted[21] in several calculations in which the $\beta$- and pair-vibrational modes were coupled. Although this allowed occasional large matrix elements for transitions to excited $0^+$ states, these matrix elements were highly sensitive to details of the microscopic wave functions of the states – e.g., to the appearance of a gap in the Nilsson orbits as discussed in (2) above – and there was no stable excitation of such states in neighboring nuclei. Although there have been similar calculations for actinide nuclei,[22] no neutron-transfer matrix elements are available for this region. However, there is no reason to believe that the results for actinide nuclei would be sufficiently different to predict an excitation that would be stable over so large a mass region.

Other possible explanations for the uniform population of these states have been considered and abandoned. Concern regarding possible reaction-mechanism effects was dispelled when the excited-state/ground-state cross-section ratio for $^{238}$U-$(p, t)^{236}$U was checked at $E_p = 27$ and 20 MeV.[23,24] In each case the ratio was in agreement with the 17-MeV value reported here. An explanation in terms of a possible deformation-dependent "second minimum" also appears to be ruled out. The excited-state moments of inertia, the $\alpha$-decay hindrance factors, and the $(p, t)$ cross section itself argue for a shape, and a microscopic wave function, closely connected to the ground state – and against the nuclear potential having a "second minimum" which by all accounts is very different from the minimum for the ground state.

It has also been suggested[25] that pairing matrix elements between pairs in orbitals whose origin is either equatorial or polar may be much stronger than matrix elements that mix equatorial with polar pairs. This would allow an excited $0^+$ state to retain two-neutron-transfer strength through any mass region in which single-particle states of both parentages were present with high density.

It is tempting to speculate that the systematic shift noted above for $(p, t)$ angular distribution patterns reflects a difference in radius between

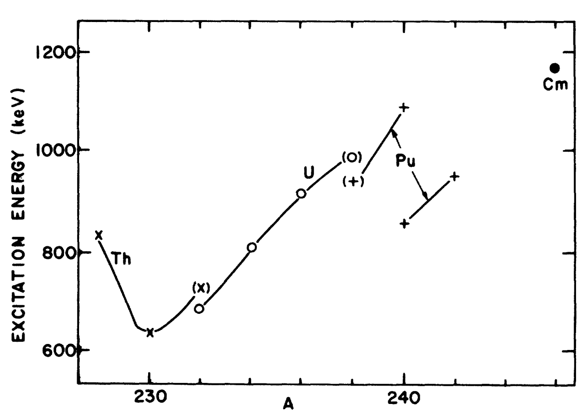


FIG. 11. Excitation energies of known $0^+$ states in actinide nuclei. Data on the Th, U, and Pu nuclei are indicated by the symbols ×, ○, and +, respectively. States in nuclei not studied in this experiment are shown in parentheses.

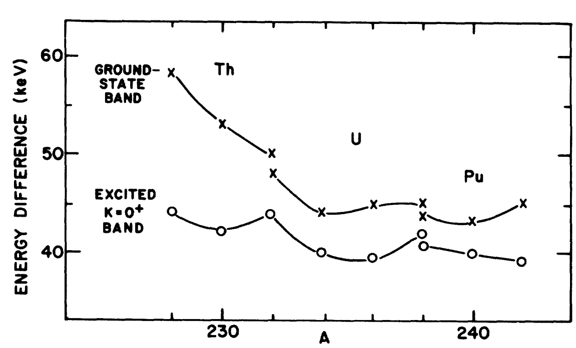


FIG. 12. Differences between the excitation energies of $0^+$ states and those of known or presumed $2^+$ members of rotational bands built on these states.

the ground state and the excited $0^+$ state and has its origin in the same features that lead to the $E0$ transitions.

Belyaev and Rumiantsev[26] have proposed a source of $0^+$ excitations which may apply to this present situation. They suggest that introduction of a two-particle spin-orbit force can lead to surface-density vibrations in heavy spherical nuclei and that these vibrational $0^+$ states would couple strongly with the ground states through $E0$ transitions. They also predict that these vibrational states would be strongly populated in two-nucleon-transfer reactions. Unfortunately, no calculations of the sort advocated by Belyaev and Rumiantsev seem to have been performed for any mass region, let alone deformed nuclei, so it is not possible to say whether such vibrations could be expected to predict the uniform population of excited $0^+$ states described above.

Other systematics of the excited $0^+$ bands are shown in Figs. 11 and 12. The excitation energy of the band heads (Fig. 11) seems to increase smoothly with increasing mass. In Fig. 12, the $0^+$-$2^+$ spacings of the ground-state bands are compared with the $0^+$-$2^+$ spacings of the excited $K=0^+$ bands. The moment of inertia for the excited band is ~15% greater than that of the ground-state band and is more stable than that of the ground-state band, remaining almost constant over the entire mass range. An additional feature which may or may not be significant is that the excited $0^+$-to-ground-state ratios in $(p,t)$ cross sections is remarkably constant within each set of isotopes. The ratio is 0.18 and 0.18 for $^{228,230}$Th, 0.14, 0.13, and 0.13 for $^{232,234,236}$U, 0.25 (0.10 + 0.15) and 0.24 for $^{240,242}$Pu, and 0.11 in $^{246}$Cm. It is of considerable interest that a recent survey of $(t,p)$ reactions on several actinide targets, including $^{234}$U-$(t,p)^{236}$U, failed to show excited $0^+$ states with cross sections more than ~2–3% of those of the ground state.[20] It can be expected that any theory which will be able to explain all these properties of the excited $0^+$ states will greatly enhance our knowledge of collective properties in general, and of the pairing force in particular.

It is interesting to note that none of the odd-parity states in the actinides seem to be excited appreciably in the $(p,t)$ reaction.

### B. W-Pt Region

As Table II shows, no excited $0^+$ states were populated strongly in the tungsten and platinum targets. Excited $0^+$ states were typically populated with 2–6% of the ground-state strength. Despite the weak excitation of these states, angular distributions (Fig. 9) are seen to be stable in shape. It is interesting that previously unknown $0^+$ states in all W isotopes are excited while the first two known excited $0^+$ states in $^{194}$Pt (those at 1.267 and 1.480 MeV) are not seen. (Their cross sections are $\leq$0.5% of the ground-state cross section.) The $0^+$ state at 1.551 MeV in $^{194}$Pt is excited with 5% of the ground-state strength.[27]

In retrospect, it is perhaps not too surprising that excited $0^+$ states are so weak in the $(p,t)$ reaction in $N \approx 110$ region. The $N \approx 90$ region is known to involve a much more rapid change of shape with neutron number. The extreme sensitivity of this effect to rapidity of shape transition is illustrated in the Sm isotopes. In the reaction $^{148}$Sm$(t,p)^{150}$Sm one excited $0^+$ state is seen with about 25% of the ground-state cross section, in $^{150}$Sm$(t,p)^{152}$Sm two excited states are seen, each with 75% of the ground-state cross section, and in $^{154}$Sm$(t,p)^{156}$Sm only one state with 7% of the ground-state strength is seen.[5] McLatchie *et al.*[6] report that in $^{154}$Sm$(p,t)^{152}$Sm the two excited $0^+$ states are populated with 25 and 3% of the ground-state strength, while in $^{152}$Sm$(p,t)^{150}$Sm the excited states carry 110 and 80% strength. It thus appears clear that the transition nuclei are $^{150}$Sm and $^{152}$Sm, where spherical and deformed components are strongly mixed.

The shape transition with neutron number is a slowly varying function of $A$ in the W–Pt region; it is not too surprising that a similar effect is not seen. However, the shape changes rapidly with proton number in this region, and results of $(^3\mathrm{He}, n)$ or possibly even studies of $(^{16}\mathrm{O}, {}^{12}\mathrm{C})$ and other $\alpha$-transfer reactions might show strong excited $0^+$ states.

## V. CONCLUSION

The most interesting feature of this work is the unexpected, uniformly strong population of excited $0^+$ states in all actinide targets studied. These states have rather weak $E2$ transitions to the ground-state band, and strong $\alpha$ decays leading to them, in addition to their strong population in the $(p,t)$ reaction. They do not fit the expected properties of $\beta$ vibrations and certainly stretch the accepted view of pairing vibrations. They perhaps may be explained in terms of the oblate-prolate model of Griffin, Jackson, and Volkov[25] or the surface-density vibrations proposed by Belyaev and Rumiantsev,[26] but no calculations exist to show whether or not such vibrations should retain their character over so large a mass range. The evidence does clearly point to a stable collective mode closely related to the ground state, but not included among the commonly considered collective excitations.

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