Levels of ^{237}Np Excited by the ^{236}U(^{3}He, d)^{237}Np and ^{236}U(α, t)^{237}Np Reactions*

TH. W. ELZE AND J. R. HUIZENGA

Nuclear Structure Research Laboratory and Departments of Chemistry and Physics, University of Rochester, Rochester, New York 14627

(Received 23 October 1969)

The ^{236}U(^{3}He, d)^{237}Np and ^{236}U(α, t)^{237}Np reactions were studied with 30-MeV ^{3}He and ^{4}He beams. Rotational bands built upon the following Nilsson proton configurations in ^{237}Np were identified: $\frac{5}{2}^+$[642] (0 keV), $\frac{5}{2}^-$[523] (60 keV), $\frac{1}{2}^-$[530] (268 keV), $\frac{3}{2}^-$[521] (514 keV). Experimental spectroscopic factors are compared with theoretical ones computed for Woods-Saxon and harmonic-oscillator-type nuclear potentials. A strong l dependence of the cross-section ratio $d\sigma(\alpha, t)/d\sigma(^3\text{He}, d)$ has been observed.

I. INTRODUCTION

DURING recent years the study of charged-particle reactions, e.g., transfer reactions, has become increasingly important for the determination of nuclear properties. In the rare-earth and actinide regions of the Periodic Table, however, only deuteron-induced transfer reactions have been studied extensively so far since mono-energetic beams of doubly-charged projectiles have not been available with energies higher than the Coulomb barriers of heavy nuclei. With these beams now available from Emperor tandem Van de Graaff accelerators, helium-ion–induced transfer reactions on actinide nuclei are feasible. This paper reports on results of measurements of single-proton transfer processes induced by 30-MeV ^{3}He and α-particle beams exciting Nilsson proton states of ^{237}Np and the rotational bands built upon them. Preliminary results have been reported already.[1]

The transfer of a proton from a helium projectile to a target nucleus in a direct type nuclear reaction can be studied in two different ways: (i) with a ^{3}He beam one measures the spectrum of the deuterons from the (^{3}He, d) reaction or (ii) with an α-particle beam one measures the spectrum of tritons from the (α, t) reaction. The information obtained from each of these experiments, however, is complementary in that the (α, t) reaction, relative to the (^{3}He, d) reaction, favors high angular momentum transfers due to its big momentum mismatch. A comparison of the differential cross sections of both reactions, therefore, should give information about the transferred l values. On the other hand, it appears to be very difficult to determine l values from angular distribution studies since DWBA (distorted-wave Born-approximation) calculations for both reactions show that the shapes of the angular distributions do not differ enough to reliably distinguish between different l values.

For the present work the nucleus ^{237}Np was chosen because the structure of its energy levels below an excitation energy of approximately 500 keV has been identified already in terms of rotational bands built upon intrinsic proton excitations.[2,3]

II. EXPERIMENTAL PROCEDURE AND RESULTS

The measurements were performed by bombarding a ^{236}U target with 30-MeV ^{3}He and α-particle beams obtained from the Emperor tandem Van de Graaff accelerator of the University of Rochester. The target[4] consisted of a 1×5-mm^2 ^{236}U strip, enriched to 99.6% ^{236}U, deposited on a 20-μg/cm^2 carbon backing. The areal density of the uranium layer was 62 μg/cm^2 and was determined by a measurement of the natural α activity with a silicon surface-barrier detector.

The deuteron and triton spectra from the ^{236}U(^{3}He, d)^{237}Np and ^{236}U(α, t)^{237}Np reactions, respectively, were analyzed with an Enge split-pole magnetic spectrograph[5] and recorded on 100-μm N.T.B.-type Kodak photographic plates. A monitor counter mounted at 45° with respect to the incoming beam detected the ^{3}He and α particles elastically scattered from the target. The output of this detector served for the intensity normalization and determination of absolute cross sections for both reactions.

DWBA calculations show that the differential cross sections of the (α, t) and (^{3}He, d) reactions have rather broad maxima between 40° and 70°. For the (α, t) measurement, the laboratory angle of 45° was chosen. The (^{3}He, d) experiment, however, was performed at 60° in order to eliminate background lines from lighter-mass impurities. In Fig. 1, the triton and deuteron spectra are shown. The energies of the various groups along with their absolute intensities are listed in Table I. The energy values are averages from both experiments. Absolute cross sections were determined with the assumption that the elastic cross sections at 45°

* Work supported by the U.S. Atomic Energy Commission.

[1] Th. W. Elze, University of Rochester Report No. UR-NSRL 23, 1969 (unpublished).

[2] E. K. Hyde, I. Perlman, and G. T. Seaborg, *The Nuclear Properties of the Heavy Elements* (Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1964).

[3] C. M. Lederer, J. M. Hollander, and I. Perlman, in *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[4] The target was obtained from the United States Atomic Energy Commission through the Isotopes Division of Oak Ridge National Laboratory, Oak Ridge, Tenn.

[5] H. A. Enge, Nucl. Instr. Methods **28**, 119 (1964); J. E. Spencer and H. A. Enge, *ibid.* **49**, 181 (1967).

for 30-MeV ^{3}He and α particles on ^{236}U are equal to the value of the Rutherford cross section.[6]

A partial level scheme of ^{237}Np as obtained by a combination of our results with data published previously[2,3] is shown in Fig. 2. The levels observed in our experiments are indicated by heavy lines. States seen in previous experiments but not observed in our measurements are drawn as thinner lines. Since, in general, the energies determined in our experiments agree within the experimental errors with the more accurate values obtained from radioactive-decay studies,[3] we ascribe the energy values given in Ref. 3 to the levels of the $\frac{5}{2}^+[642]$, $\frac{5}{2}^-[523]$, and $\frac{1}{2}^-[530]$ rotational bands. All energies are rounded off to whole keV. Based on the present data, the $\frac{3}{2}^-[521]$ band has been identified in ^{237}Np for the first time.

In the bar graph on the right side of Fig. 2, the experimental differential cross sections of both reactions are compared with each other.

III. ANALYSIS AND DISCUSSION

The first step in the interpretation of the spectra shown in Fig. 1 was to associate the deuteron and triton groups with known levels[3] on the basis of an energy fit. Nilsson configurations then were assigned to the rotational bands from a comparison of measured and calculated spectroscopic factors as discussed below.

Following Satchler,[7] the observed differential cross section for a stripping reaction with an even, nonspherical target nucleus exciting a rotational state with spin J may be written

$$(d\sigma/d\Omega)_{0^+\to J=j} = 2N' c_{jl}^2 U^2 \sigma_{lDW}(\theta, Q). \quad (1)$$

Here, $\sigma_{lDW}(\theta, Q)$ is the intrinsic single-particle stripping cross section for the transfer of a proton with orbital angular momentum l containing the angular and energy dependence of the reaction process. In the present work, the values of $\sigma_{lDW}(\theta, Q)$ were calculated with a DWBA computer code[8] for both the (^{3}He, d) and (α, t) reactions making use of the optical-model parameters[9,10] listed in Table II. Spin-orbit effects and a finite-range correction were not included in the calculations. Since the differential cross sections depend on the reaction Q value, the values of $\sigma_{lDW}(\theta, Q)$ were calculated for two different excitation energies, 0 (ground state) and 1 MeV. The cross sections for intermediate energies then were obtained by interpolation.

The quantity N' in Eq. (1) is the renormalization factor for the particular reaction under consideration. In order to normalize the (^{3}He, d) cross sections, the value of N' was taken[11] to be 4.42. From a comparison of the measured intensities of corresponding lines in the deuteron and triton spectra, the renormalization factor for the (α, t) reaction was found to be approximately 71. Since, however, this comparison involves also the theoretical cross sections of both reactions, a significant uncertainty is associated with this value.

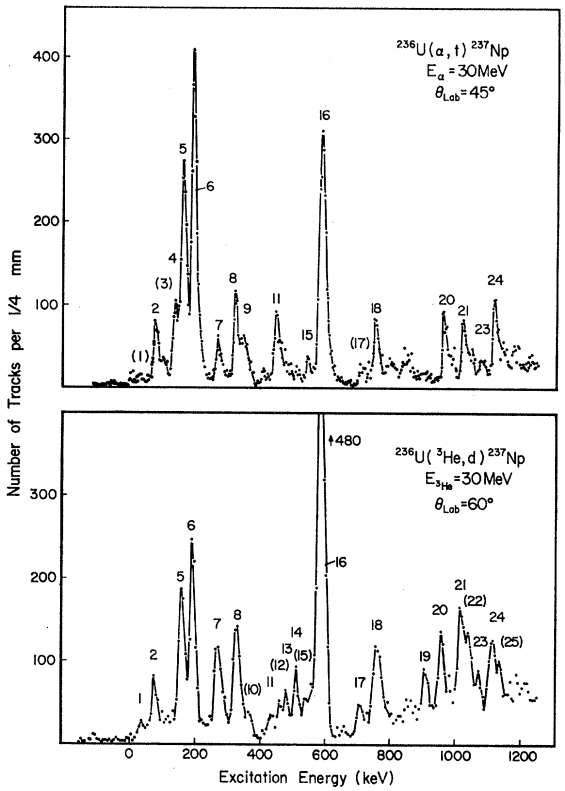

FIG. 1. Triton and deuteron spectra from the reactions ^{236}U(α, t)^{237}Np and ^{236}U(^{3}He, d)^{237}Np, respectively. The numbers ascribed to the various groups correspond to those given in Table I.

The remaining quantity $S = 2c_{jl}^2 U^2$ in Eq. (1) contains all the spectroscopic information on the states excited by the reaction.[12] In the framework of Satchler's stripping theory,[7] this quantity is expected to be independent of the reaction mechanism. The c_{jl} is an amplitude in the expansion of the deformed wave functions $|N\Omega\rangle$ in terms of spherical limit functions $|Nj l\Omega\rangle$, e.g., $|N\Omega\rangle = \sum_{jl} c_{jl} |Nj l\Omega\rangle$ and may be calculated for particular shapes of the nuclear potential. The U^2 is the probability that the orbit to be entered by the proton in the reaction is empty.

The c_{jl} coefficients have been computed for two different nuclear potentials. The use of a harmonic-oscillator well yields the c_{jl} factors tabulated by Chi[13]

[6] Th. W. Elze and J. R. Huizenga, Nucl. Phys. **A133**, 10 (1969).
[7] G. R. Satchler, Ann. Phys. (N.Y.) **3**, 275 (1958).
[8] University of Colorado code DWUCK, made available to us by J. Robbins.
[9] B. H. Wildenthal, B. M. Preedom, E. Newman, and M. R. Cates, Phys. Rev. Letters **19**, 960 (1967).
[10] J. S. Lilley and N. Stein, Phys. Rev. Letters **19**, 709 (1967); **19**, 1000 (1967).
[11] R. H. Bassel, Phys. Rev. **149**, 791 (1966).
[12] The S factor used in the text is related to the spectroscopic factor $\mathcal{S}$ defined by Satchler (Ref. 7) by the relation $\mathcal{S} = S/(2J+1)$, where J is the spin of the rotational level excited by the stripping reaction.
[13] B. E. Chi, in *Collective Models of the Nucleus*, edited by J. P. Davidson (Academic Press Inc., New York, 1968).

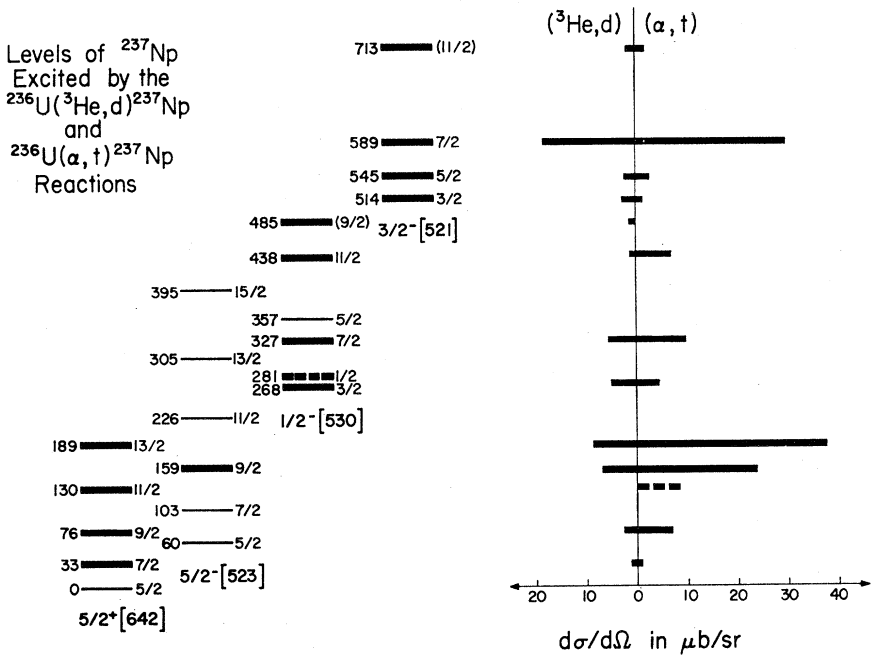

FIG. 2. Partial level scheme of ^{237}Np. Levels excited by the ^{236}U(^{3}He, d)^{237}Np and/or ^{236}U(α, t)^{237}Np reaction are drawn as heavy lines. On the right, the observed differential cross sections of both reactions are compared with each other.

TABLE I. Energy levels of ^{237}Np excited by the ^{236}U(^{3}He, d)^{237}Np and ^{236}U(α, t)^{237}Np reactions.

Line	Assignment	Energy (keV)	Cross section (μb/sr) (^{3}He, d) 60°	(α, t) 45°
1	$7/2^+[642\uparrow]$	30±4	0.8±0.2	(0.7±0.2)
2	$9/2^+[642\uparrow]$	74±2	2.3±0.3	7.0±0.4
(3)	$(7/2^-[523\downarrow])$	(98)		≈2.8
4	$11/2^+[642\uparrow]$	131±2		≈8
5	$9/2^-[523\downarrow]$	156±2	6.5±0.4	24±2
6	$13/2^+[642\uparrow]$	189±1	7.8±0.5	38±2
7	(1/2)+3/2⁻[530]	269±2	4.2±0.5	4.4±0.4
8	7/2⁻[530]	328±2	5.6±0.3	9.5±0.5
9		346±3		4.9±0.5
(10)		(365)	≈1.3	
11	11/2⁻[530]	438±4	0.9±0.2	7.0±1.4
(12)		(466)	≈1.1	
13	(9/2⁻[530])	484±4	1.5±0.4	
14	$3/2^-[521\uparrow]$	514±3	2.6±0.3	
15	$5/2^-[521\uparrow]$	545±3	≈2.2	2.9±0.5
16	$7/2^-[521\uparrow]$	589±1	18±2	30±2
17	$(11/2^-[521\uparrow])$	713±3	1.3±0.2	≈1.6
18		758±6	4±1	7±1
19		914±4	2.1±0.2	
20		961±3	3.2±0.4	7.1±0.6
21		1020±3	4.5±0.4	6.1±0.5
(22)		(1046)	≈3	
23		1072±6	1.4±0.2	2.2±0.3
24		1112±4	3.1±0.3	8.5±0.6
(25)		(1137)	≈1.7	

TABLE II. Optical-model parameters.[a]

	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a' (fm)	W_D (MeV)	$(r_0)_{Coul}$ (fm)
^{3}He [b]	175	1.14	0.723	17.5	1.60	0.81	0	1.40
Deuteron [b]	111	1.05	0.859	0	1.24	0.794	17.7	1.25
α [c]	200	1.40	0.60	20	1.40	0.60	0	1.30
Triton [c]	200	1.45	0.60	50	1.45	0.60	0	1.30
Bound state		1.25	0.65					1.25

[a] The optical potential used has the form $U(r) = -V(1+e^{X})^{-1} - i[W-4W_D(d/dX')](1+e^{X'})^{-1}$, where $X=(r-r_0A^{1/3})/a$ and $X'=(r-r_0'A^{1/3})/a'$.

[b] Reference 9.

[c] Reference 10.

for various deformations of the nucleus. Rost[14] calculated deformed wave functions for actinide nuclei assuming a Woods-Saxon–type potential. The S factors resulting from both of these calculations for a deformation of $\eta=5.0$ are compared with the corresponding experimental values in Table III. This Table includes only rotational states with spins $J\leq N+\frac{1}{2}$ since, based on a simple Nilsson model, states with higher spins are not to be excited. No configuration mixing has been taken into account. In general, there is good agreement between the theoretical S factors for the Woods-Saxon and harmonic-oscillator potentials, a result which has been observed[6] also for single-neutron states of actinide nuclei. On the whole, relative experimental S factors within each band agree quite well with the calculated ones. However, on an absolute basis, the measured

TABLE III. Observed and calculated S factors.

		S factor[a]			
		Calculated		Observed	
State	Assumed U^2	Harmonic-oscillator[b]	Woods-Saxon[c]	(^{3}He, d) [d]	(α, t) [e]
5/2+[642 ↑]	0.5	0	0	0	0
7/2+[642 ↑]	0.5	0	0	0.08	(0.02)
9/2+[642 ↑]	0.5	0.07	0.03	0.22	0.23
11/2+[642 ↑]	0.5	0.01	0	f	(0.97)
13/2+[642 ↑]	0.5	0.92	0.97	3.12	4.6
5/2−[523 ↓]	0.7	0.05	0.08	g	g
7/2−[523 ↓]	0.7	0.03	0.03	f	(0.10)
9/2−[523 ↓]	0.7	1.29	1.26	2.12	2.36
11/2−[523 ↓]	0.7	0.03	0.03	0	0
1/2−[530]	0.2[h]	0.01	0.01	0.21	0.19
3/2−[530]	0.2	0.10	0.11		
5/2−[530]	0.2	0	0	0.43	0.39
7/2−[530]	0.2	0.21	0.16		
9/2−[530]	0.2	0.04	0.08	(0.45)	
11/2−[530]	0.2	0.04	0.04	0.27	0.74
3/2−[521 ↑]	1.0	0.18	0.27	0.12	
5/2−[521 ↑]	1.0	0.04	0.03	0.16	0.13
7/2−[521 ↑]	1.0	1.49	1.30	1.28	1.42
9/2−[521 ↑]	1.0	0.15	0.19	0	0
11/2−[521 ↑]	1.0	0.14	0.21	0.37	0.19

[a] For the definition of the S factor, see text and Ref. 12.

[b] Calculated with Nilsson parameters $\mu=0.70$, $\kappa=0.05$ for shell $N=5$ and $\mu=0.62$, $\kappa=0.05$ for shell $N=6$.

[c] Calculated with Woods-Saxon parameters $V=60$ MeV, $r_0=1.262$ fm, $a=0.7$ fm.

[d] Cross section normalized with $N'=4.42$.

[e] Cross section normalized with $N'=71$.

[f] Line obscured.

[g] Doublet with $\frac{9}{2}^{+}$ [642 ↑]?

[h] Hole configuration.

[14] E. Rost (private communication). We are greatly indebted to Professor E. Rost of the University of Colorado for making these results available.

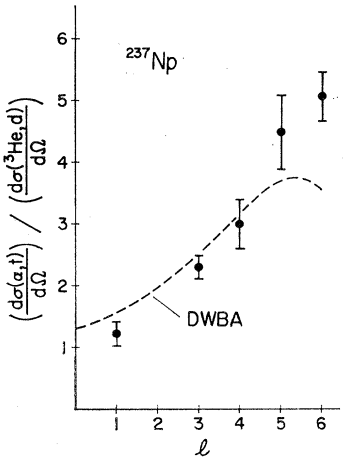

FIG. 3. The l dependence of the cross-section ratio $d\sigma(\alpha, t)/d\sigma(^3\mathrm{He}, d)$. The points are the observed cross-section ratios after reduction to a standard reaction Q value corresponding to zero excitation energy. The DWBA curve has been calculated with the optical-model parameters listed in Table II and the renormalization factors given in the text.

values are in general greater than the theoretical ones. Uncertainties associated with the quantities N', U^2, and $\sigma_{IDW}(\theta, Q)$ in Eq. (1) may be responsible for the deviations of the S factors.

First, the partial filling of the levels near the Fermi energy expressed by the quantity U^2 affects the differential cross sections. The values of U^2 listed in Table III were assumed for the various bands since the diffuseness of the Fermi surface is not known exactly. However, the S factors of the $\frac{5}{2}^+[642]$ ground-state band could not be understood assuming even the greatest possible value for U^2.

The S factors listed in Table III are calculated with the assumption of pure Nilsson configurations. Coriolis mixing, therefore, may cause differences between the experimental and theoretical values of S. A band-mixing calculation, however, taking into account all the 16 levels of the $\frac{1}{2}^-[530]$, $\frac{3}{2}^-[521]$, and $\frac{5}{2}^-[523]$ bands shows that the wave functions of these states contain less than 5% admixtures and justifies the assumption of nearly unmixed configurations. Hence, this small amount of mixing of the odd-parity states is not sufficient to account for the observed discrepancies in the values of S.

The relatively small inertial parameter of the $\frac{5}{2}^+[642]$ ground-state band of $A=4.7$ keV suggests Coriolis coupling of this band. Possible mixing partners are the $\frac{7}{2}^+[633]$ and $\frac{3}{2}^+[651]$ configurations expected at higher excitation energies.[15] However, both the $\frac{7}{2}^+[633]$ and $\frac{3}{2}^+[651]$ bands have not been found in ^{237}Np, thus making a further estimate of their mixing with the $\frac{5}{2}^+[642]$ state rather difficult.

Finally, the magnitude of the DWBA cross sections is subject to an uncertainty which, however, affects all the cross sections of a particular reaction to largely the same extent and, therefore, can be corrected for by using a suitable renormalization factor. The over-all agreement of observed and calculated S factors could be improved by multiplying the N' by a factor of approximately 1.8.

As can be seen from Fig. 2, the differential cross section of the (α, t) reaction, compared with the $(^3\mathrm{He}, d)$ cross section, gets larger as the transferred angular momentum increases, thus supporting the prediction pointed out in Sec. I. The magnitude of the cross-section ratio $d\sigma(\alpha, t)/d\sigma(^3\mathrm{He}, d)$ versus the transferred l value is plotted in Fig. 3. In this ratio, the energy dependence of the cross sections has been taken out by reducing the measured $(^3\mathrm{He}, d)$ and (α, t) differential cross sections to a standard reaction Q value corresponding to zero excitation energy of the residual nucleus. This reduction is based on the theoretical Q dependencies of the DWBA cross sections. The points represent average values of $d\sigma(\alpha, t)/d\sigma(^3\mathrm{He}, d)$ and the dashed curve is the DWBA theoretical prediction with the optical-model parameters listed in Table II. It is interesting to note that the experimental l dependence of the cross-section ratio is somewhat stronger than the calculated one, in particular for high l values. Yet, the agreement is good in view of the uncertainties involved in the DWBA calculations for both nuclear reactions.

Measurements of angular distributions for either the $(^3\mathrm{He}, d)$ or the (α, t) reactions are not very useful for making l assignments. Hence, the strong l dependence of $d\sigma(\alpha, t)/d\sigma(^3\mathrm{He}, d)$ makes the determination of this cross-section ratio advantageous for the assignment of l values in proton transfer reactions with heavy-mass targets.

ACKNOWLEDGMENTS

The authors wish to thank G. W. Korn for the development of the emulsion plates and Mrs. E. E. Korn for careful plate scanning. Thanks are also due to the crew of the tandem Van de Graaff accelerator for generous cooperation. Finally, the support of the Nuclear Structure Research Laboratory by the National Science Foundation is acknowledged.

[15] B. Nilsson, Nucl. Phys. A129, 445 (1969).