Energy levels of ^{239}U observed with the (d,p) reaction

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Energy levels of ^{239}U up to an excitation energy of 1.6 MeV have been studied with the ^{238}U(d,p) ^{239}U reaction at a bombarding energy of 12 MeV. Angular distributions $75° \leq \theta_L < 150°$ provided information on the l values transferred. Level assignments based on the (d,p) data are suggested which partially corroborate recent studies of ^{239}U with neutron-capture γ rays.

[NUCLEAR REACTIONS ^{238}U(d,p), E=12 MeV; measured E_x and $\sigma(\theta)$; ^{239}U deduced levels, l, J, π, Nilsson assignments.]

I. INTRODUCTION

New information has recently become available about the excited states of ^{239}U. At Brookhaven[1,2] and at Grenoble[3] a variety of techniques based on neutron capture have been used to study ^{239}U. These new data enable the development of a rather complete energy level scheme. However, information from the ^{238}U$(d,p)^{239}$U reaction is essential for the analysis of these new data since the (d,p) reaction gives information uniquely sensitive to the wave functions of the deformed orbitals. The previous study of ^{238}U$(d,p)^{239}$U was performed by Sheline *et al.*[4] more than 10 years ago. The present experiment reports measurements with the same reaction in which the levels in ^{239}U are more clearly resolved. This is particularly important for the group of strongly excited levels between 0.6 and 1.2 MeV excitation energy. Also, the new data contain angular distributions covering the range 75–150° which provide information about the l value of the transferred neutrons.

One motivation for pursuing this work is the hope that something interesting about the nature of the coupling between single-particle and phonon states in ^{239}U might be learned. In the 0.6–1.2 MeV region of excitation there are many complicated states, some of which appear to be strongly admixed. If enough experimental information is available it may be possible to develop a detailed understanding of these levels, their energies, spins, wave functions, and strengths in the different excitation processes, to be compared with specific calculations of the level properties. Some calculations of actinide nuclei which treat both the quadrupole and octupole modes of the residual interaction have already been performed by the Dubna group and this work has been summarized in the publication of Gareev *et al.*[5] However, if the experimental situation becomes clearer, it would be worthwhile to perform more sophisticated calculations which would provide a fit to the data. Hopefully such a work would teach us something about the nature of the particle-hole interactions in the actinides.

II. THEORETICAL ANALYSIS

The orbital assignments of the levels seen in this study and their organization into rotational bands are based mainly on the observed cross sections and their measured excitation energies. Some use is also made of the ratio of the differential cross sections at forward and backward angles which provides information about the l value of the captured neutron.

In a single-nucleon transfer reaction on a target nucleus with spin zero, the differential cross section in the simplest form is given by the following expression[6,7]:

$$d\sigma/d\Omega = (2J+1)S_J\theta_J^{\rm DW}, \tag{1}$$

where J is the spin of the final state, $\theta_J^{\rm DW}$ is the intrinsic single-particle cross section, usually obtained from calculations of a reaction mechanism which assume the distorted-wave Born approximation, and S_J is the spectroscopic factor which contains information about internal nuclear structure. For reactions on deformed nuclei, the spectroscopic factor is usually written[7] as

$$S_J^\kappa = [2/(2J+1)](C_J^\kappa)^2 P_\kappa^{\,2}, \tag{2}$$

where κ denotes the specific state being populated, P_κ is the pairing factor, and C_J^κ is the expansion coefficient in the expression for the deformed single-particle wave function. The expansion coefficients are the terms which carry the detailed sensitivity to the internal nuclear wave functions. The set of expansion coefficients are, in general, different for each Nilsson orbital. They can be computed from theory[8] and are used to predict the signature pattern in the different cross sections for a rotational band based on a particular deformed orbital. These predictions are usually checked by comparison with observed signature patterns in cases where the orbital assignment is well known. In this way it is possible to build a catalog of the cross-section signatures for different orbitals by the systematic study of various actinide nuclei. Extensive measurements of this type have been done for the actinides and are reported in the review by Chasman *et al.*[7]

The main features of the term θ_J^{DW}, the intrinsic single-particle cross section, do not change significantly for (d,p) reactions in the actinides as the target nucleus is varied and the bombarding energy held fixed. In the present work no specific calculations were made for this term. Rather, the experience of the variation in differential cross section, with angle and transferred l, was derived from experiments on other actinides, particularly the work of Macefield and Middleton.[9]

III. EXPERIMENTAL PROCEDURE

A split-pole magnetic spectrograph[10] was used to record the data. The 12 MeV deuteron beam was provided by the Argonne FN tandem Van de Graaff accelerator. The target was prepared by evaporating fully depleted uranium oxide onto a self-supporting carbon backing. The thickness of the target was about 32 μg/cm^2. Measurements were made at laboratory angles of 75°, 90°, 105°, 120°, 135°, and 150°. The data were recorded on nuclear emulsions and the tracks scanned with an automatic nuclear emulsion scanner.[11] A few peaks were hand counted to check the automatic scanner. The resulting spectra were analyzed with the automatic spectrum decomposition program AUTOFIT.[12] The spectrum obtained at 150° is shown in Fig. 1. The energy resolution width observed in most spectra was about 10 keV.

The absolute differential cross sections for the transfer reaction were measured relative to the elastic scattering cross section of the deuteron beam from ^{238}U. To normalize each spectrum, elastically scattered deuterons were recorded by a silicon monitor detector at 90°. For this angle a value of 0.70 ± 0.03 for the ratio of elastic scattering to Rutherford scattering cross sections was assumed.

The excitation energies of the levels observed below 1.6 MeV are given in Table I. The excitation energies listed are averages of the several values (usually six in number) given by the spectrum decomposition program. The errors listed are in most cases the rms deviation of the individual measurements about the average. Only levels observed at several angles are listed. A few peaks from contaminants in the target were observed to move across the spectra with angle. The measured cross sections at 90° and 150° together with the cross-section ratios are listed. The cross-section ratios listed were obtained by drawing the best straight line through all data points in the angular distributions. The spin and orbital assignments to be discussed below are shown for completeness.

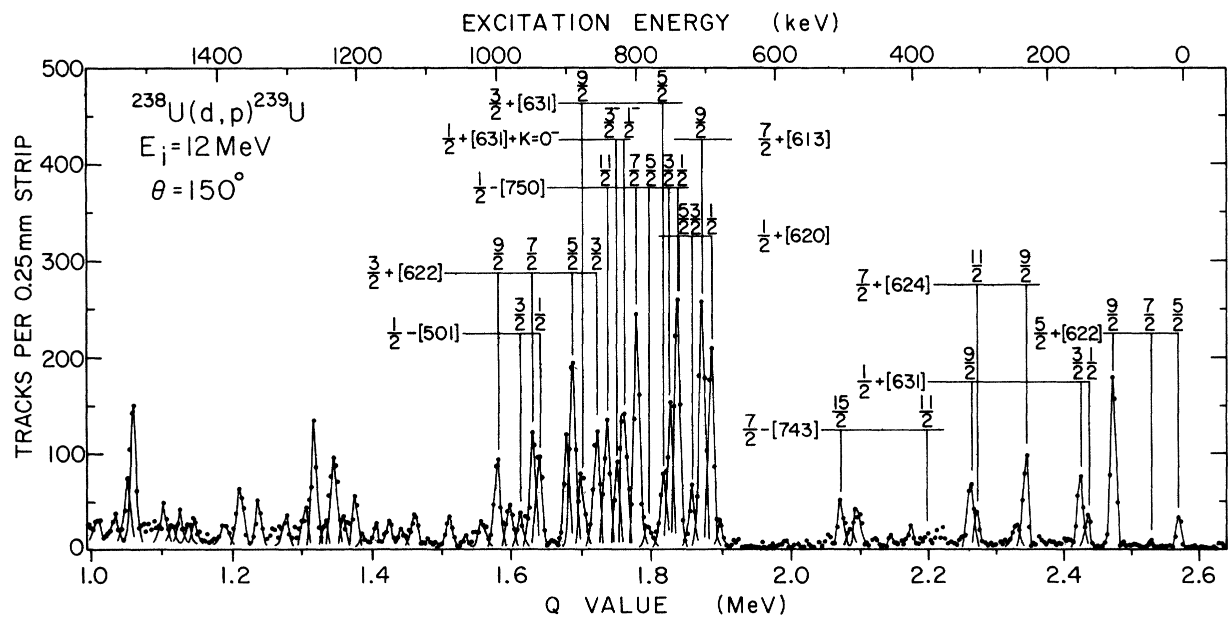

FIG. 1. Proton spectrum from the ^{238}U$(d,p)^{239}$U reaction. Orbital and spin assignments are shown. Contaminant peaks are labelled C.

TABLE I. Energy levels in ^{239}U, their excitation energy, differential cross section in the (d,p) reaction, cross section ratios 90° to 150°, spin and orbital assignments.

Excitation energy (keV)	$d\sigma/d\Omega$ at 90° (μb/sr)	$d\sigma/d\Omega$ at 150° (μb/sr)	$\frac{d\sigma(90°)}{d\sigma(150°)}$	I^π	Assignment orbital	Ref.
0	24.7 ± 4.6	13.9 ± 1.1	1.83	$\frac{5}{2}^+$	$\frac{5}{2}^+[622]$	4,9,13
43.0 ± 2.0	< 4	3.2 ± 1.0		$\frac{7}{2}^+$	$\frac{5}{2}^+[622]$	4
98.1 ± 1.5	96.1 ± 7.9	81.2 ± 3.6	1.0	$\frac{9}{2}^+$	$\frac{5}{2}^+[622]$	4,9
133.5 ± 1.5	46.3 ± 4.7	13.9 ± 2.5	2.80	$\frac{1}{2}^+$	$\frac{1}{2}^+[631]$	4,13
146.1 ± 1.5	60.6 ± 5.2	34.2 ± 3.5	1.80	$\frac{3}{2}^+$	$\frac{1}{2}^+[631]$	4,13
226.3 ± 1.5	53.9 ± 9.6	44.1 ± 3.6	1.0	$\frac{9}{2}^+$	$\frac{7}{2}^+[624]$	4,9
301.8 ± 2.0	<10	13.4 ± 2.1		$\frac{11}{2}^+$	$\frac{7}{2}^+[624]$	4,9
307.8 ± 1.5	25.3 ± 2.1	27.3 ± 2.5	0.93	$\frac{9}{2}^+$	$\frac{1}{2}^+[631]$	4
372.7 ± 2.0	8.0 ± 3.0	7.2 ± 3.1	1.1	$\frac{11}{2}^-$	$\frac{7}{2}^-[743]$	This study
498.6 ± 1.5	9.0 ± 3.0	21.1 ± 2.1	0.43	$\frac{15}{2}^-$	$\frac{7}{2}^-[743]$	This study
689.0 ± 1.5	182.7 ± 11.6	92.4 ± 16.3	1.90	$\frac{1}{2}^+$	$\frac{1}{2}^+[620]$	3,4,13
702.5 ± 1.5	96.1 ± 8.9	119.0 ± 18.2	0.81	$\frac{9}{2}^+$	$\frac{7}{2}^+[613]$	This study
717.3 ± 1.5	29.4 ± 5.2	25.4 ± 9.3	1.15	$\frac{3}{2}^+$	$\frac{1}{2}^+[620]$	3,4,13
738.3 ± 1.5	173.8 ± 12.2	120.6 ± 18.9	1.60	$\frac{1}{2}^-$	$\frac{1}{2}^-[750]$	2,3
				$\frac{5}{2}^+$	$\frac{1}{2}^+[620]$	3,4
748.0 ± 2.0	122.3 ± 11.2	59.8 ± 15.6	2.30	$\frac{3}{2}^-$	$\frac{1}{2}^-[750]$	2,3
759.0 ± 2.0	53.3 ± 7.0	37.8 ± 11.5	1.45	$\frac{5}{2}^+$	$\frac{3}{2}^+[631]$	3
781.4 ± 2.0	23.8 ± 10.0	13.6 ± 7.0	1.7	$\frac{5}{2}^-$	$\frac{1}{2}^-[750]$	3
795.9 ± 1.5	167.6 ± 22.0	109.1 ± 16.9	1.60	$\frac{7}{2}^-$	$\frac{1}{2}^-[750]$	3
814.5 ± 1.5	111.3 ± 10.0	71.1 ± 14.9	1.75	$\frac{1}{2}^-$	$\frac{1}{2}^+[631]$ $+K=0^-$	3
823.9 ± 1.5	70.8 ± 8.5	41.8 ± 12.5	2.20	$\frac{3}{2}^-$	$\frac{1}{2}^+[631]$ $+K=0^-$	3
838.3 ± 1.5	36.0 ± 5.7	62.8 ± 13.3	0.62	$\frac{11}{2}^-$	$\frac{1}{2}^-[750]$	This study
854.1 ± 1.5	75.2 ± 7.6	62.9 ± 13.0	1.28	$\frac{3}{2}^+$	$\frac{3}{2}^+[622]$	3
874.0 ± 1.5	46.4 ± 6.3	38.5 ± 5.2	1.20	$\frac{9}{2}^+$	$\frac{3}{2}^+[631]$	This study
887.6 ± 1.5	114.8 ± 10.0	89.4 ± 8.2	1.25	$\frac{5}{2}^+$	$\frac{3}{2}^+[622]$	3
897.9 ± 1.5	55.4 ± 7.4	46.5 ± 6.4	1.20			
919.3 ± 2.0	<8	3.6 ± 2.0				
936.9 ± 2.0	49.4 ± 6.7	47.2 ± 6.2	0.98	$\frac{1}{2}^-$	$\frac{1}{2}^-[501]$	3
944.8 ± 2.0	34.2 ± 6.0	50.0 ± 6.2	0.82	$\frac{7}{2}^+$	$\frac{3}{2}^+[622]$	3
963.6 ± 1.5	23.8 ± 4.6	17.5 ± 3.8	1.50	$\frac{3}{2}^-$	$\frac{1}{2}^-[501]$	3
978.4 ± 1.5	25.7 ± 4.7	24.3 ± 4.3	1.0			
996.1 ± 1.5	43.0 ± 5.7	40.8 ± 6.7	1.0	$\frac{9}{2}^+$	$\frac{3}{2}^+[622]$	3
1066.5 ± 1.5	<10	16.2 ± 3.7	0.7			
1115.0 ± 1.5	<8	16.8 ± 4.2	0.5			
1151.1 ± 2.0	<10	12.1 ± 4.3	0.92			
1197.3 ± 1.5	36.2 ± 7.8	33.8 ± 6.5	0.90			
1232.6 ± 1.5	75.5 ± 16.6	52.7 ± 7.1	1.3			
1240.0 ± 3.0	<8	15.9 ± 4.8				
1260.1 ± 1.5	49.8 ± 15.2	56.8 ± 7.1	0.85			
1273.0 ± 3.0	28.4 ± 12.2	19.8 ± 4.6	1.4			

TABLE I. (Continued).

Excitation energy (keV)	$d\sigma/d\Omega$ at 90° (μb/sr)	$d\sigma/d\Omega$ at 150° (μb/sr)	$\frac{d\sigma(90°)}{d\sigma(150°)}$	I^π	Assignment orbital	Ref.
1337.7±2.0	16.4± 7.8	22.1± 2.3	0.7			
1364.7±2.0	38.6±10.6	29.2± 2.7	1.3			
1430.3±3.0	20.6± 6.2	11.3± 5.3	1.8			
1472.9±3.0	<10	18.2± 5.6				
1515.0±2.0	91.2± 2.7	64.6± 9.0	1.3			
1524.2±3.0	24.5± 6.9	29.6± 7.1	0.9			

IV. DISCUSSION

The main features of the spectra observed in the present work are consistent with those reported by Sheline *et al.*[4] However, there are many disagreements in detail. For example, below 700 keV excitation energy, six of the levels reported by Sheline *et al.* are not observed in the present work. These are the levels reported at 165, 173, 189, 220, 623, and 651 keV. Presumably the background in the spectrum or contaminants in the target resulted in this confusion since a measurement at only one angle, 65°, had been made. Above 600 keV the improved resolution of the new data enabled many more states to be observed. Indeed, it turns out that nearly all the strong levels reported in the previous study are really complex structures, and even the better resolution of the present experiment probably has not resolved all of the levels in this region.

Most of the level assignments listed in Table I are based on previously published studies[4,13] of ^{239}U and preliminary reports[1-3] of the work at Brookhaven and Grenoble. These have been supplemented with assignments made from the currently reported (d,p) experiment. For the most part these assignments should not be regarded as final because they have not been fully checked with all the information available from the new studies nor have detailed cross-section calculations for the (d,p) reaction been made to be compared with the observed cross sections.

Specific comments are as follows: The levels at 372.7 and 498.6 keV have been assigned as the $I^\pi = \frac{11}{2}^-$ and $\frac{15}{2}^-$ members of the $\frac{7}{2}^-[743]$ band mostly on the basis of the observed cross-section ratios 90° to 150°. This assignment is consistent with the situation in the analogous nucleus, ^{241}Pu, where these same levels have been observed[14] at 445 and 571 keV and have a similar cross-section signature.

The assignment of the levels of the $\frac{1}{2}^+[620]$ band seems fairly certain. The cross-section pattern observed for the levels is quite consistent with the pattern observed for this band in other actinide nuclei. Also, the cross-section ratios 90° to 150° are in agreement with this assignment. The group observed at 738.3 keV is most likely a doublet. This is consistent with the observation by Bollinger and Thomas[13] of two levels at 734.7 and 739.2 keV which are closer than the resolution width of the present (d,p) data. The major component of the 738.3 keV group is probably the $\frac{5}{2}^+$ level of the $\frac{1}{2}^+[620]$ band and the other member of the doublet is probably the $\frac{1}{2}^-$ level of the $\frac{1}{2}^-[750]$ band.[15] The fact that the cross-section ratio for this group is 1.60 suggests that most of the strength is not a spin $\frac{1}{2}$ or $\frac{3}{2}$ level because the ratio in that case would be larger. In the ^{248}Cm$(d,p)^{249}$Cm reaction the $\frac{1}{2}^-$ level of the $\frac{1}{2}^-[750]$ band is very weak,[16] and this is consistent with the present assignment since most of the strength in the group at 738.3 keV seems to belong to the $\frac{5}{2}^+$ level and the other component appears weak. The $\frac{3}{2}^-$ member of the $\frac{1}{2}^-[750]$ band has been assigned to the 748.0 keV level. This is different from the assignment of Bollinger and Thomas.[13] However, their data allow either a $\frac{1}{2}^-$ or $\frac{3}{2}^-$ assignment for this level. In the (d,p) data[16] leading to ^{249}Cm the $\frac{3}{2}^-$ member of the $\frac{1}{2}^-[750]$ band is quite strong, which is evidence to support the $\frac{3}{2}^-$ assignment of the 748.0 keV level. Chrien *et al.*[2] and Börner *et al.*[3] have also interchanged the spin assignments of the 739 and 746 keV levels to be $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively.

The fact that no level is observed in the present data at 726.0 keV is a strong indication that a $\frac{3}{2}^+$ band whose bandhead is at 726 keV (based mostly on the neutron-capture data) is the $\frac{3}{2}^+[631]$ band and not the $\frac{3}{2}^+[622]$ band. If the latter were the case, the $\frac{3}{2}^+$ state at 726.0 keV would have been observed since the $\frac{3}{2}^+$ level of the $\frac{3}{2}^+[622]$ band is known from studies of other actinide nuclei to be strongly excited with the (d,p) reaction. A more natural location for the $\frac{3}{2}^+[622]$ band is to place it with its bandhead at 854.1 keV, as suggested by the (n,γ) studies. Then the intensity pattern observed in (d,p) for the various members is consistent with the cross-section signature observed for this band in other nuclei.

However, there is a difficulty in placing the $\frac{3}{2}^+[631]$ band so close to the $\frac{1}{2}^+[620]$ band. The problem is that this then leads to many pairs of closely spaced levels with the same spin which might strongly mix. For the $\frac{3}{2}^+$ levels the spacing is 10 keV, for the $\frac{5}{2}^+$ levels the spacing is 22 keV. Since these spacings are so small one might expect that these levels should be strongly admixed because the Coriolis matrix element between the $\frac{1}{2}^+[620]$ and the $\frac{3}{2}^+[631]$ states is quite large. An explanation for this situation may be that since one of these states is a hole state and the other a particle state, the fact that they both lie on the opposite sides of the Fermi level weakens the coupling to the extent which would allow them to lie so close to each other. The (d,p) data suggest that the mixing is not large, otherwise the cross-section signatures would probably be unrecognizable.

Börner *et al.*[3] have suggested that the 814.5 and 823.9 keV levels are the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of a band formed by coupling the $\frac{1}{2}^+[631]$ orbital to a $K=0^-$ phonon. It is surprising that the cross sections to these levels are as large as they are, since 0^- phonon excitations are not expected to be strongly excited in a one-nucleon transfer reaction. An explanation for this large strength may be that these levels are strongly admixed to nearby $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels. A similar comment can be made about the assignment by Börner *et al.* of the 936.9 and 963.6 keV levels as the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the $\frac{1}{2}^-[501]$ band. At this excitation the $\frac{1}{2}^-[501]$ state is not expected to be strongly excited in the (d,p) reaction since it is a hole state. However, there may be considerable admixing with the $\frac{1}{2}^+[631]$ state built on the $K=0^-$ phonon. The transfer strength of these $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels may be derived mainly from the only $\frac{1}{2}^-$ particle state which is expected to be strongly excited, the $\frac{1}{2}^-[750]$ state. However, the difficulty with this interpretation is that the calculated wave function as well as the component observed in other nuclei for the $\frac{1}{2}^-$ level of the $\frac{1}{2}^-[750]$ band indicate that the $\frac{1}{2}^-$ strength will be small in the (d,p) reaction leading to ^{239}U. If the assignment of Börner *et al.* is correct, it is not at all clear where the large cross section to the $\frac{1}{2}^-$ level at 814.5 keV comes from.

The present (d,p) data provide a strong test of any proposed orbital assignments made in this nucleus. However, because of the strong mixing between the various levels it may not be possible to make reliable assignments, unless mixed wave functions are computed and compared to the transfer cross section.

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