IAEA/SM-174/65

LA-UR-73-960

Conf-730823--5

DETERMINATION OF SPINS OF INTERMEDIATE STRUCTURE* RESONANCES IN SUBTHRESHOLD FISSION

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ABSTRACT

The appearance of prominent intermediate structure in subthreshold fission is currently ascribed to coupling between the normal (Class I) compound nuclear states and Class II states belonging to the second minimum in a double-humped fission barrier. This explanation requires that only Class I resonances of a single spin state be enhanced through coupling to a Class II state of the same spin. In order to verify this explanation, the fission (σ_f) and total (σ_t) cross sections of ^{237}Np for resonance energy neutrons have been measured with a polarized neutron beam and polarized target, using time-of-flight methods. Neutrons from the Oak Ridge Electron Linear Accelerator were polarized by transmission through a dynamically pumped proton sample. The ^{237}Np was polarized in a ferromagnetic medium cooled by a ^{3}He-^{4}He dilution refrigerator.

The individual fine-structure resonances comprising the Class II structure at 40 eV incident neutron energy were determined to have the same spin, $J^\pi = 3^+$. Spins of 14 other Class II structures below 1 keV were also determined, although the fine structure is unresolved. Comparison of these results with earlier data [1] on the angular distribution of fission fragments from aligned ^{237}Np reveals an apparent admixing of transition states, as evidenced by nonintegral values of the projection quantum number, K.

1. INTRODUCTION

In order to proceed to a detailed understanding of fission systematics, it is necessary to measure the spins of resonances in fissionable nuclei. In particular, the properties of the transition states in fissioning nuclei remain somewhat obscure without determination of the channel spin.

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

Previous attempts to determine spins of compound nuclear levels in fissionable nuclei have primarily involved indirect methods, such as observing deexcitation capture gamma rays, relative gamma-ray multiplicities, and combination of total and partial cross sections. The more direct method utilizing a polarized neutron beam and polarized target has previously been limited to low neutron energies, < 10 eV, where polarizing the neutron beam is a relatively simple matter. Because of the inconsistencies in those published spin assignments for fissionable nuclei, it was decided in 1968 at the Los Alamos Scientific Laboratory to undertake an experimental program to develop the equipment and techniques to polarize a wide range of fissionable targets and a neutron beam over a wide energy range.

The determination of narrow intermediate structure in the fission cross section of ^{237}Np was first reported by Paya et al.[2] Although the total cross section is characteristic of other odd-odd heavy elements, with an s-wave level spacing of ~ 0.7 eV, the fission cross section is composed of numerous structures whose mean spacing is ~ 60 eV. The explanation of this intermediate structure in terms of a double-humped fission barrier [3] requires that the individual resonances in each group or structure have the same spin, that of the "parent" state in the second well. Thus, the choice of ^{237}Np as a target nucleus was an obvious one to demonstrate this technique of spin determination and to verify the presence of intermediate structure resulting from coupling of states in the second well, Class II, to the normal, Class I, compound nuclear states.

The ^{237}Np nucleus has ground state spin and parity $5/2^+$, and the compound system ^{238}Np resulting from absorption of s-wave neutrons has $J^\pi = 3^+$ states for the target and neutron polarization parallel and 2^+ for the antiparallel case. The ratio of observed cross sections is approximated by

$$R = \frac{\sigma_{par}}{\sigma_{anti}} = \frac{1 + f_I f_n f_N}{1 - f_I f_n f_N} \tag{1)}$$

where f_N is the target polarization, f_n the neutron polarization, and $f_I = I/I+1$ for $J = I+1/2$ and $f_I = -1$ for $J = I-1/2$. Thus, in ^{238}Np, the ratio $R > 1$ for $J^\pi = 3^+$ resonances and $R < 1$ for those with $J^\pi = 2^+$.

2. EXPERIMENTAL

The technique of neutron polarization used in this experiment was first reported by Shapiro [4] in 1965. This method utilizes the strong spin dependence of the neutron-proton interaction where the cross section for scattering through the singlet state of the system is ~ 20 times larger than that for the triplet state. Thus an unpolarized neutron beam becomes polarized when filtered through a sample of polarized protons. Since the cross sections for singlet and triplet scattering vary little over the range 10 eV to 50 keV, the polarization of the transmitted beam is essentially constant over this range.

The method of dynamic nuclear polarization [5] is used to polarize the protons in the water of hydration of single crystals of $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$ (LMN). A series of LMN crystals are placed in a microwave cavity at a temperature of 1.15°K located in a homogeneous magnetic field of ~ 20 kOe in a superconducting coil. The system of free electrons and protons in the paramagnetic LMN is then "pumped" by microwaves, whereby simultaneous electron and proton spin flips are induced. Owing to their long relaxation times, the protons remain flipped, resulting in a net bulk proton polarization. In this experiment, a neutron polarization of ∿ 55% with a transmission through the LMN of 18% was realized. The difficulty of this technique arises primarily from the fact that the "pumped" transition is forbidden and, hence, narrow. High stabilization of the microwave source and high homogeneity of the magnetic field are required over long periods of time. In addition, the large size of the cryogenic and vacuum equipment, coupled with a fast nuclear magnetic resonance system to monitor the polarization, makes the equipment complex.

The method used to polarize the fissionable target involves thermal equilibrium techniques. The simplest of the thermal equilibrium techniques is the brute-force method, whereby the interaction between an externally applied magnetic field with the nuclear magnetic moment at low temperature results in a net polarization. With currently available magnetic fields and attainable temperatures, polarization of < 1% are achieved by this method. However, by choosing a suitable ferromagnetic system containing the desired target, the large hyperfine fields may result in high polarization.

In this experiment, a target of $NpA\ell_2$ was fabricated and attached to a ^{3}He-^{4}He dilution refrigerator. This dilution refrigerator, which utilizes the fact that the dissolving of ^{3}He in ^{4}He is a heat-absorbing process, is capable of maintaining a temperature of < 0.01°K, with no external heat input. The natural radioactivity of the 2.5 g of ^{237}Np used here resulted in an operating temperature of 0.135°K, however. This target was also placed in a superconducting coil whose field was parallel to the LMN magnetic field. In order to reduce eddy-current heating in the sample, the entire cryogenic apparatus was suspended from a 2300-kG marble slab supported by pneumatic pistons.

The fission neutrons were detected in 12 liquid scintillator cells, each 5 in. x 5 in. Pulse shape discrimination techniques were used to reduce the gamma-ray background.

The Oak Ridge Electron Linear Accelerator (ORELA) was used as a pulsed source of neutrons.

3. EXPERIMENTAL RESULTS

The relative fission cross section has been measured from 1-1000 eV by detecting fission neutrons at 0° and 90° relative to the incident beam. In addition, the transmission has been measured from 1-102 eV. The target was located 13.4 meters from the source and the transmission detector was positioned at 15.2 meters. The ORELA was operated at a repetition rate of 1000 pps with a pulse length of 30 ns, resulting in an average power of 50 kW. With these parameters, the useful energy range of the fission data was determined by the signal-to-background ratio; whereas the transmission data were limited by resolution.

The data are composed of four pairs of runs, each run of approximately 24-h duration. Each pair is composed of one run with the beam and target polarization parallel and another with the direction of polarization anti-parallel. The polarization of the neutron beam only was reversed; this was achieved by pumping transitions of electron-proton pairs which are parallel rather than those which are antiparallel. This reversal only required a change in magnetic field or, equivalently, in microwave pumping frequency, of $\sim$ 0.2%. Thus, no substantial change in operating conditions resulted from neutron polarization reversal.

In processing the data, each pair of runs was treated identically in order to preserve the normalization. An average background was subtracted from both runs in each pair, rather than a separate one for each run. After initial processing, the data were integrated over each resonance and the ratio, R, of the integrals for the parallel and antiparallel geometries was determined. This resulted in four independent measurements of J for each resonance.

The resonances observed in fission are listed in Table I. The quantities $R_\mu = \langle R \rangle$ are the mean ratios determined from the four pairs of runs. The two columns of errors represent the standard deviations from the mean and the statistical errors. The J values indicated are determined from the R_μ.

The single uncertainty in extracting J values from such data is knowledge of the target polarization relative to the applied magnetic field. Either the magnetic moment of the target nucleus may be negative or the hyperfine field may be opposite to the impressed field. In the data presented here, the evidence appears to be conclusive that the target polarization is parallel to the applied field and, hence, that for $R_\mu > 1$, $J = 3$. The strongest evidence arises from the factor f_I in Eq. (1). This predicts a greater deviation from unity of R_μ for a resonance with $J = I - 1/2 = 2$ than for one with $J = I + 1/2 = 3$. Knowing the neutron beam polarization, f_n, Eq. (1) may be solved for f_N. From Table I, the average R_μ for resonances with $J = 3$ indicated in the table is 1.17 ± 0.02 and 0.79 ± 0.04. From Eq. (1), one arrives at $f_N = 0.20$ from the $J = 3$ resonances and $f_N = 0.21$ from the $J = 2$ resonances. If, however, the assumption is made that the polarization is antiparallel to the applied field, then one determines $f_N = 0.30$ for the $J = 3$ states and $f_N = 0.14$ for those with $J = 2$. Clearly, the former assumption appears more valid. As supporting evidence, calculations [6] of hyperfine fields in actinide compounds based on systematic interpretation of Mössbauer effect data indicate that, for a hyperfine field of the magnitude of that observed in $\mathrm{NpA}\ell_2$, the sign must be positive. Further evidence relies upon the assumption that the level density, where no nonstatistical mechanism is present, should vary according to $2J + 1$. In Table II, the resonances observed in transmission are listed with the spins determined in this experiment. Of these 94 resonances, 57 are assigned $J = 3$ and 37 are assigned $J = 2$. Although the error is large on this sampling, the $2J + 1$ dependence is supported with these assignments and strongly violated for the opposite spin assignments.

The fission data in the region of the 40-eV structure are shown in Fig. 1. The enhancement of the compound nuclear levels is distributed over nine individual resonances. The curve labeled $\sigma_{par}-\sigma_{anti}$ is consistently greater than unity over each individual fine structure resonance, indicating that each resonance has the same spin, $J = 3$. A sample of the transmission data is shown in Fig. 2, over the range 4-18 eV. Here the plot of $T_{par}-T_{anti}$ demonstrates the clear distinction between resonances of different spin.

4. DISCUSSION

The inherent difficulty in determining spins by methods less direct than that employed in this experiment are well known. Preliminary results of an experiment on ^{235}U using the equipment and techniques reported here are given in Table III. Comparison of spin assignments determined here and those assignments resulting from indirect methods are quite poor. Although some individual measurements are consistent, no single technique involving indirect methods appears to be at all reliable. For example, the results of Corvi et al. [7] are in excellent agreement, whereas the results of Weigmann et al., [8] using a similar technique, are in agreement on only 44% of the resonances studied. Although far less effort has been expended on the system ^{237}Np+n, comparison of J assignments from the data presented here and from a measurement [9] of the total, scattering, and capture cross sections further demonstrates the ambiguity of indirect spin determination. As shown in Table IV, the two sets of spin assignments are in no better than random agreement. Not only do the assignments for the resonances belonging to the group at 40 eV differ, but those below 26 eV are in agreement in only four out of nine cases.

Reference 9 also indicates a possible spin dependence of the mean capture width for resonances in each spin state. In that work, $\langle \Gamma_\gamma \rangle = 47$ meV for those resonances assigned $J = 3$ and $\langle \Gamma_\gamma \rangle = 57$ meV for those assigned $J = 2$. However, as Table V demonstrates, when the spin assignments from the experiment described here are applied to the capture widths of Ref. 9, the mean width is the same for both spin states. Similarly, examining a total of 62 resonances whose reduced neutron widths are compiled in Ref. 16 and whose J values are determined here, no spin dependence is observed, within the sizeable errors. The average values, $\langle \Gamma_n^0 \rangle$, for each J value are also given in Table V.

However, interpretation of the results of Kuiken, Pattenden, and Postma [1] with the J values assigned here is somewhat enlightening. In that experiment, the angular distribution of fission fragments from an aligned ^{237}Np target was studied. For the experimental conditions realized in the alignment experiment, the angular distribution of fission fragments may be expressed as

$$\omega(\theta) = 1 + A_2 f_2 P_2(\cos\theta) \qquad (2)$$

where f_2 is the alignment parameter and A_2 is given by

$$A_2 = \frac{15}{4}\,\frac{I}{I+1}\left\{\frac{3K^2}{J(J+1)} - 1\right\} \qquad (3)$$

The intent of the experiment was to glean information about the K-quantum number, the projection of J on the nuclear symmetry axis. However, this task is made difficult by the lack of knowledge of the J values for each resonance studied.

The nature of the deformation barriers and the possible effects upon the observed K values is discussed by Kuiken et al. Current evidence in the form of a broad low peak under the 40 eV group, observed by Paya et al., [2] and the lack of lines in the gamma-ray spectrum corresponding to transitions between intermediate levels in the second well, indicate very weak coupling between the compound nuclear levels and the intermediate levels. This corresponds to a situation where the second barrier, at higher deformation, is lower than the first barrier. In this case, there may be some admixing of higher transition states, although Kuiken et al. assume this admixing to be small.

In Table VI, a list of those resonance groups observed in both the present work and by Kuiken et al. is given, along with the J assignments, the measured A_2 values, and the theoretical A_2 values. Poor resolution averages several of the A_2 values over more than a single fine structure resonance, in the 40-eV group, or over more than a single group, at higher energies. Using the assignment from Ref. 9 of J = 2 for the resonances in the group at 40 eV, Kuiken et al. concluded that the evidence was consistent with an integral K value, K = 2, for those resonances. However, the present assignment of J = 3 to this group makes this interpretation less tenable and implies an admixture of K = 3 and K = 2 components. For most of the resonances in the 40-eV group, the K = 3 component seems predominant, although alone insufficient to explain many of the measured A_2 values. Interpretation of the alignment results becomes more ambiguous at higher energies, owing to larger statistical errors. The structure at 119 eV has a measured A_2 value in between that expected for a resonance with (J:K) = (3:3) and one with (3:2). Similarly, the A_2 values for the three structures at 231, 283, and 370 eV, all of which are assigned J = 2, are most consistent with a mixture of K = 2 and K = 1 components. The pairs of structures near 200 and 870 eV were unresolved in the alignment data and, since the members of these pairs are of opposite spin, are difficult to interpret. The remaining structures appear to be consistent with integral K assignments of (J:K) = (3:2).

Some conclusions may be deduced from the mean A_2 values for each spin state, shown in Table VI. In both cases, K = 0 transition states appear to be unavailable. The observed $\langle A_2 \rangle$ values are consistent with the explanation that the K = 2 channel is generally preferred with (J:K) = (2:1) and (3:3) partially open. The mean A_2 value for the J = 3 resonances would imply that the K = 3 channel is preferred for resonances of this spin, but this is primarily a result of the small errors on those individual resonances in the 40-eV structure. Those resonances in the 40-eV group appear to preferentially decay through K = 3 transition states, whereas the remaining J = 3 structures prefer K = 2 channels.

5. CONCLUSION

From the experimental results described here, several conclusions may be deduced. The Strutinsky theory of a double-humped fission barrier is substantiated as the mechanism by which intermediate structure in subthreshold fission is explained. The coupling of the Class II states in the second potential minimum to the compound nucleus states in the first minimum selects resonances of a single-spin state, that of the "parent" Class II state. From correlation of existing data on the angular distribution of fission fragments from aligned ^{237}Np with the data presented here, it is concluded that, at least in the odd-odd system ^{237}Np+n, there is a substantial admixing of transition states, evidenced by nonintegral values of the projection quantum number, K. Although all values of K from zero to J are allowed, the value K = 2 appears to be predominant for resonances of both J = 2 and J = 3, with contribution from K = 3, J = 3 and K = 1, J = 2 states.

In contrast to the fission results, the total cross section shows no intermediate structure with a 2J+1 distribution of level densities. Similarly, no nonstatistical spin dependence is observed in the capture or neutron widths.

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TABLE I

FISSION MEASUREMENTS

E_o	$R_\mu = \left\langle \frac{R_{par}}{R_{anti}} \right\rangle$	σ_μ	Statistical Error	J
26.6	1.259	± .060	0.185	3
30.4	1.086	.074	0.059	3
37.1	1.163	.064	0.085	3
38.9	1.091	.031	0.048	3
39.2	1.134	.036	0.066	3
39.9	1.169	.023	0.024	3
41.3	1.201	.041	0.051	3
46.0	1.160	.035	0.094	3
50.4	1.409	.084	0.218	3
119	1.207	.046	0.060	3
188	0.467	.153	0.344	2
195	0.818	.080	0.112	2
201	1.160	.036	0.049	3
207	1.393	.176	0.413	3
229	0.721	.218	0.212	2
234	0.839	.133	0.113	2
253	1.316	.091	0.138	3
283	0.946	.140	0.103	(2)
370	0.804	.143	0.168	2
373	0.745	.151	0.119	2
427	1.514	.284	0.223	3
476	0.819	.160	0.186	2
668	1.459	.616	0.618	3
718	1.918	.409	0.635	3
808	1.984	.306	0.339	3
873	0.810	.209	0.164	2
884	1.182	.078	0.207	3

TABLE II

J ASSIGNMENTS FROM TRANSMISSION

E_o	J
1.47	2
1.96	3
3.07	(3)
3.85	3
4.26	2
4.86	2
5.76	3
6.36	3
6.65	2
7.18	(2)
7.42	3
8.29	3
8.96	3
9.28	2
10.2	2
10.7	3
10.8	3
11.1	2
12.2	(3)
12.6	2
13.1	(3)
15.8	(3)
16.1	2
16.8	2
17.6	3
18.9	2
19.1	3
19.9	(3)
20.4	2
21.1	3
22.0	2
22.9	3
23.7	3
24.0	2
25.0	3
26.2	3
26.6	3
28.5	2
28.9	(2)
29.5	(2)
30.4	3
31.3	3
33.4	3
33.9	2
34.7	3
35.2	2
36.4	3
37.1	3
38.2	3
38.9	3
39.2	3
39.9	3
41.3	3
43.6	2
45.7	2
46.0	3
46.3	3
47.3	2
48.8	2
49.8	3
50.4	3
52.2	2
52.6	2
53.9	2
55.0	3
56.1	(2)
58.4	3
59.5	2
60.0	3
61.0	3
61.7	3
62.5	3
62.9	3
65.0	(3)
65.7	3
66.7	3
67.5	3
68.0	2
68.7	3
70.3	3
71.1	3
74.4	(2)
78.4	3
79.2	2
80.7	3
82.2	3
86.5	3
87.7	2
90.9	3
93.4	2
97.9	2
98.6	2
100.3	3
101.1	2

TABLE III

^{235}U J ASSIGNMENTS

E_o	PRESENT WORK	POLARIZATION [10]	CAPTURE [11]	CAPTURE [8]	CAPTURE [7]	CAPTURE [12]	γ-MULTIPLICITY [13]	SCATTERING [14]	SYMMETRY [15]
1.13	4	4	-	-	-	-	3	-	-
2.04	3	3	3	-	3	3	4	-	-
3.14	3	3	-	-	-	-	3	-	-
3.61	4	4	-	-	-	-	3	-	-
4.84	4	4	-	-	4	4	4	-	-
6.17	3	-	-	-	-	-	-	-	-
6.38	4	4	-	4	4	3	4	-	-
7.07	4	4	-	3	-	-	3	-	-
8.73	4	4	-	-	-	-	3	3	-
9.27	4	-	-	3	-	-	3	-	-
10.2	4	-	-	-	-	-	3	-	-
11.7	4	4	4	-	4	-	4	4	-
12.4	3	3	3	4	3	-	4	3	-
12.9	4	-	-	-	-	-	-	-	-
14.2	3	-	-	-	-	-	-	-	-
14.6	3	-	3	-	3	-	-	-	-
15.4	4	-	-	3	4	-	3	-	4
16.1	4	-	4	3	4	-	4	-	4
16.7	4	-	-	3	-	-	3	-	4
18.1	3	-	-	-	-	-	3	-	-
19.0	4	-	-	-	-	-	-	-	-
19.3	4	-	-	4	-	-	4	4	4
20.7	4	-	-	-	-	-	-	-	-
21.1	4	-	-	3	4	-	-	-	4
22.9	4	-	-	3	4	-	3	-	4
23.4	4	-	-	4	4	-	-	4	-

TABLE III - page 2

E_o	PRESENT WORK	POLARIZATION [10]	CAPTURE [11]	CAPTURE [8]	CAPTURE [7]	CAPTURE [12]	γ-MULTIPLICITY [13]	SCATTERING [14]	SYMMETRY [15]
23.6	3	-	-	-	-	-	-	-	4
24.2	3	-	-	-	3	-	-	-	3
25.6	3	-	-	-	-	-	-	-	3
27.8	4	-	-	4	-	-	3	-	4
29.7	4	-	-	-	-	-	-	-	-
30.6	3	-	-	-	-	-	-	-	-
30.9	4	-	-	3	4	-	-	-	4
32.0	4	-	3	4	-	-	4	4	4
33.5	4	-	-	4	-	-	4	4	4
34.4	4	-	-	3	-	-	4	4	3
34.9	3	-	-	-	-	-	-	-	4
35.2	4	-	-	4	-	-	4	4	-
35.3	3	-	-	-	-	-	-	-	-
38.4	4	-	-	-	-	-	-	-	3
39.4	4	-	-	4	-	-	4	3	3
40.5	4	-	-	-	-	-	-	-	4
41.9	3	-	-	-	3	-	-	3	4
44.0	4	-	-	-	-	-	-	-	4
44.6	4	-	-	-	-	-	-	-	3
45.9	4	-	-	-	-	-	-	-	4
48.0	4	-	-	-	-	-	-	-	4
48.3	3	-	-	-	-	-	-	-	-
48.8	3	-	-	-	-	-	-	-	4
49.5	4	-	-	-	-	-	-	-	3
51.3	4	-	-	-	-	-	-	4	4
55.1	4	-	-	-	-	-	-	4	-
56.6	4	-	-	-	-	-	-	3	4
PERCENT AGREEMENT		100	83	44	100	67	50	78	67

TABLE IV

COMPARISON OF J ASSIGNMENTS

E_o	Present Work J	Poortmans et al.[9] J
5.76	3	3
10.8	3	3
11.1	2	2
12.6	2	3
16.1	2	2
20.4	2	3
22.0	2	3
23.7	3	3
25.0	3	2
26.6	3	2
30.4	3	2
46.0	3	(3)
47.3	2	(3)
50.4	3	2

43% Agreement

TABLE V

J DEPENDENCE - AVERAGE WIDTHS

J = 2	J = 3
$\langle \Gamma_{\gamma} \rangle = 51.7 \pm 3.2$ meV	$\langle \Gamma_{\gamma} \rangle = 52.3 \pm 1.7$ meV
$\langle \Gamma_{n}^{o} \rangle = 0.019 \pm 0.007$ meV	$\langle \Gamma_{n}^{o} \rangle = 0.018 \pm 0.006$ meV

TABLE VI

J vs A_2 PARAMETERS

E_o	J	A_2 [15]
26.6	3	2.98 ± 1.21
30.4	3	3.50 ± 0.47
37.1	3	0.62 ± 0.97
38.9	3	*1.82 ± 0.45
39.2	3	
39.9	3	2.73 ± 0.26
41.3	3	2.36 ± 0.46
46.0	3	1.57 ± 1.00
50.7	3	3.25 ± 1.06
119	3	2.56 ± 0.21
193	2	*-0.13 ± 0.57
203	3	
231	2	1.84 ± 1.45
253	3	-0.02 ± 1.30
283	(2)	0.57 ± 1.72
371	2	1.47 ± 1.34
427	3	-0.37 ± 1.87
873	2	*1.86 ± 1.74
884	3	

THEORETICAL A_2 VALUES

(J:K)	A_2	(J:K)	A_2
(2:0)	-2.679	(3:0)	-2.679
(2:1)	-1.339	(3:1)	-2.009
(2:2)	+2.679	(3:2)	0
		(3:3)	+3.348

MEAN OBSERVED A_2 VALUES

J = 2

$\langle A_2 \rangle$ = 1.38 ± 0.35

J = 3

$\langle A_2 \rangle$ = 2.42 ± 0.24

40-eV group $\langle A_2 \rangle$ = 2.56 ± 0.24

Other groups $\langle A_2 \rangle$ = 0.76 ± 0.50

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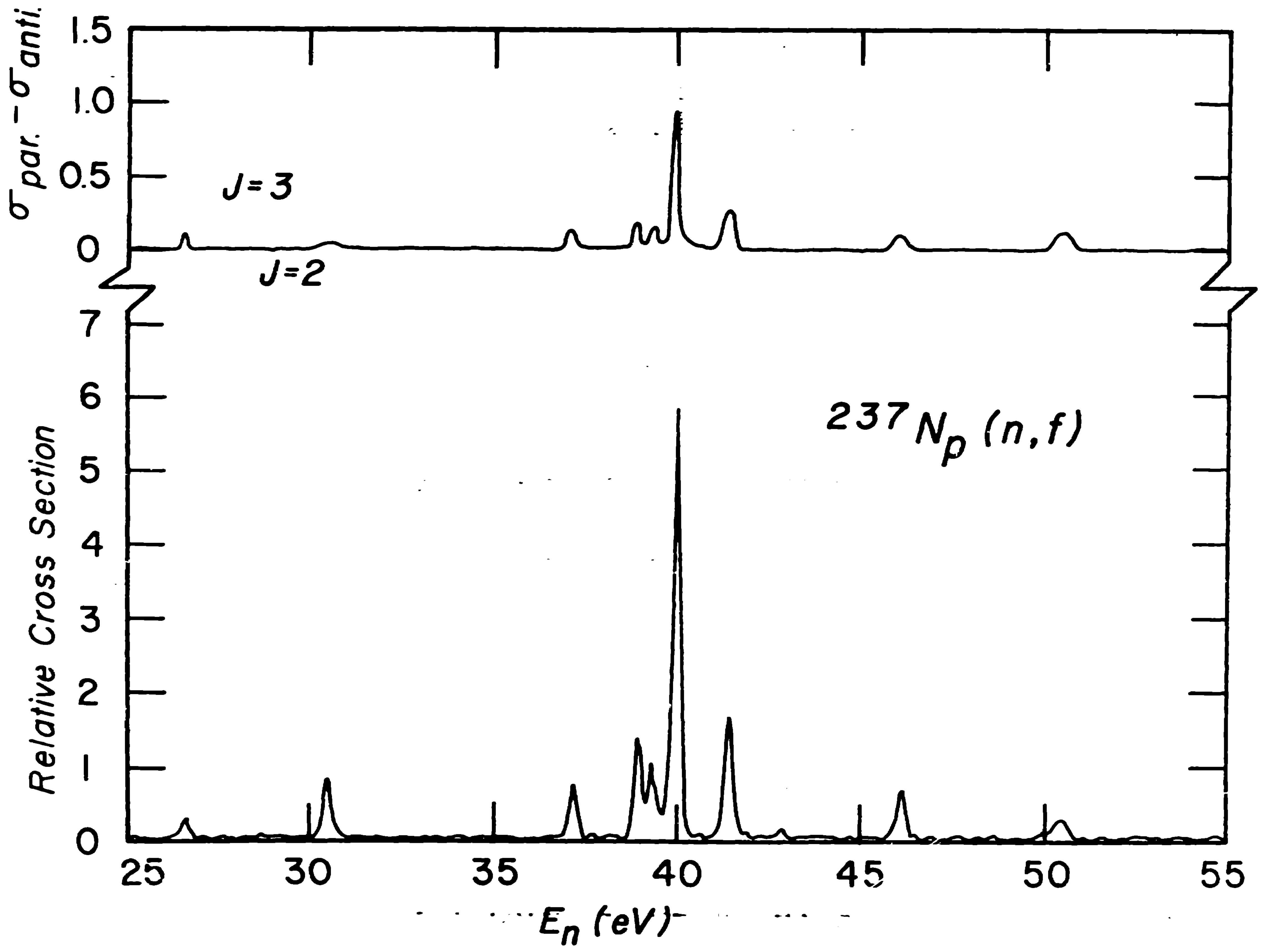
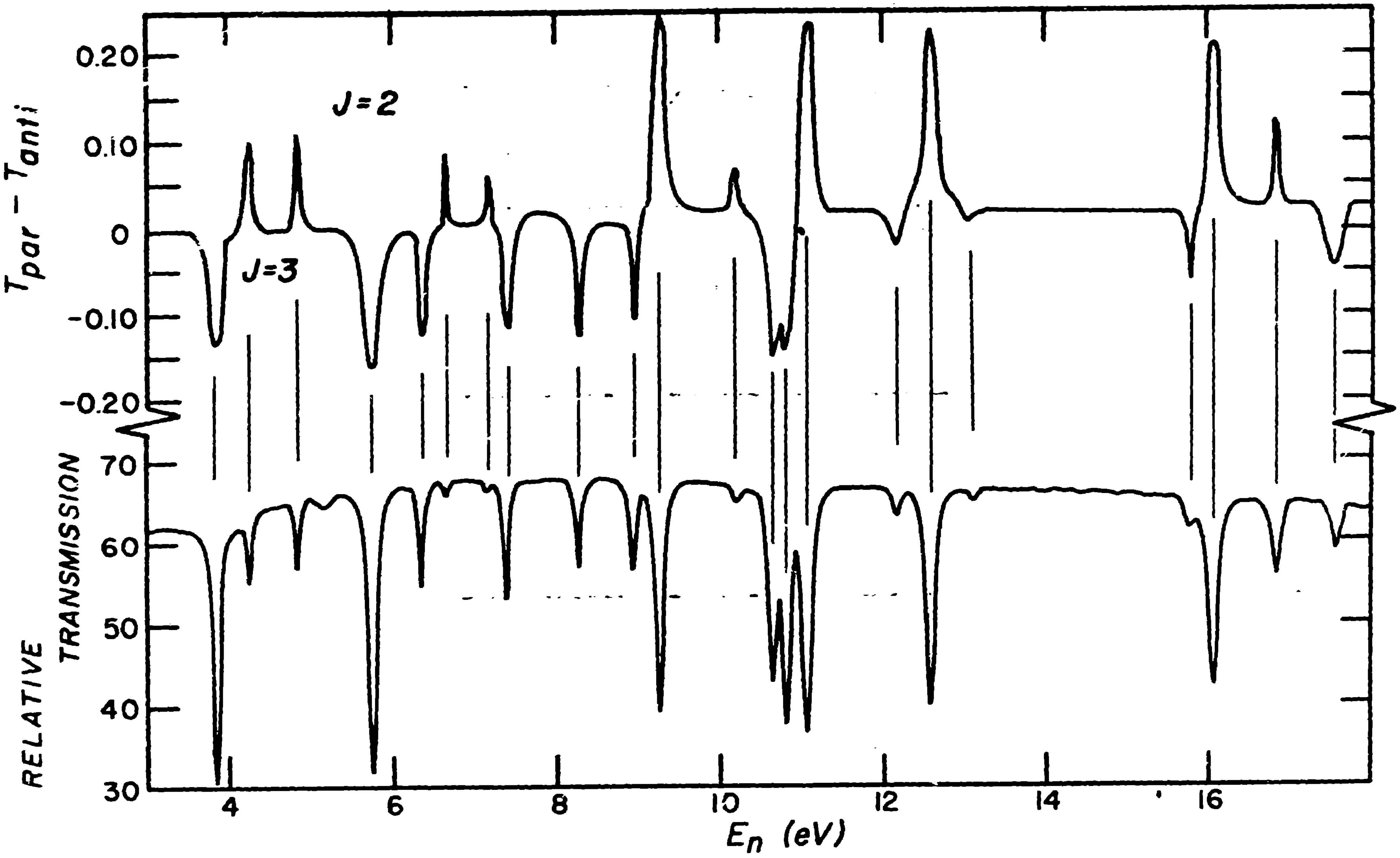
*Unresolved.

FIGURE CAPTIONS

Fig. 1. The fission data in the region of the group at 40-eV. The upper curve representing the difference between the cross sections measured with beam and target polarization parallel and anti-parallel is consistently greater than unity over each of the nine individual resonances, indicating J = 3 in each case.

Fig. 2. A sample of the transmission data. The upper curve dips below zero for resonances with J = 3 and protrudes above zero for those with J = 2.


$\sigma_{par.} - \sigma_{anti.}$
1.5
1.0
0.5
0
J=3
J=2
Relative Cross Section
7
6
5
4
3
2
1
0
$^{237}Np\ (n,f)$
25
30
35
40
45
50
55
E_n (eV)


J=2
J=3
0.20
0.10
0
-0.10
-0.20
$T_{par} - T_{anti}$
70
60
50
40
30
RELATIVE TRANSMISSION
4
6
8
10
12
14
16
E_n (eV)