Spin Determination of Resonances in the Neutron-Induced Fission of ^{235}U†

G. A. Keyworth, C. E. Olsen, and F. T. Seibel
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544

and

J. W. T. Dabbs and N. W. Hill
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 6 August 1973)

A pulsed beam of polarized neutrons and a polarized ^{235}U target have been used to determine the spins of 65 resonances below 60 eV. Comparison of these spin assignments with those determined by less direct methods reveals poor agreement in general. Interpretation of recent data on the angular distribution of fission fragments from aligned ^{235}U with the present spin assignments reveals the absence of the $K=0$ channel and an apparent admixing of transition states.

A detailed understanding of fission systematics requires knowledge of the spins of fission resonances. Previous attempts to determine the spins of of compound-nuclear resonances in fissile nuclei have primarily involved indirect methods, such as observing de-excitation γ rays, relative γ-ray multiplicities, and combinations of total and partial cross sections. The more direct method utilizing a polarized neutron beam and polarized target has previously been applied[1,2] only for neutrons of energy less than 15 eV, where the method of polarizing neutrons by Bragg reflection from a polarized cobalt-iron crystal is effective.

The experimental method employed here has been treated in detail elsewhere.[3] Briefly, a pulsed neutron beam from the Oak Ridge Electron Linear Accelerator was polarized by transmission through a dynamically polarized proton target. The ^{235}U, in the compound uranium monosulfide, was polarized in a ^{3}He-^{4}He dilution refrigerator operated at 0.02°K and in a magnetic field of 5 kOe. The hyperfine field on the ^{235}U nucleus in this compound has been determined[4] by Mössbauer spectroscopy to be 3.3 MOe. The neutrons resulting from fission in the ^{235}U target were detected in an array of liquid scintillators positioned at 10° and 90° with respect to the incident beam.

The ^{235}U nucleus has ground-state spin and parity $\frac{7}{2}^-$, and the compound system resulting from absorption of s-wave neutrons has $J^\pi=3^-$ or 4^-. The ratio of observed resonance cross sections for the target and neutron polarizations parallel and antiparallel is approximated by

$$R=\frac{\sigma_{\text{par}}}{\sigma_{\text{anti}}}=\frac{1+f_I f_N f_n}{1-f_I f_N f_n}, \qquad (1)$$

where f_N is the target polarization, f_n the neutron polarization, and $f_I=I/(I+1)$ for $J=I+\frac{1}{2}$ and $f_I=-1$ for $J=I-\frac{1}{2}$. The choice of absolute value of spin assignments from this work is predicated upon the assumption that the quantity μH, where μ is the ^{235}U magnetic moment and H is the hyperfine field, is negative. This assumption is substantiated by the one-to-one correspondence between the present assignments and those of Corvi *et al.*[5] In these measurements, $R>1$ for $J^\pi=4^-$ resonances and $R<1$ for those with $J^\pi=3^-$. The mean observed ratios for resonances assigned in Table I with $J^\pi=4^-$ are $R=1.116\pm0.004$ for neutrons detected at 90° and 1.100 ± 0.006 for those observed at 10°. Similarly, for resonances with $J^\pi=3^-$, the observed ratios are 0.912 ± 0.004 at 90° and 0.942 ± 0.008 at 10°.

The resonances observed below 60 eV whose spins have been assigned are listed in Table I. Of these 65 resonances, 44 are assigned $J^\pi=4^-$ and 21 are assigned 3^-. The fact that the number of resonances in each spin state deviates from the ratio $2J+1$ expected is ascribed to the fact that the spins of approximately one-half of the total number of resonances in this energy range are not assigned. As shown in Table II, the average fission width for resonances with $J^\pi=3^-$ is nearly twice as large as that for the 4^- case. Thus, more resonances with $J^\pi=3^-$ are likely to be missed, since the average ratio $\Gamma_n\Gamma_f/\Gamma$ will be smaller. These average widths were extracted from a recent paper[14] describing a multilevel fit to the ^{235}U fission and capture cross sections. From these average widths, the number of fission channels, N_{eff}, contributing to the cross section is estimated to be 1.1 for resonances with $J^\pi=3^-$ and 0.8 for those with $J^\pi=4^-$. The

TABLE I. ^{235}U spin assignments.

E_0 (eV)	Present Work	Polarization[a]	Capture[b]	Capture[c]	Capture[d]	Capture[e]	γ-Multiplicity[f]	Scattering[g]	Scattering[h]	Symmetry[i,j]
1.13	4	4	-	-	-	-	3	-	-	-
3.14	3	3	-	-	-	-	3	-	-	-
3.61	4	4	-	-	-	-	3	-	-	-
4.84	4	4	-	-	4	4	4	-	-	-
5.41	4	-	-	-	-	-	-	-	-	-
6.17	3	3	-	-	-	-	-	-	-	-
6.38	4	4	-	4	4	3	4	-	-	-
7.07	4	4	-	3	-	-	3	-	-	-
8.73	4	4	-	-	-	-	3	3	3	-
9.27	4	4	-	3	-	-	3	-	-	-
10.2	4	4	-	-	-	-	3	-	-	-
11.7	4	4	4	-	4	-	4	4	4	-
12.4	3	3	3	4	3	-	4	3	4	-
12.9	4	-	-	-	-	-	-	-	-	-
13.3	4	-	-	-	-	-	-	-	-	-
13.8	3	-	-	-	-	-	-	-	-	-
14.2	3	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	4
20.7	4	-	-	-	-	-	-	-	-	-
21.1	4	-	-	3	4	-	-	-	-	4
22.9	4	-	-	3	4	-	3	-	-	4
23.4	4	-	-	4	4	-	-	4	-	} 4
23.6	3	-	-	-	-	-	-	-	-	}
24.2	3	-	-	-	3	-	-	-	-	3
25.6	3	-	-	-	-	-	-	-	-	3
26.4	3	-	-	-	-	-	-	-	-	4
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	-	} 3
35.3	3	-	-	-	-	-	-	-	-	}
38.4	4	-	-	-	-	-	-	-	-	3
39.4	4	-	-	4	-	-	4	3	-	3
40.5	4	-	-	-	-	-	-	-	-	4
41.3	4	-	-	-	-	-	-	-	-	-
41.6	3	-	-	-	-	-	-	-	-	-
41.9	3	-	-	-	3	-	-	3	-	4
42.3	4	-	-	-	-	-	-	-	-	-
42.7	4	-	-	-	-	-	-	-	-	-
44.0	4	-	-	-	-	-	-	-	-	4
44.6	4	-	-	-	-	-	-	-	-	3
45.1	3	-	-	-	-	-	-	-	-	-
46.8	4	-	-	-	-	-	-	-	-	-
47.0	4	-	-	-	-	-	-	-	-	4
48.3	3	-	-	-	-	-	-	-	-	-
48.8	3	-	-	-	-	-	-	-	-	4
49.5	4	-	-	-	-	-	-	-	-	3
51.3	4	-	-	-	-	-	-	4	-	4
52.3	3	-	-	-	-	-	-	-	-	3
55.1	4	-	-	-	-	-	-	4	-	-
56.0	4	-	-	-	-	-	-	-	-	-
56.6	4	-	-	-	-	-	-	3	-	4
58.2	3	-	-	-	-	-	-	-	-	4
58.7	4	-	-	-	-	-	-	-	-	3
Percent Agreement	-	100	80	44	100	50	52	79	50	62*
No. Assignments	65	13	5	18	13	2	23	14	4	29*

*Excluding resonances in brackets

[a]Ref. 2.
[b]Ref. 6.
[c]Ref. 7.
[d]Ref. 5.
[e]Ref. 8.
[f]Ref. 9.
[g]Ref. 10.
[h]Ref. 11.
[i]Ref. 12.
[j]Ref. 13.

fact that resonances with large fission widths are preferentially missed implies that the estimated values of N_{eff} are low. However, the implication that more channels are probably available for 3^- states than for 4^- states is significant.

Additional information concerning the configuration of fission channels may be gleaned with the present spin assignments from interpreting recent data[15] on the angular distribution of fission fragments from aligned ^{235}U. These alignment data do not reveal spin information, but rather the projection, K, of the spin on the nuclear symmetry axis is determined. For the experimental conditions realized in the alignment experiment, the angular distribution of the fission

TABLE II. Spin-dependent parameters. The measured A_2 values were extracted from Ref. 1, and the quantities $\langle\Gamma_f\rangle$ and $\langle D\rangle$ for each spin state were derived from Ref. 5.

$J^\pi = 3^-$		$J^\pi = 4^-$	
$\langle A_2\rangle = -1.26 \pm 0.08$		$\langle A_2\rangle = -1.80 \pm 0.04$	
Calculated A_2 values			
$(J{:}K)$		$(J{:}K)$	
(3:0)	-2.92	(4:0) [a]	
(3:1)	-2.19	(4:1)	-2.48
(3:2)	0	(4:2)	-1.17
(3:3)	$+3.65$	(4:3)	$+1.02$
		(4:4)	$+4.08$
$\langle\Gamma_f\rangle = 0.235$		$\langle\Gamma_f\rangle = 0.130$	
$\langle D\rangle = 1.33$		$\langle D\rangle = 1.03$	
$N_{\rm eff}(J=3)/N_{\rm eff}(J=4) = 1.4$			

[a]Parity forbidden.

fragments may be expressed as

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

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 mean A_2 values for those resonances whose spins are assigned in Table I and which were resolved in Ref. 15 are given in Table II along with the theoretical A_2 values for each combination of J and K. Interpretation of these A_2 values implies that the K values for resonances of each spin state are nonintegral, resulting from an admixing of transition states. The implication is that only the $K=1$ and $K=2$ channels are available for resonances of each spin state. Although this would be expected for the $J=4$ states, since the $K=0$ channel is parity forbidden, it is in marked contrast with predictions of the Bohr channel theory of fission for the $J=3$ resonances, where the $K=0$ channel should be favored. However, a possible explanation is offered in Refs. 15 and 16 based upon the existence of a double-humped fission barrier. The presence of relatively widely spaced class-II levels in the second well which may couple to a number of class-I compound-nuclear states in the first minimum may introduce a distribution of K values characteristic of only very few class-II states. Thus the lack of evidence for resonances of $J=3$ with $K=0$ might imply the lack of availability of nearby $K=0$ class-II states.

Table I shows a comparison between spins assigned here and by less direct methods. Those low-energy resonances which have been examined by similar polarization techniques,[1,2] but where Bragg reflection was used to polarize the neutron beam, are in complete agreement with the present assignments. From neutron capture measurements, several authors[6-8] have attempted to assign spins by observing the de-excitation γ rays. The agreement between the present assignment and those resulting from the capture measurements is poor, with the notable exception of Ref. 5. It is interesting to note that the thirteen resonances assigned in Ref. 5 agree with the present work, whereas, in a similar experiment described in Ref. 7, only eight resonances out of eighteen assigned are in agreement. The widely used method of measuring the scattering and total cross sections is somewhat hindered in ^{235}U by the low ratio of Γ_n/Γ. Accordingly, the results of Refs. 10 and 11 are in rather poor agreement with the present work. As an additional evaluation of the scattering technique as applied to fissionable nuclei, comparison of spin assignments in the system ^{237}Np $+n$ from a measurement[3] using the same polarization techniques employed in the present work and a measurement[17] of the scattering cross section results in agreement for only six out of fourteen resonances. A final, and perhaps most interesting, example is the comparison with spins assigned by observing the ratio of symmetric to asymmetric fission. Ostensibly, the agreement between the present assignments and those from Refs. 12 and 13 is not exceptional. However, the symmetry measurements were somewhat hampered by resolution. Thus, the agreement becomes poorer with increasing energy. Below 30 eV, there is agreement in nine out of ten cases, consistent with a correlation between symmetry of fission and spin.

In addition to pointing out the ambiguities resulting from indirect methods of spin determination, it is significant to note the total number of resonances whose spins are assigned in Table I. Only the polarization results described here result in assignment of valid spins to a substantial fraction of the total number of resonances present over a relatively broad energy range. The present results were determined from a preliminary experiment involving only 48 h of data acquisition, and it is expected that future measurements will both extend the energy range of the spin assignments in $^{235}U+n$ and decrease the number of unassigned resonances in the range discussed here.

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

[1]R. I. Schermer, L. Passell, G. Brunhart, C. A. Reynolds, V. L. Sailor, and F. J. Shore, Phys. Rev. 167, 1121 (1968).

[2]E. R. Reddingius, H. Postma, C. E. Olsen, D. C. Rorer, and V. L. Sailor, "Spins of Low Energy Neutron Resonances in ^{235}U" (to be published).

[3]G. A. Keyworth, J. R. Lemley, C. E. Olsen, F. T. Seibel, J. W. T. Dabbs, and N. W. Hill, "Spin Determination of Intermediate Structure in the Subthreshold Fission of ^{237}Np" (to be published).

[4]G. K. Shenoy, M. Kuznietz, B. D. Dunlap, and G. M. Kalvius, Phys. Lett. 42A, 61 (1972).

[5]F. Corvi, M. Stefanon, C. Coceva, and P. Giacobbe, Nucl. Phys. A203, 145 (1973).

[6]R. G. Graves, R. E. Chrien, D. J. Garber, G. W. Cole, and O. A. Wasson, Phys. Rev. C 8, 787 (1973).

[7]H. Weigmann, J. Winter, and M. Heske, Nucl. Phys. A134, 535 (1969).

[8]W. R. Kane, Phys. Rev. Lett. 25, 953 (1970).

[9]M. Asghar, A. Michaudon, and D. Paya, Phys. Lett. 26B, 664 (1968).

[10]F. Poortmans, H. Ceulemans, E. Migneco, and J. Theobald, in *Proceedings of the Second International Conference on Nuclear Data for Reactors, Helsinki, Finland, 1970* (International Atomic Energy Agency, Vienna, Austria, 1970), p. 449.

[11]F. B. Simpson, L. G. Miller, and M. S. Moore, Nucl. Phys. A164, 34 (1971).

[12]G. A. Cowan, B. P. Bayhurst, and R. J. Prestwood, Phys. Rev. 130, 2380 (1963).

[13]G. A. Cowan, B. P. Bayhurst, R. J. Prestwood, J. S. Gilmore, and G. W. Knobeloch, Phys. Rev. C 2, 615 (1970).

[14]G. De Saussure, R. B. Perez, and W. Kolar, Phys. Rev. C 7, 2018 (1973).

[15]N. J. Pattenden and H. Postma, Nucl. Phys. A176, 225 (1971).

[16]J. W. T. Dabbs, C. Eggerman, B. Cauvin, A. Michaudon, and M. Sanche, in *Proceedings of the Second International Atomic Energy Symposium on Physics and Chemistry of Fission, Vienna, Austria, 1969* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 321.

[17]F. Poortmans, H. Ceulemans, J. Theobald, and E. Migneco, in *Proceedings of the Third Conference on Neutron Cross Sections and Technology, Knoxville, Tennessee, 1971*, edited by R. Macklin, CONF-710301 (U.S. AEC Division of Technical Information, Oak Ridge, Tenn., 1971), Vol. 2, p. 667.

Characteristics of the Reaction $p+p\to p+X$ at 205 GeV/c*

S. J. Barish, D. C. Colley,† and P. F. Schultz
Argonne National Laboratory, Argonne, Illinois 60439

and

J. Whitmore
National Accelerator Laboratory, Batavia, Illinois 60510
(Received 6 August 1973)

The inelastic reaction $p+p\to p+X$ is studied at 205 GeV/c. The distribution of the square of the missing mass, M^2, shows a large diffractivelike peak at low M^2 due to two-, four-, and six-prong events. The slope of the invariant cross section versus t decreases with increasing M^2. The energy dependences of the multiplicity moments for the recoiling system X are similar to those for corresponding moments for $p+p\to$ (n charged particles).

The existence of excited states of the proton has been established by experiments at beam momenta below ~30 GeV/c. Some of these states with low mass have been found to be produced diffractively, i.e., with approximately energy-independent cross sections, and therefore are also expected to occur at higher energies. In this Letter we present results on the inelastic reaction $p+p\to$ (slow p) $+X$ obtained using data from a 50 000-picture exposure of the 30-in. liquid-hydrogen bubble chamber to a beam of 205-GeV/c protons at the National Accelerator Laboratory. The objectives of our analysis were to study the diffractivelike excitation of the beam proton by examining the distribution of the square of the missing mass, M^2, recoiling against the slow proton, and to investigate the characteristics of the process. Data at 102[1] and 303 GeV/c[2] and