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Neutron resonance spectroscopy of ^{113}In and ^{115}In

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The neutron total cross section for natural indium was measured for $E_n = 25-500$ eV with the time-of-flight method at the Los Alamos Neutron Scattering Center. The neutron capture reaction was studied on a highly enriched sample (99.99%) of ^{115}In. A total of 47 previously unreported resonances were observed. The combination of the two measurements allowed assignment of the new resonances to ^{113}In or ^{115}In. Resonance parameters were extracted for all of the neutron resonances observed.

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I. INTRODUCTION

Recently, parity violation has been observed for compound nuclear resonances in a number of nuclei by measuring the helicity dependence of the neutron total cross section [1–6]. The parity nonconserving (PNC) longitudinal asymmetry is the fractional difference in the resonance cross section for positive and negative helicity neutrons. For *p*-wave resonances parity violation appears to be a general feature: several resonances with nonzero PNC asymmetries have now been observed in individual nuclei and asymmetries as large as 10% have been measured [5,6]. A new approach to symmetry violation treats the compound nuclear system as chaotic and assumes that the symmetry-breaking matrix elements are random variables [7–9].

Although significant progress has been achieved, there remain many questions. One unexpected experimental result was the observation that all seven asymmetries measured for *p*-wave resonances in ^{232}Th (with statistical significance $> 2.4\sigma$) has the same sign, which is inconsistent with a purely statistical description. There have been a number of proposed explanations of this experimental observation [10–19]. All of these explanations seem to require unreasonably large weak matrix elements. In order to clarify the reaction mechanism and to search for possible mass dependence of the root-mean-square PNC matrix elements, it is important to obtain more experimental data of this type in other regions of the nuclear periodic table. Experimentally, it is advantageous to be near a *p*-wave strength function maximum, which makes the region near $A = 100$ attractive. Additional considerations include the availability of sufficient target material, the level density, and the state of knowledge for the relevant neutron resonances (in the neutron energy range up to a few hundred eV).

Indium is near the maximum of the 3*p* peak in the neutron strength function, enhancing the *p*-wave resonances. The isotopic abundance of ^{115}In is 95.72%, which makes the use of natural samples feasible for parity violation studies. Earlier measurements at Columbia [20] reported 49 *s*-wave resonances in ^{115}In, 27 *p*-wave resonances in ^{115}In, and 26 *s*-wave resonances in ^{113}In (for $E_n < 500$ eV). Simple statistical arguments suggest that the set of *p*-wave resonances in ^{115}In and the set of *s*-wave resonances in ^{113}In are incomplete; there should be about the same number of *s*-wave resonances in the two isotopes and many more *p*-wave resonances than *s*-wave resonances. We therefore decided to study neutron resonances in indium. We first measured the neutron total cross section via transmission with a natural indium sample; many resonances were observed in addition to those reported previously. However, these new resonances may be intrinsically weak *p*-wave resonances in ^{115}In or relatively weak *s*-wave resonances in ^{113}In which appear further reduced by the ratio of the isotopic abundance of ^{113}In and ^{115}In in the target. From the total cross-section data for natural indium one cannot distinguish between the two choices. We then studied this energy region with a highly enriched sample of ^{115}In (99.99%). Although insufficient material was available for a transmission measurement, the sample was suitable for study via the capture reaction. With the aid of the capture data the reso-

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nances could be assigned to ^{113}In or ^{115}In. The new results, when combined with the previously known resonances, imply a total of 50 p-wave resonances in ^{115}In which are suitable for the study of parity violation.

In Sec. II the experimental methods are described. The identification of the resonances (assignment to ^{113}In or ^{115}In and presumed orbital angular momentum value) is discussed in Sec. III. The analysis to determine the resonance parameters is described in Sec. IV. The final section gives a brief summary.

II. EXPERIMENTAL METHOD

The 800-MeV proton beam pulse from the Los Alamos Meson Physics Facility (LAMPF) linac is injected into a proton storage ring (PSR) and is compressed to a pulse length of $\sim$250 ns. The extracted proton pulse strikes a tungsten target and neutrons ($\sim$20 per proton) are produced by the spallation process. The neutrons are then moderated. A detailed description of the target-moderator geometry at the Los Alamos Neutron Scattering Center (LANSCE) is given by Lisowski *et al.* [21]. Flight path 2 at LANSCE is used by the TRIPLE Collaboration to study parity violation. The details of the TRIPLE experimental setup are given by Roberson *et al.* [22].

This beam line and the associated neutron detectors and data acquisition system were used to measure neutron resonances in indium. The neutrons were detected with a system of ^{10}B-loaded detectors at 56 m from the neutron source. To avoid difficulties created by the very high count rates, the detectors were operated in current mode [23].

The neutron time-of-flight spectra were obtained with a sample of natural indium (thickness 0.231 at/b, chemical purity 99.99%). The indium sample was located at the exit of the neutron spin rotation device, approximately 9.7 m from the neutron source. The sample was cooled with liquid nitrogen to reduce Doppler broadening. With this experimental arrangement resonances could be resolved in the energy region $E_n = 25-500$ eV. A sample transmission spectrum in the region 25–50 eV is shown in Fig. 1. The strong resonances are known from previous measurements. The arrows indicate the locations of three resonances which had not been observed previously. As noted in the Introduction, these resonances may be in ^{113}In or ^{115}In. (From comparison with the literature the new resonances do not correspond to any known contaminant s-wave resonance.)

An additional measurement was performed with a highly enriched ^{115}In sample (99.99% ^{115}In). The enriched indium sample was 9.61 g of indium metal pressed in a circular disk of area 20.8 cm^2. The sample was obtained on loan from the Soviet State Pool of Stable Isotopes. There was an insufficient amount of material to perform a transmission experiment. Therefore, the neutron capture reaction was studied. By measuring the capture gamma rays one obtains virtually the same information as in the transmission experiment, since at these low energies the total width is essentially equal to the capture width for p-wave resonances.

The gamma-ray measurements were made with the indium target placed at a distance of 59.9 m from the neutron source. The gamma-ray detector consisted of two $9.8\times 9.8\times 30.5$ cm^3 CsI (pure) crystals connected by light guides to 7.6 cm Hamamatsu R1848 photomultiplier tubes. Fast high current bases from Thorn EMI (TB 1108) were used. The surfaces of the CsI crystals were located 10 cm from the center of the beam to the left and right of the beam. The crystals were shielded from neutrons scattered from the indium by 5 cm of ^{6}Li-loaded polyethylene (10% ^{6}Li by weight). The crystals and target were placed inside a two-layer shielding house. The inner layer consisted of 10 cm of lead and the outer layer consisted of 15 cm of 5% boron-loaded polyethylene.

Fast amplifiers and fast single-channel analyzers were used to process the signals. The lower level pulse height discrimination was set at 1 MeV and the upper level discrimination at 6 MeV. The data acquisition system used a Canberra multiscaler with a 8192 channel memory and was set with a 100 ns channel width. A sample time-of-flight spectrum for neutron energies $E_n = 25-50$ eV is shown in Fig. 2. The three large resonances are known s-wave resonances in ^{115}In. One of the three new resonances observed in the transmission spectrum is seen on the high-energy side of the large resonance near 40 eV. The resonance near 36 eV is due to ^{79}Br, which was present in the capture sample holder. Other than bromine, no other contaminants were observed over the entire energy range of interest.

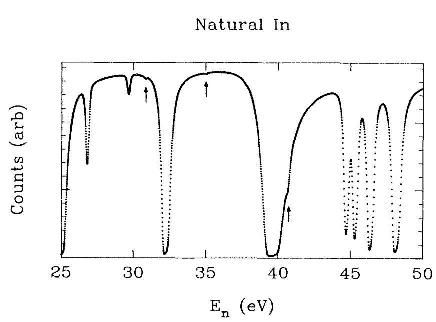

FIG. 1. Neutron transmission for natural indium in the energy range $E_n = 25-50$ eV.

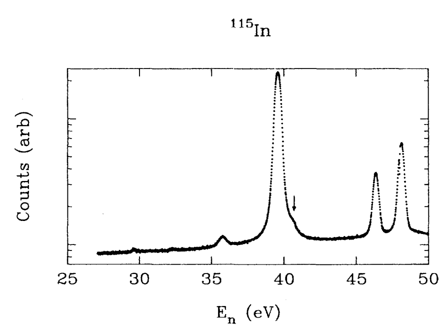

FIG. 2. Gamma-ray yield for ^{115}In in the energy range $E_n = 25-50$ eV.

III. RESONANCE IDENTIFICATION

The new transmission data on the natural indium target yield 43 new resonances which were not observed in the previous measurements [20]. As noted above, in the energy range of interest the earlier measurements reported 44 *s*-wave resonances in ^{115}In, 22 *s*-wave resonances in ^{113}In, and 27 *p*-wave resonances in ^{115}In. Since the two isotopes have the same ground-state spin and parity ($I^{\pi}=9/2^{+}$) and similar neutron separation energies, the level density in the two isotopes should be approximately equal. Therefore, the set of observed *s*-wave resonances in ^{113}In is incomplete. In the simplest statistical model the number of *p*-wave resonances should be about three times the number of *s*-wave resonances. Therefore, the set of *p*-wave resonances in ^{115}In also is incomplete. The new resonances are either *s*-wave resonances in the 4.28% abundant isotope ^{113}In or *p*-wave resonances in the dominant ^{115}In isotope. This conclusion assumes that the set of *s*-wave resonances in ^{115}In is complete. There is strong evidence supporting this assumption from the statistical analysis performed by Hacken *et al.* [20], as well as from our statistical analysis of these data.

The transmission data do not distinguish between these two most likely origins of the new resonances. In the capture gamma-ray experiment 21 of the new resonances are observed, therefore identifying them as ^{115}In resonances. Two weak resonances which Hacken *et al.* [20] assigned as ^{113}In resonances were observed in the capture data, and were reassigned to ^{115}In. In addition, four more new resonances were observed in the capture spectra. These four resonances are near large ^{113}In resonances and were obscured in the spectra measured with the natural indium target. However, the fact that a resonance is not observed with the highly enriched ^{115}In sample is not in itself sufficient evidence to identify such a resonance as belonging to ^{113}In. Since the experiments were so different, there could be a different threshold for observability in the two measurements. The capture experiment could fail to observe all levels below a certain strength in either isotope. In order to test for this possibility, the 49 resonances (47 new plus the two reassigned to ^{115}In) were ordered by their observed strength. The product $ag\Gamma_n$ is listed in Table I, where a is the relative isotopic abundance, g the statistical weight factor, and Γ_n the neutron laboratory width. (Since *a priori* the resonance can belong to either isotope, the measurement yields the abundance ratio "a" times $g\Gamma_n$.) The resonances observed with the enriched ^{115}In target are labeled with an asterisk. Since even the weakest of the 47 new resonances was observed with the enriched target, it is reasonable to tentatively assign the unobserved resonances to ^{113}In.

The new resonances assigned to ^{113}In were combined with the earlier ^{113}In resonances; all of the known ^{113}In resonances are listed in Table II. The new resonances are indicated by an asterisk. In the resonance analysis (see Sec. IV below) all of the new resonances in ^{113}In were assumed to be *s* wave. Although this is the simplest and most reasonable assumption, there may be some strong *p*-wave resonances included.

High-quality neutron resonance data yield fluctuation properties which obey the predictions of the Gaussian orthogonal ensemble (GOE) of random matrix theory [24–26]. The present neutron resonance data should

TABLE I. New resonances ordered by their $ag\Gamma_n$ values.

E_n (eV)[a]	$ag\Gamma_n$ (meV)[b]
66.4*	0.000 038
66.9	0.000 038
55.4	0.000 056
58.2	0.000 085
57.2	0.000 089
51.1	0.000 11
58.7*	0.000 13
59.1	0.000 14
35.0	0.000 15
30.9	0.000 21
74.2	0.000 21
142.4	0.000 24
71.9	0.000 36
103.7*	0.000 41
122.2	0.000 47
119.2	0.000 80
89.2	0.000 99
75.0	0.001 2
77.9*	0.001 4
88.4*	0.001 6
107.2	0.001 6
85.5*	0.002 8
40.7*	0.003 9
317.0*	0.006 4
156.5*	0.007 3
200.6	0.008 5
219.7*	0.013
275.0*	0.013
285.1*	0.013
196.4	0.017
147.6	0.022
99.2	0.036
264.5*	0.041
146.9*	0.043
276.9*	0.043
389.5*	0.055
347.0	0.069
190.9*	0.077
134.1	0.11
313.4*	0.11
428.7	0.14
394.7*	0.15
408.5	0.17
398.2*	0.20
463.8	0.21
481.4*	0.23
333.5*	0.26
325.8*	0.28
467.4	0.44

[a]Resonances labeled with an asterisk were observed in the highly enriched ^{115}In target.
[b]The quantity a is the fractional abundance of the two isotopes ^{113}In and ^{115}In in the natural indium target, g is the statistical weight factor, and Γ_n is the neutron laboratory width.

agree with GOE. Probably the most sensitive simple test of the fluctuation properties of the eigenvalues is the Dyson-Mehta Δ_3 statistic. The Dyson-Mehta Δ_3 statistic for a sequence of levels with the same quantum numbers

TABLE II. ^{113}In resonance parameters.

E_n (eV)[a]	$g\Gamma_n$ (meV)	$g\Gamma_n^0$ (meV)[b]
1.80[c]	<0.11	<0.08
4.70	0.069	0.032
14.65	2.9	0.75
21.55	1.4	0.30
25.00±0.04	4.60±0.09	0.92
26.80±0.05	0.116±0.003	0.0224
30.86±0.05*	0.005±0.002	0.0008
32.23±0.06	4.46±0.09	0.79
35.03±0.06*	0.003±0.002	0.0005
44.71±0.08	1.06±0.03	0.16
45.32±0.08	1.02±0.03	0.15
51.1±0.1*	0.0023±0.0006	0.00032
55.4±0.1*	0.0012±0.0003	0.00016
57.2±0.1*	0.0019±0.0004	0.00025
58.2±0.1*	0.0018±0.0004	0.00024
59.1±0.1*	0.0030±0.0004	0.00039
66.9±0.1*	0.0008±0.0001	0.0001
70.3±0.1	2.15±0.09	0.256
71.9±0.1*	0.008±0.006	0.0009
74.2±0.1*	0.004±0.002	0.0005
75.0±0.1*	0.03±0.01	0.003
89.2±0.2*	0.021±0.004	0.0022
91.6±0.2	14.4±0.4	1.50
93.0±0.2	3.6±0.2	0.38
99.2±0.2*	0.77±0.05	0.077
103.8±0.2	12±1	1.2
107.2±0.2*	0.03±0.01	0.003
119.2±0.2*	0.02±0.02	0.002
122.2±0.2*	0.010±0.008	0.0009
123.2±0.2	7.4±0.4	0.67
134.1±0.2*	2.4±0.4	0.21
142.4±0.3*	0.005±0.005	0.0004
147.6±0.3*	0.47±0.09	0.039
196.4±0.3*	0.4±0.2	0.03
200.6±0.4*	0.2±0.1	0.01
203.1±0.4	34.9±0.7	2.45
228.1±0.4	0.7±0.1	0.05
234.4±0.4	9±1	0.6
236.0±0.4	2.5±0.7	0.17
239.0±0.4	2.4±0.6	0.15
241.5±0.4	6.7±0.7	0.43
270.5±0.5	4.1±0.5	0.25
314.1±0.6	2.5±0.5	0.14
347.0±0.6*	1.5±0.9	0.08
408.5±0.7*	3.6±0.4	0.18
428.7±0.8*	3±1	0.1
441.4±0.8	7.0±0.8	0.33
463.8±0.8*	4±2	0.2
467.4±0.8*	9±3	0.4

[a]Resonances labeled with an asterisk are new. The other resonances were previously reported by Hacken et al. [20].
[b]Γ_n^0 is the s-wave neutron reduced width.
[c]The levels below 25 eV are from Hacken et al. [20]. No errors are reported for these resonances.

(in practice, this usually means J and π) between the energy limits $E_{\min}$ and $E_{\max}$ is

$$\Delta_3(L) \equiv \min_{A,B} \frac{1}{E_{\max}-E_{\min}} \int_{E_{\min}}^{E_{\max}} [N(E)-AE-B]^2 dE \ , \tag{1}$$

where L is an integer and $N(E)$ is the number of levels in the energy interval $[E_{\min}, E_{\max}]$ with energies less than or equal to E. For a given L the energy interval is divided into subintervals of length LD (D is the average level spacing) which overlap by $LD/2$. Δ_3 is calculated for each of these subintervals, and the value of Δ_3 for that value of L is determined by averaging the values obtained from all subintervals of size LD. For Poisson statistics the expected value is $L/15$, while for GOE statistics the expected value for large L is approximately

$$\Delta_{3_{\mathrm{GOE}}}(L) \cong \frac{1}{\pi^2}(\ln L - 0.068) \ . \tag{2}$$

For the present case, since the spin of the target nucleus is $I=\frac{9}{2}$, the s-wave neutrons can form resonances with total angular momentum $J=4$ or 5. Assuming that the level density is proportional to $(2J+1)$, the relative level densities for the spin-4 and -5 states are 9 and 11. The Δ_3 limit [Eq. (2)] is for a sequence with a single spin and parity. Here the experimental data should be compared with the Δ_3 values for two GOE sequences combined, with a relative level density of 9 and 11. This comparison is shown in Fig. 3 for s-wave resonances in ^{115}In. The original spin assignments of Hacken et al. were used. It is surprising that the agreement is better with the single sequence than the mixed sequence. However, the data show spectral rigidity and disagree strongly with the Poisson prediction. Since the Δ_3 values increase rapidly when levels are missed or spins are misassigned, the experimental results indicate that the s-wave sequence in ^{115}In has few spin misassignments or missing levels. Therefore, the new levels in ^{115}In are likely to be p-wave resonances, and not additional weak s-wave resonances.

The corresponding Δ_3 plot for the levels in ^{113}In is

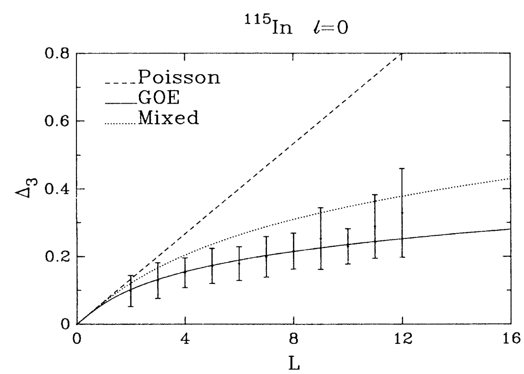

FIG. 3. The Δ_3 statistic for 48 s-wave resonance in ^{115}In. The solid curve is for one pure GOE sequence, the dashed curve for a Poisson sequence, and the dotted curve for two GOE sequences with relative densities of 9 and 11.

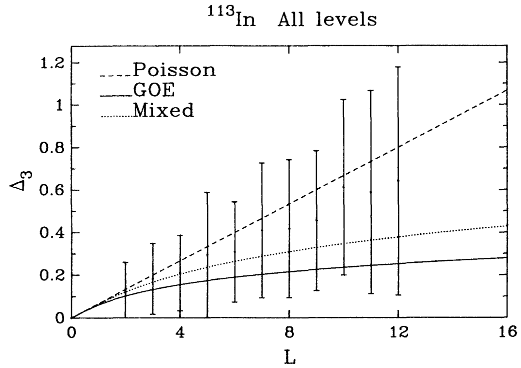

FIG. 4. The Δ_3 statistic for 49 (presumed) s-wave resonances in ^{113}In. The solid curve is for one pure GOE sequence, the dashed curve for a Poisson sequence, and the dotted curve for two GOE sequences with relative densities of 9 and 11.

shown in Fig. 4. The calculated curves are the same as for the s-wave resonances in ^{115}In. The experimental values are much closer to the Poisson limit, but the uncertainties are so large that no strong conclusion can be reached. Some of the new resonances may be strong p-wave resonances in ^{113}In. A variety of statistical tests were applied to these data. The results are suggestive but do not definitively label specific resonances as p-wave.

IV. RESONANCE ANALYSIS

The neutron transmission data obtained with the natural indium target were analyzed with the R matrix code SAMMY [27] developed at Oak Ridge National Laboratory for analysis of neutron resonance data. A sample fit to the data is shown in Fig. 5 for the $E_n = 25-50$ eV range. The resulting values of $g\Gamma_n$ and the reduced widths $g\Gamma_n^0$ are listed for ^{113}In in Table II; the values of $g\Gamma_n$ and the reduced widths $g\Gamma_n^0$ (and $g\Gamma_n^1$) for the s- and p-wave resonances in ^{115}In are listed in Tables III and IV. For ^{113}In all of the resonances were assumed to be s-wave resonances.

These resonance parameters yield the following values for the s- and p-wave neutron strength functions $S_0 = \langle g\Gamma_n^0 \rangle / D_0$ and $S_1 = \langle g\Gamma_n^1 \rangle / 3D_1$:

$$S_0(^{115}\text{In}) = (0.30 \pm 0.06) \times 10^{-4} ,$$

$$S_1(^{115}\text{In}) = (3.2 \pm 0.6) \times 10^{-4} ,$$

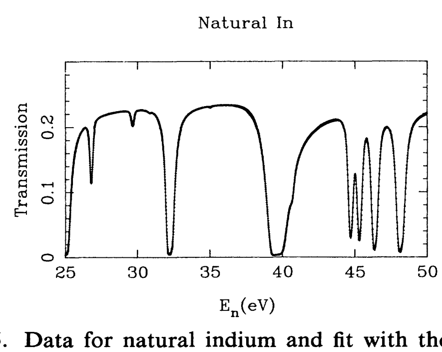

FIG. 5. Data for natural indium and fit with the R-matrix resonance code SAMMY in the energy range $E_n = 25-50$ eV.

and

$$S_0(^{113}\text{In}) = (0.43 \pm 0.09) \times 10^{-4} .$$

The values for ^{115}In should be reliable, but the value for ^{113}In is questionable because of the assumption that all of the resonances are s wave.

The comparison with the GOE prediction for Δ_3 indicated that the s-wave sequence in ^{115}In is rather pure and complete, but that the s-wave sequence in ^{113}In has an admixture of resonances with other spin or parity values. We attempted to determine which of the resonances were most likely to be of different character, presumably p wave. We applied the Dyson F statistic to the ^{113}In data.

TABLE III. ^{115}In s-wave resonance parameters.

E_n (eV)	$g\Gamma_n$ (meV)	$g\Gamma_n^0$ (meV)
1.457	1.67	1.38
3.85	0.17	0.086
9.04	0.81	0.27
12.02	0.06	0.016
22.73	0.51	0.107
39.56±0.07	2.06±0.02	0.328
46.37±0.08	0.129±0.004	0.019
48.14±0.08	0.23±0.01	0.033
62.93±0.11	0.34±0.02	0.043
69.47±0.12	0.20±0.01	0.024
80.79±0.14	0.85±0.03	0.095
83.21±0.15	3.07±0.06	0.337
94.30±0.17	1.09±0.04	0.112
125.8±0.2	1.72±0.06	0.153
132.8±0.2	1.33±0.14	0.115
150.1±0.3	2.0±0.1	0.16
164.4±0.3	7.36±0.14	0.577
168.0±0.3	1.3±0.1	0.10
177.7±0.3	1.93±0.07	0.145
186.4±0.3	9.6±0.2	0.70
205.5±0.4	9.7±0.3	0.68
211.9±0.4	0.29±0.02	0.020
223.5±0.4	13±2	0.87
226.6±0.4	2.3±0.4	0.15
249.5±0.4	17.2±0.5	1.09
266.6±0.5	2.9±0.4	0.18
288.4±0.5	12±1	0.73
293.7±0.5	19±5	1.1
319.0±0.6	7.7±0.4	0.43
339.5±0.6	2.1±0.6	0.11
353.2±0.6	10.4±0.8	0.55
361.8±0.6	7.2±0.5	0.38
370.6±0.7	3.8±0.2	0.20
382.8±0.7	6±3	0.3
401.5±0.7	15±1	0.74
411.2±0.7	12±1	0.59
421.5±0.7	5.0±0.5	0.24
437.2±0.8	0.52±0.04	0.025
448.4±0.8	8.3±0.7	0.39
453.4±0.8	6.0±0.9	0.28
456.6±0.8	4.6±0.6	0.22
469.8±0.8	1.9±0.3	0.088
477.5±0.8	1.5±0.1	0.069
498.2±0.9	1.5±0.1	0.067

The F statistic was developed by Dyson to detect the presence of missing or spurious levels in a nearly perfect sequence of levels. The test was first used by the Columbia group [28] as a diagnostic for their erbium data. The spirit of the approach is that a missing or spurious level shows as an increased fluctuation in the natural scatter of the F statistic. Our results were suggestive, indicating a number of possible candidates for p-wave resonances in the sequence. However, since the indications were not definitive, we have not labeled specific resonances in ^{113}In as p wave.

The neutron reduced widths are expected to obey the Porter-Thomas distribution

$$P(y)=\exp(-y/2)/(2\pi y)^{1/2} , \tag{3}$$

where $y=\gamma_i^2/\gamma_{\rm avg}^2$, γ_i^2 is the s-wave neutron reduced width for the ith resonance and $\gamma_{\rm avg}^2$ is the average s-wave

TABLE IV. ^{115}In p-wave resonance parameters.

E_n (eV)[a]	$g\Gamma_n$ (meV)	$g\Gamma_n^1$ (meV)[b]
29.67±0.05	0.0011±0.0001	3.3
40.66±0.07*	0.0041±0.0005	7.6
58.70±0.10*	0.00014±0.000 02	0.15
66.40±0.12*	0.000040±0.000 002	0.036
73.04±0.13	0.011±0.001	8.5
77.89±0.14*	0.0015±0.0006	1.1
85.50±0.15*	0.003 ±0.001	2
86.32±0.15	0.017±0.001	10.0
88.40±0.16*	0.0017±0.0005	1.0
100.8±0.2	0.032±0.002	15
103.7±0.2*	0.0004±0.0002	0.2
110.8±0.2	0.016±0.002	6.7
114.3±0.2	0.072±0.004	29
120.6±0.2	0.025±0.003	9.1
144.1±0.3	0.093±0.007	26
145.7±0.3	0.036±0.007	10.0
146.9±0.3*	0.045±0.008	12
156.5±0.3*	0.008±0.003	2
158.6±0.3	0.052±0.005	13
162.2±0.3	0.11±0.02	27
174.2±0.3	0.096±0.005	20.0
190.9±0.3*	0.08±0.04	10
192.4±0.3	0.37±0.09	67
194.5±0.3	0.05±0.04	10
198.7±0.3	0.034±0.009	5.9
214.1±0.4	0.09±0.01	10
219.7±0.4*	0.014±0.006	2.1
246.7±0.4	0.09±0.03	10
264.5±0.5*	0.04±0.02	5
275.0±0.5*	0.01±0.01	1
276.9±0.5*	0.04±0.01	5
282.3±0.5	0.05±0.02	6
285.1±0.5*	0.014±0.006	1.4
302.8±0.5	0.21±0.07	19
304.1±0.5	0.16±0.09	15
308.2±0.5	0.06±0.02	5
313.4±0.6*	0.11±0.09	10
317.0±0.6*	0.007±0.005	0.6
325.8±0.6*	0.29±0.06	24
329.5±0.6	0.18±0.06	14
333.5±0.6*	0.3±0.1	20
336.7±0.6	0.4±0.1	30
344.7±0.6	0.11±0.04	8.5
367.0±0.6	0.38±0.05	26
379.0±0.7	0.71±0.04	46
389.5±0.7*	0.058±0.006	3.7
394.7±0.7*	0.2±0.1	10
398.2±0.7*	0.2±0.1	10
431.2±0.8	0.09±0.05	5
474.0±0.8	0.6±0.2	30
481.4±0.8*	0.2±0.1	10
488.1±0.9	0.16±0.05	7.3
493.7±0.9	0.18±0.06	7.8

[a]Resonances labeled with an asterisk are new.
[b]Γ_n^1 is the p-wave neutron reduced width.

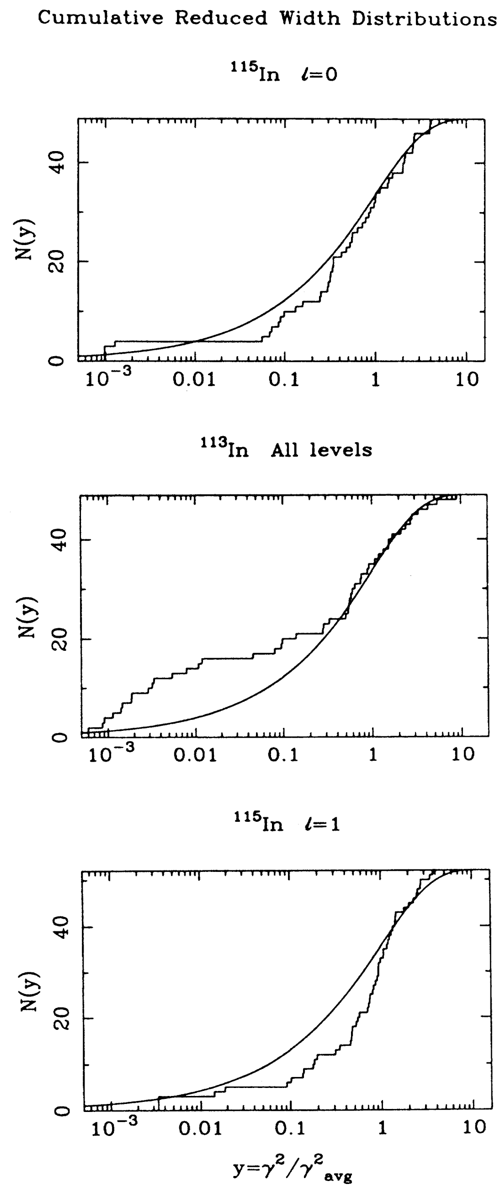

FIG. 6. Cumulative reduced width distributions compared with the Porter-Thomas distribution. (a) s-wave resonances in ^{115}In, (b) all resonances in ^{113}In, (c) p-wave resonances in ^{115}In.

neutron reduced width. It is convenient to consider the cumulative reduced width distribution. The experimental distributions for *s*- and *p*-wave resonances in ^{115}In and for all resonances in ^{113}In are shown in Fig. 6 and compared with the integral of the Porter-Thomas distribution. As expected the *s*-wave distribution in ^{115}In agrees with the Porter-Thomas prediction, but the agreement for the *p*-wave resonances in ^{115}In and the resonances in ^{113}In is not very good.

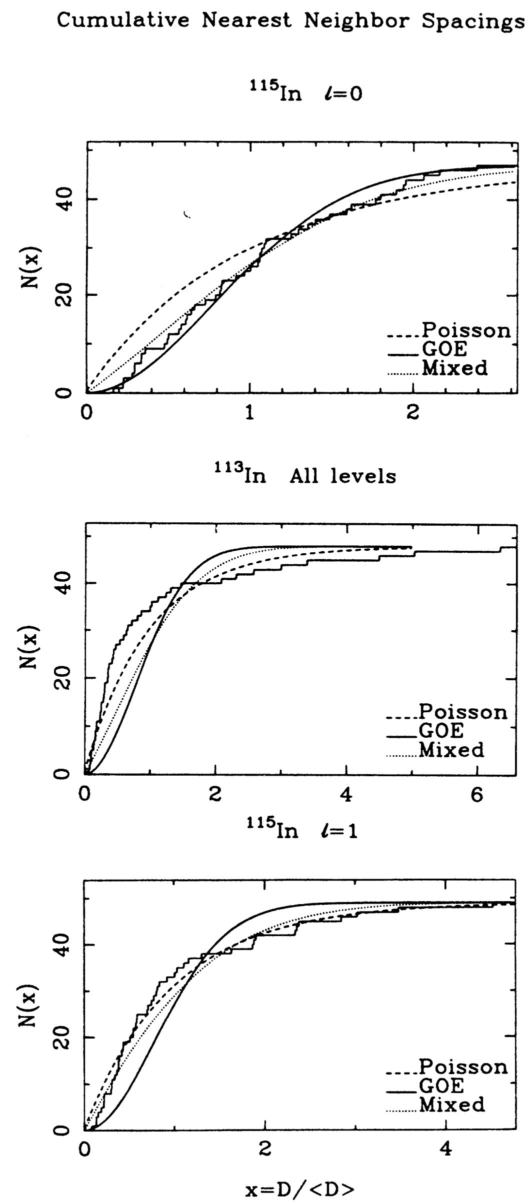

FIG. 7. Cumulative nearest-neighbor spacing distributions compared with the Wigner, Poisson, and mixed GOE sequences. (a) *s*-wave resonances in ^{115}In, (b) all resonances in ^{113}In, (c) *p*-wave resonances in ^{115}In. Note that for the *s*-wave resonances there are two GOE sequences combined ($J=4$ and 5) with relative densities of 9 and 11, and for the *p*-wave resonances there are four GOE sequences combined ($J=3$, 4, 5, and 6) with relative densities of 7, 9, 11, and 13.

The nearest-neighbor spacing distributions for states of the same symmetry are expected to obey the Wigner distribution

$$P(s)=\frac{\pi}{2}xe^{-\pi x^2/4} . \tag{4}$$

The dimensionless spacing parameter $x=D_i/D$, where $D_i=(E_{i+1}-E_i)$ and D is the average level spacing. In Fig. 7 the cumulative spacing distribution is shown for the *s*-wave sequence in ^{115}In. For comparison the predictions for the Poisson, Wigner, and the appropriate mixed sequence are shown. (The *s*-wave mixed sequence is composed of two pure GOE sequences for $J=4$ and 5, with relative densities 9 and 11.) The experimental data agree well with the two-sequence GOE curve. However, for the ^{113}In data the spacing distribution disagrees strongly with the GOE prediction, suggesting there are a number of resonances of different character mixed into the *s*-wave sequence. For the *p*-wave sequence in ^{115}In, the appropriate mixed sequence prediction is for four GOE sequences ($J=3$, 4, 5, and 6) with relative densities, 7, 9, 11, and 13. This mixture is closer to the Poisson distribution than to the single-sequence GOE prediction.

V. SUMMARY

The neutron total cross section for natural indium was measured for $E_n=25-500$ eV and the neutron capture reaction was studied in the same energy range with a highly enriched ^{115}In target. A total of 47 previously unreported resonances were observed. Of these new resonances 21 were observed in the capture reaction and therefore assigned to ^{115}In. Since even the weakest of these new resonances was observed in the capture experiment, the new resonances which were not observed with the enriched ^{115}In sample were assigned to ^{113}In. Two weak resonances previously identified as belonging to ^{113}In were observed with the enriched ^{115}In target and were reassigned to ^{115}In.

The new resonances were analyzed with the *R*-matrix code SAMMY and the resonance parameters determined. The Dyson-Mehta Δ_3 statistic, the reduced width distribution, and the nearest-neighbor spacing distribution were determined for the three data sets: the *s*- and *p*-wave ^{115}In resonances, and the ^{113}In resonances. The *s*-wave ^{115}In set appears to be rather pure and close to complete, while the ^{113}In set seems to have an admixture of *p*-wave resonances, and the *p*-wave ^{115}In set is incomplete. The present results imply a total of 50 probable *p*-wave resonances between $E_n=25$ and 500 eV in ^{115}In which are suitable for study of parity violation.

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