Test of Fermi gas model predictions of level density in ^{137}Xe

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We have studied the unbound levels of ^{137}Xe via neutron resonance reactions and β decay of ^{137}I. High-resolution neutron transmission data revealed a total of 35 resonances below a neutron energy of 500 keV. At least 27 of the resonances are *p*-wave resonances. The near absence of *s*-wave resonances in this energy region resulted in an extremely low value for the *s*-wave neutron strength function. The current γ-ray data complement earlier studies of γ rays and delayed neutrons following the β decay of ^{137}I. By combining all data, we have obtained a detailed picture of the level density in ^{137}Xe for a wide range of angular momenta. With the exception of $\frac{1}{2}^+$ and $\frac{1}{2}^-$ levels, the overall agreement is good between the current data and predictions of the Fermi gas model.

I. INTRODUCTION

In a recent publication,[1] we reported on a study of high-lying levels of ^{87}Kr. This study was made by a combination of β-decay and neutron resonance spectroscopy. Among heavy nuclides, in only one other case, ^{137}Xe, can the same combination of high-resolution spectroscopic methods be used to study levels in the unbound region. The conditions are different, however, because the relatively high spin of ^{137}I (J^π is probably $\frac{7}{2}^+$ for this β-decaying parent of ^{137}Xe) does not permit population of those low-spin levels which are also excited as *s*- and *p*-wave neutron resonances of ^{136}Xe. A direct comparison of the level properties observed with the two methods, as was made for ^{87}Kr in Ref. 1, is thus not possible for ^{137}Xe. An application of both methods is nevertheless of considerable interest because together they provide a means for studying the level density in the unbound region in greater detail than would be possible otherwise. The neutron separation energy of ^{137}Xe, 4025.4 ± 0.3 keV (Refs. 2 and 3), is one of the lowest known for any $A>20$ nuclide resulting from neutron capture by a stable isotope. Such a low value permits scrutiny of a little known region of excitation energy. We can expect to observe, for example, how the density of levels is approaching the statistical distribution expected in the higher unbound region.

The existing experimental information on nuclear level densities is dominated by results from neutron resonance reactions. The reason for this is, of course, the superior resolution and sensitivity attained in these reactions. Although all levels cannot be detected, a knowledge of the experimental sensitivity combined with the well-known Porter-Thomas distribution of neutron widths permits fairly accurate estimates to be made of the total number of levels present in an energy window above the neutron separation energy.

Specifically, the interaction of, respectively, *s*-wave and *p*-wave neutrons with ^{136}Xe will excite $\frac{1}{2}^+$ and $\frac{1}{2}^-$, $\frac{3}{2}^-$ levels in ^{137}Xe, while allowed β transitions from ^{137}I are expected to populate $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{9}{2}^+$ levels. The weakness of the first-forbidden β transitions deduced[4] for the decay of ^{137}I suggests that few, if any, negative parity levels in the unbound region will be significantly populated. Nevertheless, a combination of β-decay and neutron resonance spectroscopy will yield information on unbound levels possessing a wide range of angular momenta.

In the bound region, the β-decay data will be reasonably complete at only low and moderate excitation energies because the inability to detect the presence of weakly populated levels[5,6] will become increasingly more important at higher excitation energies. Some caution is thus needed in the interpretation of these data.

The experimental work reported here consists of a study of the neutron total cross section of ^{136}Xe performed at the Oak Ridge Electron Linear Accelerator (ORELA) and a measurement in Studsvik of γ transitions following the decay of ^{137}I. Further information on the unbound levels in ^{137}Xe was obtained from the results of delayed neutron spectroscopy published by Ohm *et al.*[7] and from an extrapolation of the density of negative parity states determined in an earlier decay scheme study.[4]

II. EXPERIMENTAL AND DATA ANALYSIS

A. Neutron transmission

The measurements were made at the 80-m flight path of the ORELA under running conditions similar to those for the ^{86}Kr measurements described in Ref. 1. The sample consisted of one liter (≈ 6.7 g) of Xe gas, enriched to 93.6% in ^{136}Xe. The only significant impurities were ^{134}Xe (5.7%), ^{132}Xe (0.6%), and ^{131}Xe (0.1%). In the neutron transmission measurements, the sample was contained in a cylindrical stainless steel cell at a pressure of about 2.5 MPa, resulting in a target thickness of 0.0222 atoms/b. Two sets of data were taken, one emphasizing the low-energy regions with a ^{6}Li glass scintillator as the neutron detector, and the other optimized for neutrons with energies from about 15 keV and upwards employing a liquid scintillator. The latter data are displayed in Fig. 1. Both data sets included runs taken with an empty target cell and runs where the enriched Xe gas had been replaced with natural Xe. It turned out that all the reso-

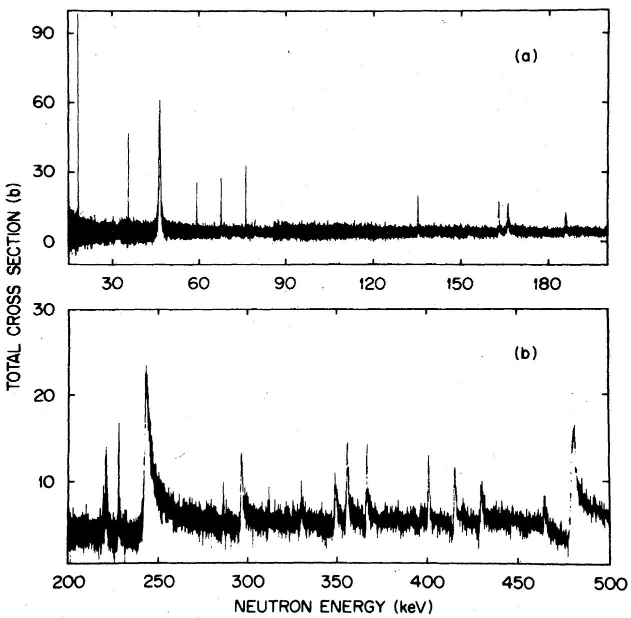

FIG. 1. The total cross section of ^{136}Xe up to 500 keV as deduced from the transmission measurements. Note that the energy scales have different dispersions for the two panels. The lowest energy portion of the cross-section curve has been omitted from this figure because no ^{136}Xe resonances were identified below 18 keV in the transmission data.

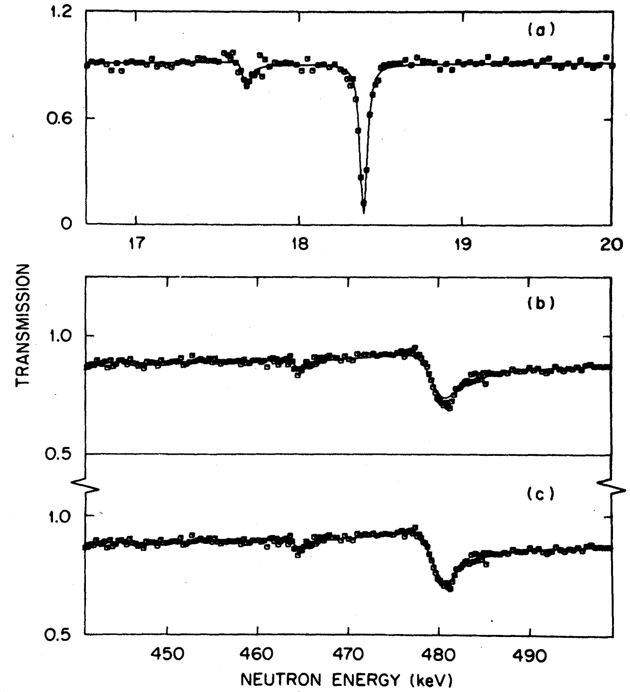

FIG. 2. Some examples of multilevel fits (solid lines) to the transmission data. (a) The resonance near 18.4 keV has a width which is not significantly larger than the experimental resolution of 0.1%. The fitted curve shows a $p_{1/2}$ assignment for this resonance and gives a slightly better fit than does the possible alternative of $p_{3/2}$. The ^{134}Xe resonance near 17.7 keV has a width exceeding the experimental resolution. The peak cross section is thus proportional to the statistical weight factor which here gives a unique $p_{3/2}$ assignment. (b) The strong resonance near 480 keV could not be fitted adequately as shown with the shape of a single $p_{3/2}$ resonance. (c) It was necessary to also introduce a $p_{1/2}$ resonance with nearly the same energy to obtain the good reproduction of the shape of the transmission dip.

nances (which were weak) observed below a neutron energy of 18 keV with the enriched Xe gas sample appeared more strongly in the run with the natural Xe. With due regard to the unlikely event that a weak resonance in ^{136}Xe accidentally coincides with a strong resonance in another isotope of Xe, we conclude that the current transmission data give no evidence for resonances in ^{136}Xe below a neutron energy of 18 keV.

Although the experimental techniques used for the current work are straightforward and similar to those of other neutron transmission experiments at ORELA (e.g., see Ref. 8 for a fuller description of common experimental practice), the relatively small number of ^{136}Xe atoms present in the sample imposed greater restrictions on the useful energy ranges of the data. Therefore, only the energy regions up to about 80 keV and up to 500 keV, respectively, were analyzed in the two sets of ^{136}Xe data. The extracted values for resonance parameters were found to be in excellent agreement in the region of overlap. Throughout this paper we will, however, use only the values obtained from the data taken with the liquid scintillator because of their higher precision over the entire region of interest here.

A computer code, SAMMY,[9] based on R-matrix multilevel formalism, was employed for the determination of resonance parameters from the transmission data. Some features of this code have been discussed in recent publications (e.g., see Refs. 1 and 8) and will not be repeated here. The analysis yields both the l values and the spins for those resonances with widths exceeding the experimental resolution of about 0.1%. For somewhat weaker resonances, it is not possible to extract the spins, although l values may still be determined (see Fig. 2). In particular, the strong interference between resonance and potential scattering for $l=0$ makes s-wave resonances readily identifiable. It is therefore interesting to note that we could not positively identify any s-wave resonances in ^{136}Xe in the energy region up to 500 keV. The resonance data, which are summarized in Table I, show that of the 35 observed resonances, 27 were found to be p wave, another four can have $l=1$ or 2, and only the four weakest unassigned resonances could possibly be s wave.

B. Decay of ^{137}I

The γ rays following the decay of ^{137}I were studied using mass separated samples at the OSIRIS (Ref. 10) facility in Studsvik. The experimental method was nearly identical to that of a previous investigation[4] of this decay. The main differences were that the counting time was more than doubled and a HPGe γ-ray spectrometer with superior performance was utilized. The resulting improvement in sensitivity was about a factor of 3, implying that γ rays with intensities of 0.005%/decay were well

TABLE I. Neutron widths for resonances in ^{136}Xe + n.

E_n[a] (keV)	l	J^{π}[b]	$g\Gamma_n$[c] (eV)	$g\Gamma_n$[d] (eV)
18.393	1	$\frac{1}{2}^-,(\frac{3}{2})^-$	25 *2*	4.5 *4*
35.629	1		24 *2*	1.7 *2*
46.410	1	$\frac{1}{2}^-$	573 *12*	27.5 *6*
59.179	1		24 *3*	0.82 *10*
67.644	1		65 *4*	1.85 *12*
76.150	1	$\frac{3}{2}^-,(\frac{1}{2})^-$	89 *4*	2.16 *10*
79.301			8 *3*	
135.39	1	$\frac{1}{2}^-$	163 *10*	1.86 *11*
163.04	1	$\frac{1}{2}^-$	195 *12*	1.77 *11*
166.15	1	$\frac{1}{2}^-$	320 *15*	2.83 *13*
185.88	1	$\frac{1}{2}^-$	186 *15*	1.44 *12*
217.90	1,2		49 *10*	(0.31)
219.46	1		122 *15*	0.77 *10*
220.95	1	$\frac{1}{2}^-$	573 *30*	3.61 *19*
227.96	1	$\frac{3}{2}^-$	483 *22*	2.94 *14*
232.24			27 *10*	
243.43	1	$\frac{3}{2}^-$	5900 *400*	33.3 *23*
252.62			49 *15*	
253.47			42 *15*	
286.24	1		131 *30*	0.62 *14*
296.54	1	$\frac{1}{2}^-$	1070 *70*	4.8 *3*
311.84	1		123 *30*	0.53 *13*
329.99	1		288 *45*	1.16 *18*
348.99	1	$\frac{1}{2}^-$	910 *100*	3.5 *4*
355.64	1	$\frac{3}{2}^-$	1130 *90*	4.2 *3*
366.59	1	$\frac{3}{2}^-$	770 *80*	2.8 *3*
383.65	1,2		85 *35*	(0.29)
396.48	1,2		170 *60*	(0.57)
400.91	1	$\frac{3}{2}^-$	700 *60*	2.3 *2*
415.26	1	$\frac{3}{2}^-$	910 *90*	2.9 *3*
429.77	1	$\frac{1}{2}^-$	890 *100*	2.7 *3*
447.15	1,2		107 *50*	(0.32)
464.50	1	$\frac{1}{2}^-$	480 *100*	1.4 *3*
479.89	1	$\frac{3}{2}^-$	6200 *400*	17.1 *10*
480.75[e]	1	$\frac{1}{2}^-$	470 *300*	1.3 *8*

[a]Resonance energies based on absolute time of flight are accurate to $\approx 0.08\%$.
[b]From a detailed analysis of the magnitude and shape of the transmission dip.
[c]From the area of the transmission dip. In our notation 25 *2* $=25\pm2$, etc.
[d]Reduced width for p-wave neutrons based on a nuclear radius of 6.96 fm.
[e]This $p_{1/2}$ resonance was needed in addition to the 479.89-keV resonance to fit the transmission dip at this energy. See also Figs. 2(b) and (c).

over the detection limit in the 4.0—4.5-MeV region, and even weaker γ rays were seen at higher energies. From the unbound levels in ^{137}Xe, we observed (see Table II) a total of 40 γ rays—a factor of 2 more than had been previously reported. The γ-ray spectrum is shown in Fig. 3.

The $\gamma\gamma$-coincidence measurements reported in Ref. 4 showed that less than 0.1%/decay of the total γ-ray intensity over 4 MeV was coincident with lower energy γ rays. The high-energy γ rays listed in Table II are therefore all taken to represent transitions to the ground state.

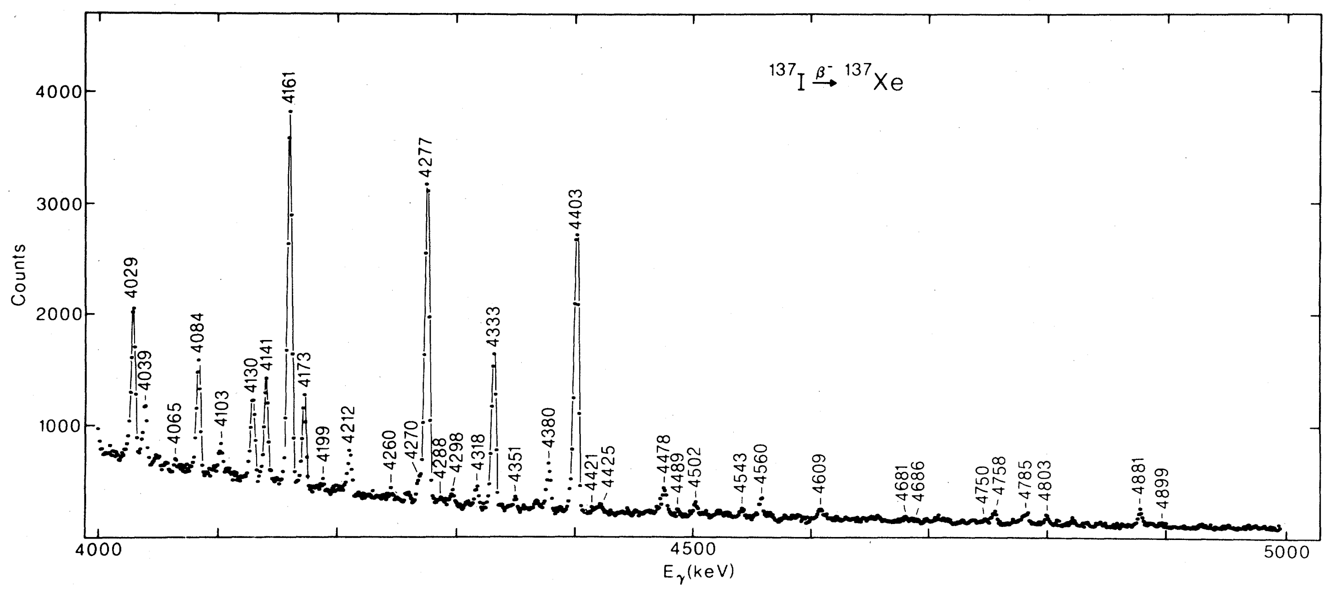

FIG. 3. High-energy region of the γ-ray spectrum from the $A=137$ isobars recorded at the OSIRIS facility. Gamma rays higher than 4025.4 keV represent transitions from unbound levels in ^{137}Xe.

III. DISCUSSION

A. Introductory remarks

Even a cursory glance at the neutron resonance data (Table I shows no $\frac{1}{2}^+$ resonances and a nearly equal number of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ resonances) suggests that the distribution of resonance spins and parities is different from the predictions of the statistical Fermi gas model. This finding is not quite unexpected because the low neutron-binding energy of ^{137}Xe places the lower part of the neutron resonance region in an energy interval where the specific nuclear structure may still dominate the level spectrum. The neutron-binding energy is very nearly the same as the $N=82$ neutron shell gap. It is thus of some importance to give a detailed account of the total number of levels present in the region spanned by the data of Table I, and, as far as possible, their distribution on spins and parities. The available experimental information consists of the currently described neutron resonance and γ-ray measurements, an earlier decay scheme study,[4] and the delayed neutron data of Ohm *et al.*[7] The different experimental methods are selectively sensitive for detecting different subsets of levels, and none of the methods provide a complete enough picture of a subset because of the fluctuations in the nuclear matrix elements between different transitions that cause some transition intensities to be unobservably small. To find the total number of transitions (which in the following is taken to be the same as the number of levels), it is thus necessary to use statistical methods to estimate how many transitions have remained unobserved. Such estimates can be made with some accuracy as long as the corrections are small. It is also possible to obtain an idea about the uncertainty of these estimates.

B. Neutron resonances

Despite the good resolution of about 0.1% obtained in the ORELA time-of-flight measurements, the instrumental resolution remains the main limiting factor for the experimental sensitivity. Consequently, neutron resonances having widths somewhat less than 0.1% of the resonance energies cannot always be assigned unique l values, and very weak resonances may escape detection altogether. For a given class of resonances, the number of missed resonances can be estimated from the experimental detection limit and the Porter-Thomas distribution of resonance widths. By applying the graphs of Fuketa and Harvey,[11] we find that for ^{136}Xe about three to six resonances may have been missed in the region up to 500 keV neutron energy. This estimate was made as if all resonances were p wave, which is a good approximation because at least 77% of the observed resonances are $l=1$.

Apart from the few undetected resonances, Table I shows eight weak resonances for which the data did not permit firm l-value assignments. Only four of these weak resonances can possibly originate from s-wave neutron interactions, but other l values are not excluded. The very weakness of the four unassigned resonances is actually an indication that they are probably not s wave. To gain a better understanding of the probability for s-wave assignments, one may make a comparison with the frequency distribution given by the Porter-Thomas law. The total probability of finding resonances with reduced widths up to and including the experimental values can be easily estimated, provided that a mean reduced width for s-wave neutrons has been determined. This quantity is, of course, unknown for ^{137}Xe but can be assumed to be within the range 1.5–6 eV. The assumption is guided by data[12] for other valence nuclei and by the average reduced width of the currently observed p-wave resonances. The probabili-

TABLE II. Gamma rays from unbound levels in ^{137}Xe following the decay of ^{137}I.

Gamma-ray energy[a] (keV)	Intensity[a,b] (% decay)	Gamma-ray energy[a] (keV)	Intensity[a,b] (%/decay)
4028.92 *15*	0.115 *12*	4402.78 *15*	0.22 *2*
4038.96 *15*	0.045 *5*	4420.7 *10*	0.005 *2*
4064.6 *6*	0.008 *3*	4424.7 *6*	0.008 *2*
4083.87 *15*	0.083 *8*	4477.8 *3*	0.019 *2*
4103.3 *3*	0.019 *2*	4489.4 *8*	0.0036 *11*
4129.99 *15*	0.064 *6*	4501.9 *6*	0.0059 *15*
4140.98 *15*	0.069 *6*	4543.3 *6*	0.0074 *15*
4160.94 *15*	0.27 *2*	4559.9 *4*	0.014 *2*
4173.11 *15*	0.063 *6*	4609.3 *4*	0.0093 *12*
4199.1 *7*	0.006 *2*	4680.6 *7*	0.0049 *13*
4211.6 *2*	0.033 *3*	4685.8 *10*	0.0030 *15*
4260.4 *4*	0.009 *2*	4750.3 *10*	0.0042 *15*
4270.3 *4*	0.014 *2*	4758.0 *5*	0.010 *2*
4276.53 *15*	0.25 *2*	4784.7 *6*	0.010 *2*
4288.1 *8*	0.007 *3*	4802.5 *13*	0.0034 *13*
4298.3 *5*	0.011 *3*	4880.5 *3*	0.014 *2*
4318.2 *5*	0.012 *3*	4899.0 *9*	0.005 *2*
4332.78 *15*	0.114 *10*	5132.2 *20*	0.0021 *11*
4350.5 *6*	0.008 *2*	5148.8 *12*	0.0033 *11*
4379.7 *2*	0.036 *4*	5170.2 *8*	0.0058 *15*

[a]In our notation 4028.92 *15* =4028.92±0.15, 0.115 *12* =0.115±0.012, etc.
[b]The intensity normalization was made using the known absolute intensity of 12.8%/decay for the 1218.0-keV γ ray (see Ref. 4).

ty values thus derived and given in Table III show that none of the four weak resonances is particularly likely to be s wave. It is thus quite possible that ^{137}Xe is completely lacking s-wave strength in the first 500 keV of unbound levels.

From the preceding discussion and the probability test of Table III, we conclude that the true number of resonances is about 40 up to 500 keV neutron energy in ^{137}Xe and that practically all of these are likely to be p wave. It is useful for later discussion of the level density to attempt a distribution of the total number of p-wave resonances into different spin groups. Guided by the distribution of firmly assigned resonances listed in Table I, we suggest that about 24 resonances are $\frac{1}{2}^-$ and about 16 are $\frac{3}{2}^-$. The somewhat interdependent uncertainties of these numbers are hard to estimate, but may be on the order of 25–30%.

The neutron strength function, which is a measure of the reduced neutron width per unit of excitation energy, is defined as

$$S_l=[1/(2l+1)]\Sigma g\Gamma_n^l/\Delta E \ ,$$

where ΔE is the energy interval being studied. From the data of Table I, the p-wave strength function is deduced as $S_1=(8.7\pm2.4)\times10^{-5}$ for the first 500 keV of unbound levels in ^{137}Xe. This value is not significantly altered by inclusion of the weak unassigned resonances.

A direct derivation of an upper limit of the s-wave strength function from the data (on the four possible s-wave resonances) may not be quite meaningful because the strength function is an average property that is well defined only when the resonances are numerous and reasonably closely spaced. The currently analyzed region of 500 keV is nonetheless a substantial averaging interval; therefore, we quote an upper limit of $S_0\leq1\times10^{-6}$ from the data of Table I. This value is about an order of magnitude smaller than found[12] for other nuclides in this region. Such a low value of s-wave strength is highly unusual in a heavy nucleus and is matched only by the reaction ^{208}Pb + n.

TABLE III. Estimated probabilities (P) for s-wave assignments of weak resonances in ^{137}Xe. The average reduced width $g\Gamma_n^0$ has been assumed to be in the range 1.5–6 eV.

E_n (keV)	$g\Gamma_n^0$ (eV)	$P(l=0)$
79.30	0.030	<0.05–0.12
232.24	0.056	<0.08–0.16
252.62	0.098	<0.10–0.21
253.47	0.083	<0.10–0.19

C. Levels populated in the β decay of ^{137}I

The β-decay data provide information on levels with higher angular momenta than those observed in the neutron resonance measurements. The most direct information comes from the measurements of high-energy γ rays reported here and from the delayed neutron data.[7] Some additional information can be extrapolated from the level-scheme study,[4] particularly concerning negative parity levels.

The ground state of ^{137}I has $J^\pi=\frac{7}{2}^+$ from shell model systematics and a total β-decay energy that exceeds the neutron-binding energy of ^{137}Xe by about 1.8 MeV. Allowed β transitions will populate levels in ^{137}Xe with $J^{\pi}=\frac{5}{2}^{+}, \frac{7}{2}^{+}, \frac{9}{2}^{+}$. Such levels are not present at low energies in ^{137}Xe because this is a valence nucleus with an unpaired neutron in the $N=82-126$ shell. The low-energy part of the level spectrum is dominated by negative parity levels, which are fed by relatively weak first-forbidden β transitions. A considerable fraction of the β decays of ^{137}I does therefore populate relatively high-lying levels of ^{137}I as discussed in Refs. 4 and 7. The subsequent decays of these levels can be studied by γ-ray and delayed neutron spectroscopy. Levels with excitation energies greater than the neutron-separation energy and having a negative parity are not expected[4] to receive a significant population in the β decay. The γ-ray data of Table II and the delayed neutron data of Ohm *et al.*[7] thereby provide a basis for determining the number of $\frac{5}{2}^{+}-\frac{9}{2}^{+}$ levels present in the energy region analyzed in the neutron resonance reaction.

It is well known that the total γ-ray widths of levels in the neutron resonance region are fairly constant, while the neutron widths fluctuate within a Porter-Thomas distribution. The average value of the total neutron widths is strongly energy dependent via the neutron penetrability, as illustrated in Fig. 4. Consequently, only rarely will a given level have similar widths for both neutrons and γ rays. Instead, a nearly clean separation exists between levels observed as neutron-emitting states and those seen in the γ-ray measurements. Inspection of Fig. 4 shows that the separation of the different dominating decay modes also serves to separate levels with different angular momenta in the region up to about 0.5 MeV over the neutron separation energy. Levels with $J^{\pi}=\frac{5}{2}^{+}$ will have an open neutron channel, while the g-wave neutron decay of $\frac{7}{2}^{+}$ and $\frac{9}{2}^{+}$ levels will be nearly completely blocked in comparison with the γ-ray channel.

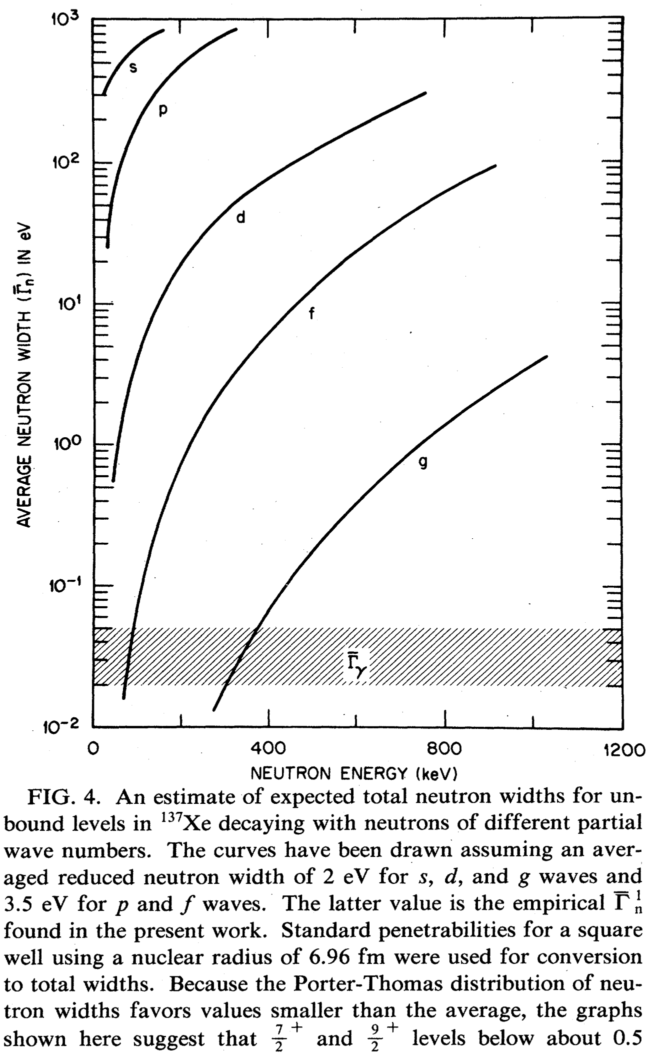

FIG. 4. An estimate of expected total neutron widths for unbound levels in ^{137}Xe decaying with neutrons of different partial wave numbers. The curves have been drawn assuming an averaged reduced neutron width of 2 eV for *s*, *d*, and *g* waves and 3.5 eV for *p* and *f* waves. The latter value is the empirical $\bar{\Gamma}_n^1$ found in the present work. Standard penetrabilities for a square well using a nuclear radius of 6.96 fm were used for conversion to total widths. Because the Porter-Thomas distribution of neutron widths favors values smaller than the average, the graphs shown here suggest that $\frac{7}{2}^{+}$ and $\frac{9}{2}^{+}$ levels below about 0.5 MeV neutron energy are unlikely to decay by neutron transitions.

We can thus use the delayed neutron data reported by Ohm *et al.*[7] to deduce the total number of $\frac{5}{2}^{+}$ levels, provided that allowance is made for unobserved neutron transitions. The intensities of the delayed neutron groups will be given by the β-decay matrix elements, which, like the neutron resonance widths, are expected to follow a Porter-Thomas distribution.[13] From the data of Ref. 7, the minimum detectable neutron intensity is taken to be about 15% of the average intensity for the 0.5-MeV-wide energy interval of interest here. Disregarding the energy-dependent variation of the matrix elements within this region, one finds that about one-third of the levels have not been detected. The total number of $\frac{5}{2}^{+}$ levels is thus about 20 rather than the 13 actually observed by Ohm *et al.*[7] By varying the value for the experimental detection limit within reasonable limits, the uncertainty in this number is obtained as about 3.

The total number of γ-decaying levels, representing $J^{\pi}=\frac{7}{2}^{+}$ and $\frac{9}{2}^{+}$, is a little harder to judge because only the ground state γ transitions from the high-lying levels have been observed. Here, we expect both (1) the matrix elements for individual γ rays from a given level and (2) the matrix elements for the β feedings to these levels to be Porter-Thomas distributed. The intensities of the ground-state γ rays are, however, expected to represent, on the average, a considerable fraction of the total β feeding to the level through the E_{γ}^{3} (or higher) dependence of γ-ray intensities. The distribution of intensities for the ground-state transitions will thus be wider than a Porter-Thomas distribution but more narrow than the product distribution,[14] which applies to these matrix elements. The γ-ray data for the first 0.5 MeV of unbound levels show the average intensity to be about 11 times higher than the detection limit. This finding would imply that about one-third of the transitions remain undetected if the intensity distribution is twice as wide as the Porter-Thomas distribution, which may be a representative choice. With a total of 26 observed ground-state transitions, the number of missed γ rays would thus be about 13. The exact number is somewhat sensitive to the choice of distribution. A pure Porter-Thomas distribution gives about eight missed levels and the product distribution about 20. The total number of $\frac{7}{2}^{+}$ and $\frac{9}{2}^{+}$ levels is in the following discussion taken to be 39, with an uncertainty of 6.

The decay scheme study[4] of ^{137}I gives the only available

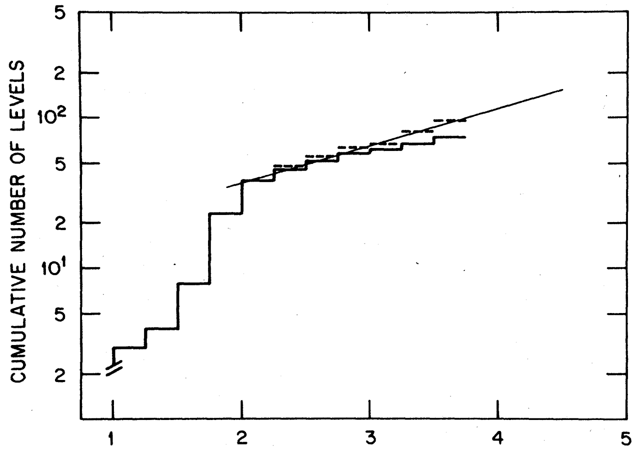

FIG. 5. Cumulative plot of observed levels with $J^\pi = \frac{5}{2}^- - \frac{9}{2}^-$ in ^{137}Xe in bins of 0.25 MeV. The dashed line includes an estimated correction for levels which have been missed in the experimental decay scheme of Ref. 4. The rather even slope of the curve from about 2 MeV and upwards suggests that about 40 levels are expected in the region 4.0—4.5 MeV discussed here.

guidance as to the total number of negative parity levels with $J = \frac{5}{2} - \frac{9}{2}$ in ^{137}Xe. It was suggested in Ref. 4 that there are no positive-parity levels with these angular momenta present below about 3.5 MeV and that all β transitions to levels below this energy consequently are first forbidden. This suggestion is based on the deduced $\log ft$ values and on simple arguments concerning the expected gross level structure of the valence neutron nucleus ^{137}Xe. It is well known that the smallness of an individual β-decay matrix element never can be taken as an argument that this particular β transition should be first forbidden,[15] but the weakness without exception of the ≈ 70 observed β transitions to levels below 3.5 MeV in ^{137}Xe does indeed support the suggestion that few, if any, of these levels possess a positive parity. It is also a good approximation to assume that all these levels have angular momenta in the range $\frac{5}{2} - \frac{9}{2}$, because other spin values would require feeding by first-forbidden unique β transitions or feeding solely by γ rays from higher lying levels. The latter has been observed for only the first two excited states. We show in Fig. 5 a staircase plot of the observed levels in ^{137}Xe up to an energy of about 3.5 MeV together with an estimated correction for missed levels. Again, this estimate is based on an assumed Porter-Thomas distribution of β-decay matrix elements. The straight line in this figure may be used for an extrapolation to the total number of $\frac{5}{2}^- - \frac{9}{2}^-$ levels expected between 4.0 and 4.5 MeV. This number is about 40, provided that there is no drastic change in the level density. The accuracy of such an extrapolation can always be questioned, but we think that this number is probably correct to within 50%.

D. Level density

Despite the quoted large uncertainties, the data on levels in the first 500 keV of the unbound region, which are summarized in Table IV, are some of the most comprehensive and accurate data ever obtained for unbound levels with a wide range of angular momenta in a heavy nucleus. We also show in Table IV the predicted numbers from the often-used Fermi gas model of Gilbert and Cameron.[16] These authors give the density of levels with a given spin, including both parities, as

$$\rho(E,J) = \frac{\sqrt{\pi}}{12} \frac{\exp(2\sqrt{aU})}{a^{1/4} U^{5/4}} \times \frac{(2J+1)\exp[-(J+1/2)^2/2\sigma^2]}{2\sqrt{2\pi}\sigma^3} \ (\mathrm{MeV}^{-1}) ,$$

where

$$U(\mathrm{MeV}) = E - P(N) - P(Z) .$$

The pairing energies $P(N)$ and $P(Z)$ are zero, respectively, for odd values of N or Z, and E is the excitation energy. Following Harris,[17] we have used $P(Z) = 1.15$ MeV for ^{137}Xe. Several prescriptions exist for the spin cutoff parameter. We have chosen to use the relation

$$\sigma^2 = 0.0888\sqrt{aU} A^{2/3} ,$$

originally proposed by Gilbert and Cameron.[16] To allow a little more freedom to this model the statistically distributed Fermi gas levels need not be chosen equidistant but with spacings falling within a Wigner distribution.[12,18] For an interval containing n levels with an average spacing of D, Lynn[18] has given the variance of the level spacing within a Wigner distribution as

$$\mathrm{var} D = 0.273 D^2/n .$$

This relation can be used to obtain the standard deviation for the mean number of levels with a given J^π as given in

TABLE IV. Total number of levels of ^{137}Xe in the region 4.03—4.53 MeV.

J^π	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-, \frac{7}{2}^-, \frac{9}{2}^-$	$\frac{1}{2}^+$	$\frac{5}{2}^+$	$\frac{7}{2}^+, \frac{9}{2}^+$
Experiment	$(24\pm8)^a$	$(16\pm5)^a$	$(40\pm20)^b$	$(\leq 4)^a$	$(20\pm3)^c$	$(39\pm6)^d$
Fermi gas model[e]	7±2	14±2	52±7	7±2	17±3	35±4

[a]Deduced from the current neutron resonance data.
[b]Extrapolated from the level scheme of Ref. 4. See also Fig. 4 and the text.
[c]Deduced from the delayed neutron data of Ref. 7. See also the text.
[d]Deduced from the current measurements of γ rays following the decay of ^{137}I. See also the text.
[e]Best overall fit corresponding to a level density parameter of $a = 12.3$ MeV^{-1}. The uncertainties are based on the assumption of a Wigner distribution of level spacings as described in the text.

Table IV. This is a way to illustrate the significance of the differences between experimental data and the statistical model predictions when dealing with a relatively small number of levels.

The overall agreement between the current data and the predictions of the Fermi gas model is good, with the exception of the $J^\pi = \frac{1}{2}^+$ and $\frac{1}{2}^-$ levels. It is not unexpected that local variations of the level density may produce gaps or overabundance in the spectra for a particular spin group. The shell model study of ^{136}Xe by Baldridge and Dalton[19] shows this very clearly when energy intervals with widths of 0.25 MeV are considered. It is, however, surprising to note the very substantial deviations from the predicted number of levels in the current study of ^{137}Xe because this nucleus has a considerably more complex level spectrum than does ^{136}Xe due to the additional neutron in the $N = 82-126$ shell. Furthermore, the studied interval of 0.5 MeV is fairly wide. It is also of interest to note that the Fermi gas model fails here with respect to the low spin levels. They form the resonances that determine the neutron-induced nuclear reaction rates. These reactions are the most important ones in models of the nucleosynthesis, and calculations of reaction rates are often made for nuclei having neutron separation energies well below the relatively low-lying region studied here. The current data are a good illustration of the fact that the local nuclear structure there might be considerably different from the statistical model predictions. Reactions induced by charged particles are much less sensitive to the specific nuclear structure or to the absence or overabundance of a particular spin group because these reactions proceed generally through several different high l values.

The Fermi gas and other statistical models for nuclear level densities assume that high-lying levels are equally distributed for both parities. The current neutron resonance data show that this is not the case for $J = \frac{1}{2}$ levels in ^{137}Xe. It appears plausible that the 4.0–4.5-MeV region of excitation energy in ^{137}Xe actually represents the lower part of a transition region where the discrete nuclear structure is giving way to level properties better described by statistical models. This region has been studied now in some detail for the first time.

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