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# STUDY OF GAMMA RAY MULTIPLICITY SPECTRA FOR RADIATIVE CAPTURE OF NEUTRONS IN $^{113,115}$In

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## ABSTRACT

Neutron radiative capture measurements were performed for the enriched isotopes $^{113}$In and $^{115}$In on the neutron spectrometer at the Neutron Physics Laboratory of the Joint Institute for Nuclear Research employing the gamma ray multiplicity technique and using a "Romashka" multi-sectional 4p detector on the 500 m time base of the IBR-30 booster. The gamma multiplicity spectra of resolved resonances were obtained for the 20-500 eV energy range. The mean gamma ray multiplicity was determined for each resonance. The dependence of the ratio S of the low-energy coincidence multiplicity spectrum to the high-energy coincidence multiplicity spectrum on resonance energy exhibits a non-statistical structure. This structure was found to correlate with the local neutron strength function.

## Introduction

Using the gamma ray multiplicity spectrometry technique in conjunction with the time-of-flight method [1], a large volume of varied data may be obtained on radiative capture of neutrons in the resonance region and on the characteristics of resonance levels. This article presents the results of a study of the (n,γ) reaction in indium-113 and 115[1] in the energy region up to 500 eV. Indium-115 has already been fairly closely studied [2, 3] and non-statistical effects in the behaviour of the radiation strength function were found and some parameters of excited levels determined. In contrast to $^{115}$In, $^{113}$In has been little studied and there are significant gaps in the data on its neutron resonance parameters, for instance spins and radiation widths. Since we had enriched indium isotopes at our disposal, it seemed to us useful to augment the information on the resonance characteristics of their neutron cross-sections.

## Experiment

The measurements were carried out in booster regime on the IBR-30 reactor at the Neutron Physics Laboratory of the Joint Institute for Nuclear Research (W = 10 kW, $f_{burst}$ = 100 Hz, $\tau_{burst}$ = 4 μs) using a 16-section gamma ray detector with NaI(Tl) crystals and a total volume of 36 L [4] on a 500 m time base.

The enriched isotopes $^{113}$In and $^{115}$In were used as radiator samples in powdered oxide form in aluminium containers with a diameter of 70 mm. For $^{113}$In, the enrichment level was 87.2% and the sample thickness $3.74 \times 10^{-4}$ atoms/barn and $6.07 \times 10^{-4}$ atoms/barn; for $^{115}$In, the enrichment level was 99.9% and the sample thickness $6.79 \times 10^{-4}$ atoms/barn.

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1 The $^{113}$In and $^{115}$In isotopes were supplied by the Institute for Nuclear Research and Nuclear Power, Sofia, Bulgaria.

For each sample, the time spectra were measured from the first to the eighth multiplicity at a total gamma ray cascade energy output in the detector of 2-8 MeV with a discrimination threshold of 100 keV in each spectrometer channel. The time resolution of the spectrometer was 8 ns/m which meant that the well-resolved resonances in the 20-500 eV neutron energy region could be identified.

Parallel with radiative capture, instances of neutron scattering were also registered. The neutron flux was monitored using 2 $^{3}$He counters. A boron carbide filter (10 mm) was placed permanently in the beam in order to suppress unexpected background neutrons.

**Results and Discussion**

Measurements were performed on a thin sample of $^{113}$In for a period of 72 hours and on a thick sample for a period of 22 hours. For $^{115}$In, the overall duration of the measurements was 54 hours. Typical time-of-flight spectra for the third multiplicity of both isotopes are shown in Figs 1 and 2. The initial processing involved determining the areas $S_k$ under the resonance peaks for the time-of-flight spectra of the different multiplicities $k = 1\text{-}8$, the proportion of capture events $p_k = S_k/\Sigma_k(S_k)$ which correspond to simultaneous registration by the detector of k gamma rays, and the mean multiplicity values $\langle k \rangle = \Sigma_k(kp_k)$ for each resonance.

Using the initial results obtained, an attempt was made to determine the spins using various techniques. The first technique consisted in tracing the dependence of the mean multiplicity on the resonance energy. Where the spin effect is strong, the resonances can be divided fairly clearly into two groups according to the $\langle k \rangle$ values. An example of this is the data on $^{147,149}$Sm in Refs [5, 6]. For $^{113}$In and $^{115}$In, no such correlation is found, as is illustrated in Fig. 3 and Table 2 which show the energy dependences of the mean multiplicities for different spins of $^{115}$In (the spin values are taken from Ref. [3]). The findings for $^{113}$In were similar. Here, the changes in the mean multiplicity from resonance to resonance were small and showed no grouping tendency, which confirms the data in Table 1. Our next attempt to determine the spin effect involved a comparison of the distributions of the multiplicities for various resonances. Figure 4 shows the averaged distributions of the multiplicities for two spin systems in $^{115}$In and illustrates graphically the weakness of the effect which, incidentally, has long been noted in the literature [7, 8] where $^{115}$In is cited as the worst example. Apart from the above, two other approaches were used but the calculations did not yield any positive results.

Apart from the mean multiplicity values for individual resonances of both isotopes, Tables 1 and 2 give the values of S which is the ratio of the sum of the third to the sixth multiplicities to the value of the second multiplicity $S = \Sigma_k S_k / S_2$ and characterizes the correlation between the soft part of the gamma ray spectrum and the hard part. From Figs 5 and 6 it is clear that the dependence of S on the neutron resonance energy exhibits a systematic strong modulation which correlates with the local neutron strength function. This behaviour of S may be interpreted as a manifestation of non-statistical structural effects.

As we know, if we can identify a direct capture component in the radiative capture mechanism in addition to the component which passes through a compound nucleus, then the experiment indicates the presence of strong single particle transitions or one-, two- and three-quasiparticle initial states.

In some cases, the presence of initial states may be observed directly through the intermediate structure from the intensity of high-energy gamma transitions to low-lying levels, or in the radiation strength function relative to resonance energy. Effects of this kind for $^{115}$In were noted in Refs [2, 3] but, on the other hand, it should also be noted that the measurements of another group [9] did not confirm the presence of an intermediate structure.

The analysis of our results confirms the conclusions of Refs [2, 3] for $^{115}$In and indicates the presence of the same effect in $^{113}$In. It is true that the high experimental error levels make it difficult to draw definite conclusions. We plan to continue our study of the isotopes of indium using a Ge detector. The neutron time spectra were processed using the ANS [10] and GRAFIKA (written by Yu.N. Kopasch) programs which were developed especially for this type of problem.

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Table 1

Resonance characteristics for indium-113

| $E_0$ (eV) | <k> | S |
|---|---|---|
| 21.55 | 3,0474±0,0221 | 2,48±0,02 |
| 24,09 | 3,0239±0,0147 | 2,35±0.01 |
| 32,24 | 3,0197±0,0165 | 2,42±0,01 |
| 44,71 | 2,9387±0,0593 | 2.23±0.05 |
| 45,38 | 3,0598±0,0517 | 2,50±0,04 |
| 70.29 | 3.0353±0,0332 | 2,45±0,03 |
| 91.59 | 3,0074±0,0204 | 2,34±0,02 |
| 93,00 | 3,0529±0,0454 | 2,48±0,04 |
| 103.88 | 3,0051±0,0244 | 2,40±0,02 |
| 123.33 | 3,0213±0.0403 | 2,43±0,05 |
| 134.05 | 2,9860±0,0504 | 2,41±0.04 |
| 203,21 | 3.056±-0,0346 | 2,49±0.03 |
| 228.38 | 3,0069±0.0398 | 2,32±0.03 |
| 234,61 | 2,8956±0,1057 | 2,38±0.08 |
| 236.01 | 2.9985±0,0599 | 2,28±0.05 |
| 239,30 | - | - |
| 241,51 | 2.9620±0.0690 | 2,31±0.07 |

Table 2

Resonance characteristics for indium-115

| $E_0$ (eV) | J | <k> | S |
|---|---|---|---|
| 22,73 | 5 | 2,9879±0,0247 | 2.35±0.02 |
| 39,64 | 5 | 2,9117±0,0180 | 2,11±0.01 |
| 46,36 | 4 | 2.9390±0,0291 | 1,99±0,03 |
| 48,17 | 5 | 2,8704±0,0708 | 1,81±0,04 |
| 62,92 | 4 | 2,9302±0,0551 | 2,20±0,04 |
| 69,50 | - | 2,9076±0.0981 | 2.18±0.07 |
| 80,95 | 4 | 2,9328±0,0462 | 2.20±0.03 |
| 83,34 | 5 | 3,0136±0,0241 | 2,33±0,03 |
| 94,43 | 5 | 2,9442±0,0379 | 2,13±0,03 |
| 125,99 | 4 | 3,0038±0,0443 | 2,23±0,03 |
| 132,98 | 5 | 3,0260±0,0405 | 2,35±0,03 |
| 150.29 | 5 | 3,0025±0,0487 | 2,41±0,04 |
| 164,70 | 4 | 3,0219±0.0319 | 2,38±0,07 |
| 168.23 | 5 | 2,9894±0,0933 | 2,64±0,08 |
| 178,05 | 4 | 3,0322±0,0678 | 2,45±0,05 |

Table 2 (continued)

| $E_0$(eV) | J | <k> | S |
|---|---|---|---|
| 187,0 | 4 | 3,0062±0,0282 | 2,41±0,02 |
| 205,6 | 5 | 2,9319±0,0276 | 2,22±0,02 |
| 224,0 | 5 | 2,9797±0,0335 | 2,30±0.03 |
| 226,8 | - | 3,0676±0,1104 | 2,24±0.07 |
| 250,2 | - | 2,9938±0,0252 | 2,37±0,02 |
| 267,0 | - | 2,9859±0,0782 | 2,45±0,06 |
| 289,19 | 4 | - | - |
| 294,7 | 4 | - | - |
| 354,1 | 5 | - | - |
| 362,8 | 4 | - | - |
| 371,3 | 5 | - | - |
| 382.0 | - | 2.9220±0,1021 | 2.34±0.08 |
| 402,4 | 5 | 3.0163±0.0440 | 2.38±0,04 |
| 411,6 | 4 | 2.9756±0.0444 | 2,27±0,03 |
| 422.8 | 5 | 2,8789±0.0739 | 2.33±0.06 |
| 448,9 | - | 2,9021±0,0754 | 2,49±0,06 |
| 453,9 | - | 2.9903±0.0769 | 2.33±0.06 |
| 469.6 | - | 2,9442±0,1158 | 2.55±0,09 |
| 477.6 | - | 3.0342±0.2350 | 3.05±0.20 |
| 503,7 | - | 2.9288±0.0606 | 2.32±0.05 |
| 525.5 | - | 2.8175±0,0819 | 2.09±0.06 |

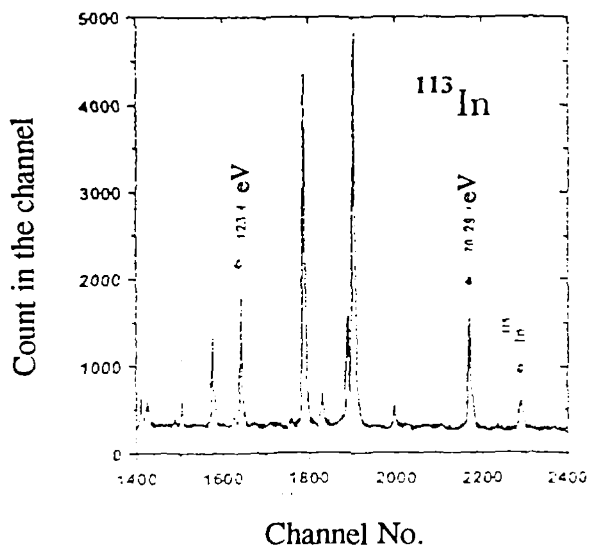


Fig. 1. Time-of-flight spectrum of triple gamma ray coincidences for indium-113

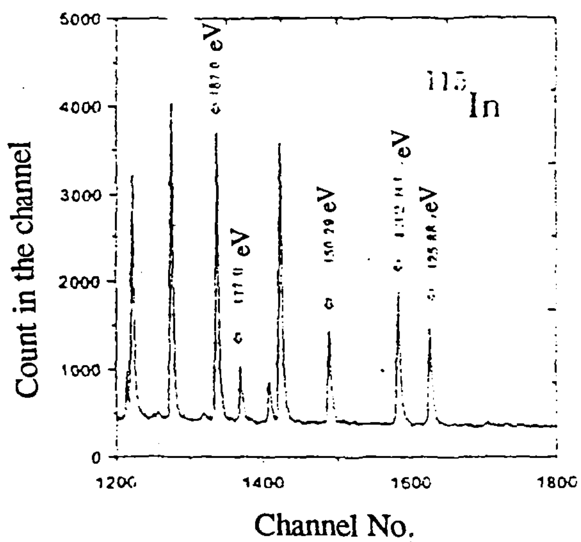


Fig. 2. Time-of-flight spectrum of triple gamma ray coincidences for indium-115.

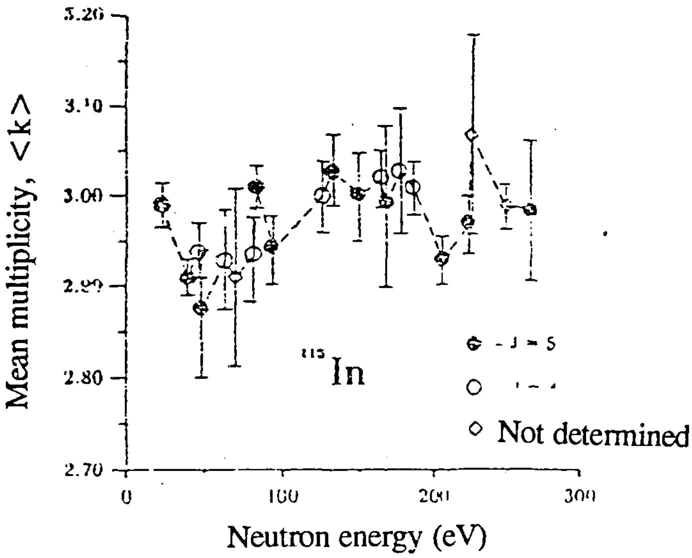


Fig. 3. Dependence of the mean multiplicity on resonance energy for indium-115.

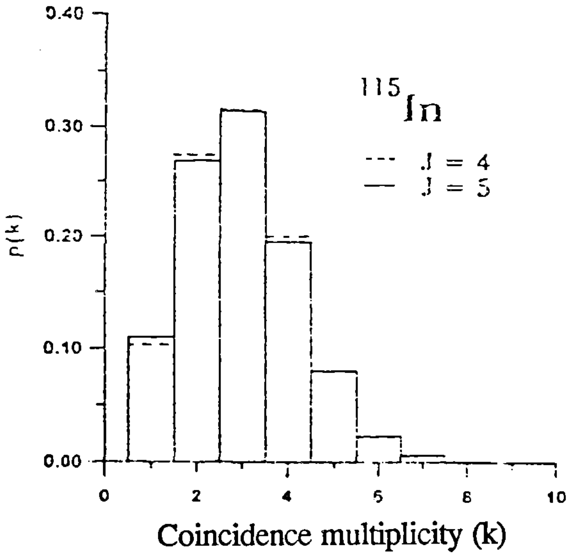


Fig. 4. Experimental distribution of the gamma ray multiplicity for resonances with different spins in indium-115.

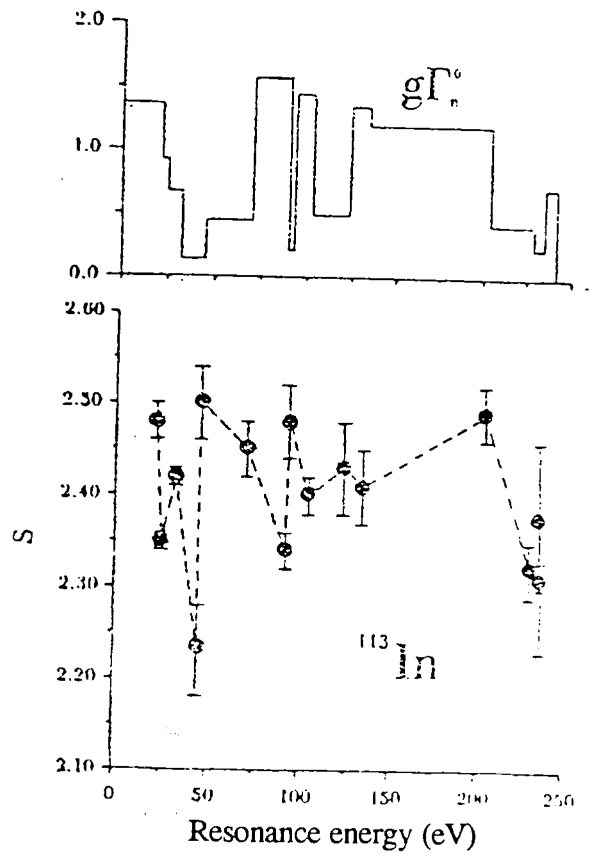


Fig. 5. Energy dependence of the local strength function and the ratio S for indium-113.

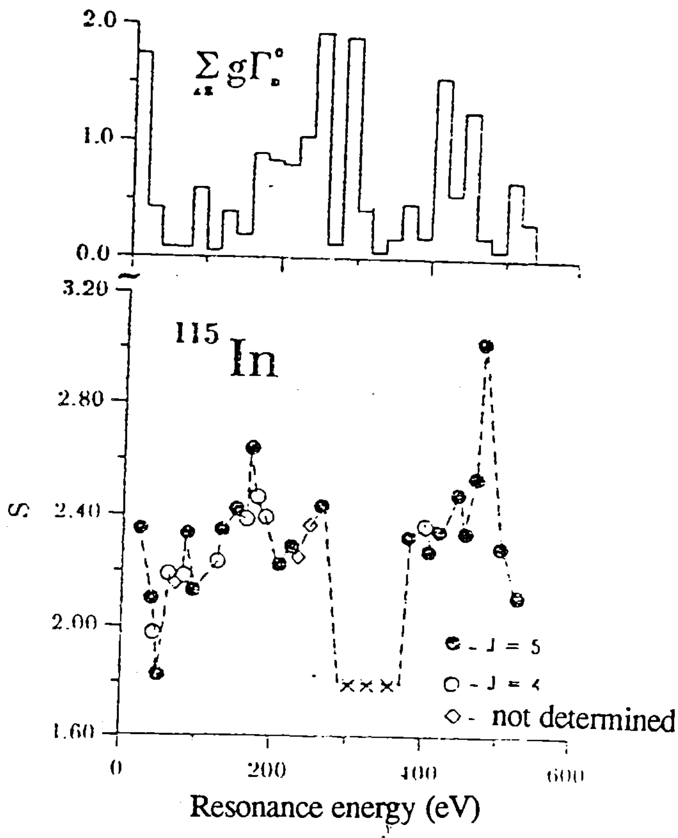


Fig. 6. Energy dependence of the local strength function and the ratio S for indium-115.

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