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NEUTRON RESONANCE AVERAGING WITH FILTERED BEAMS

MASTER

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Abstract

Neutron resonance averaging using filtered beams from a reactor source has proven to be an effective nuclear structure tool within certain limitations. These limitations are imposed by the nature of the averaging process, which produces fluctuations in radiative intensities. The fluctuations have been studied quantitatively. Resonance averaging also gives us information about initial or capture state parameters, in particular the photon strength function. Suitable modifications of the filtered beams are suggested for the enhancement of non-resonant processes.

Introduction

Just above an excitation energy corresponding to particle binding in the nuclear system, there is a region, or energy window, in which radiative de-excitation is a significant decay mode. In this window, the metastable states or resonances are well-separated and can be excited by slow neutrons with exceptionally-high cross sections. This slow neutron "window" has provided an important source of information about nuclear structure on one hand, and about highly-excited nuclear states on the other. Much of this information has been provided by neutron capture γ -ray spectroscopy.

While the observation of γ -transitions from individual resonances provides the maximum information, it appears that for most questions arising in nuclear theory, a suitable averaging over resonances is sufficient. For example, in the assessment of photon strength functions, the averaging must in any case be taken. Thus when Bollinger suggested,¹ in 1966, a direct experimental method for averaging, it soon became evident that for most

applications of the (n,γ) method to nuclear models, the averaging technique is preferred, since it at once (a) avoids the necessity for tedious accumulation of many discrete complete spectra, (b) gives directly the most important quantity desired, i.e., the mean primary γ -ray strength, and (c) can produce an average over a very large number of resonances. As we shall see in subsequent sections, part of the price to be paid for avoidance of the discrete resonance measurements is a loss of the knowledge of the absolute values of the partial radiative widths, $\Gamma_{\gamma\lambda f}$. Another important disadvantage is the loss of the ability to discriminate among different capturing states; states of varying spin and parity are included.

Averaging Techniques

The basis of the direct experimental resonance-averaging technique is the use of a neutron spectrum which has a suitably-defined and limited range in energy. Definition of this energy range can often be accomplished by combining the properties of the source with the properties of a transmission filter of some kind, to produce a situation in which the capture reaction occurs over a limited energy range.

There are three major averaging techniques that have been applied to (n,γ) reaction studies. These involve filters of boron, scandium, and iron (or ^{56}Fe) applied to the spectrum of reactor neutrons. It is interesting to observe that in these averaging methods, the fission reactor remains the neutron source of choice.

Boron Filter Technique

The boron filter technique was developed by Bollinger and his colleagues² at the Argonne CP-5 reactor in the period 1966-1970. The arrangement features an internal target facility surrounded by a ^{10}B absorber placed in a thru-tube passing the edge of the CP-5 core (thermal flux = $3 \times 10^{13} \text{ n/cm}^2/\text{sec}$ at $R_{Cd}=7$).

The combination of the $1/E$ epithermal reactor spectrum and the $1/v$ ^{10}B absorption cross section results in the spectrum of Fig. 1, which shows a broad incident neutron spectrum peaking under 100 eV, but extending to 10 keV

Fig. 1. Spectra of incident and captured neutrons in a holmium sample of the Argonne CP-5 facility (Ref. 4).

Fig. 2. Population paths for various final states reached from neutron capture on a spin 5/2 target (Ref. 3).

and beyond. The captured neutron spectrum for a typical sample, however, differs from the incident spectrum because of the absorption properties of the sample. The combination of the E^{-1} reactor spectrum, the $E^{-1/2}$ absorber cross section, and the $E^{-1/2}$ sample cross section produces a crudely defined averaging interval which is not large compared to the typical resolution of a γ -ray detector. Because of this fact, the detector conveniently averages over a number of contributing resonances in this interval, and a suitably averaged transition strength is obtained.

The spectroscopic utility of resonance-averaging has been well documented²⁻⁵. Subject to the usual statistical model assumptions that the γ -ray strength function is independent of the initial and final state spins, then the population patterns for the final states are simply determined by how many ways that particular final state can be fed by a transition of a particular multipolarity (Fig. 2). Furthermore, there is a sizable intensity difference to be expected depending on the radiation multipolarity, and thus a parity dependence of the final state population is evident.

Transmission Filters

While the internal target arrangement described above was effective for a limited number of targets, a number of drawbacks are readily apparent.

1) Targets internal to a reactor are subjected to constraints on size, and physical/chemical form, on purity, on temperature stability, and other factors related to the hostile environment in which they are placed. Activation of sample impurities can also be a significant problem.

2) The use of the boron filter in a geometry in which it surrounds the target makes it difficult to define the captured neutron spectrum precisely. Closely coupled to this difficulty is the fact that the boron-reactor spectrum results in a peak capturing rate at low energy (see Fig. 1), typically near 100 eV. Thus, low energy resonances may contribute heavily and distort the averaging. A very thorough attempt has been made to evaluate fluctuations from capturing states located at low energies (<500 eV) in ref. 3. However, the difficulties can be gauged by noting that for the heavier elements, holmium and gadolinium, the observed fluctuations exceed the calculated fluctuations by a factor of 2.

3) It is difficult to alter the neutron spectrum.

Fig. 3. Transmission curves for the BNL 2 keV and 24.3 keV scandium and ^{56}Fe filters.

These disadvantages are largely overcome using an external target combined with an appropriate transmission filter.³ A number of such filters have been suggested,⁶ but only two, scandium and iron, have been used for (n, γ) studies. Figure 3 shows the transmission peaks at 2 and 24 keV resulting from the scandium and ^{56}Fe filters at the Brookhaven National Laboratory

Fig. 4. Neutron group structure from the 24.3 keV filter.

no problem because the average capture cross section falls, as does the reactor spectrum. The weighting of these higher groups goes roughly as E^{-2} , and they contribute only a few percent to the observed (n, γ) spectrum.

Discrete Resonance Averaging

Using the neutron time-of-flight technique, it is of course possible to measure the partial radiative widths for the resolved resonance region, and average them after the fact. This procedure gives the maximum possible information. The capturing states can be separated by spin and parity (in

High Flux Beam Reactor (BNL HFBR).³ This figure shows the superior spectrum definition alluded to in point 2) above. With regard to point 3), the BNL filters are mounted in a rotatable collimator assembly which permits changing a filter in a matter of a few seconds.

It might be expected that a problem could arise from the transmission of neutrons at cross section minima located at higher energies. The spectrum from the BNL HFBR ⁵⁶Fe filter has been measured by Greenwood⁷ using hydrogen filled recoil detectors (Fig. 4). Clearly distinct neutron groups are present at higher energies, but they present

principle, at least). They can also be categorized according to size (small or large widths). Much discrete resonance work has been done at Brookhaven,^{8,9} Oak Ridge,¹⁰ and Dubna,¹¹ with particular emphasis placed on the studies of width correlations and non-statistical effects. Perhaps the most relevant point to be made about the discrete resonance region is that these time-of-flight measurements are capable of yielding absolute values for partial radiative widths and therefore absolute values for photon strength functions. The filter averaging techniques cannot yield absolute values. Discrete resonance average is limited usually to several tens of resonances. The most complete set is due to Sahal et al.¹², who report 49 resonances for $^{173}\text{Yb}(n,\gamma)^{174}\text{Yb}$.

Quantitative Aspects of Averaging

Since the success of the averaging method in producing a complete set of states of known spin and parity depends on combining certain assumptions with a purely statistical decay of the compound nucleus, the apparent experimental success which the method has displayed for heavy nuclei represents a vindication of these assumptions. In spite of this global vindication, there will always be the possibility of exceptions—for example, a failure of the statistical assumption for a certain class of initial or final states, or a failure of the various assumptions covering the neutron and photon strength functions, or other related quantities. Furthermore, the spectra obtained by averaging provides direct experimental information on the distribution of radiative strength in nuclei—the photon strength functions. In the remainder of this review, I will concentrate on the information that averaging gives us about the properties of the initial states—the resonances, rather than the nuclear structure aspects. The latter have been reviewed extensively by many others, much more qualified than I to treat this aspect.

The discussion starts with an expression of the averaged capture cross sections to a specific final state:

$$\langle \sigma_n, \gamma \rangle = 2\pi^2 k^2 \sum_{J, l} g_{Jl}^2 D_{Jl}^{-1} \langle \Gamma_n \Gamma_{\gamma if} / \Gamma \rangle$$

The following assumptions are made to simplify the above expression:

- a) Consider only $l=0,1$ and ignore higher partial waves.
- b) Consider dipole transitions only, E1 and M1.
- c) The neutron and photon strength functions are spin independent, and invariant over a limited range of excitation energy.
- d) The reduced neutron and photon widths are uncorrelated Porter-Thomas variables.
- e) The total radiation widths are independent of spin, parity, and excitation energy.
- f) The level density of initial states is given by $\rho_J = D^{-1} J = \rho_0(2J+1)\exp[-J(J+1)/2\sigma^2]$ where 0 indicates spin 0 states, and σ , the spin cutoff factor is taken to be 3.5.

The evaluation of the quantity $\langle(\Gamma_n \Gamma_{\gamma if}/\Gamma)\rangle$ over the resonances is conveniently accomplished by Monte Carlo methods, such as the code RACA at BNL.⁴ Some model has to be assumed for the photon strength functions $S(E1)$ and $S(M1)$. For the former, the Brink-Axel¹³ hypothesis suggests a power law expression of the form E_γ^n , where n is approximately 5. For the latter, a similar form can be assumed, with an n varying from 3 to 5. There is some evidence, as we shall see, for a Lorentzian form for both electric and dipole strength functions.

For filtered beam experiments, the energy-averaging intervals are nearly rectangular in form (Fig. 3). For scandium $\Delta E \approx 850$ eV, centered at 2000 eV, and for ⁵⁶Fe, $\Delta E \approx 1900$ eV centered at 24,300 eV. At these higher neutron energies, we can use the averaged cross section expressions directly to infer γ -ray intensities, since sample self-absorption effects, for neutrons or γ rays, are negligible.

Several simple observations concerning the above expressions may be in order. In the low energy limit, the correlation between Γ and Γ_n may be ignored, since $\Gamma \gg \Gamma_n$. There Γ is spin independent, and the pattern of Fig. 2 is accurate; this is the situation with respect to boron filtering. At higher energies, the Γ becomes quite spin dependent through the dependence on Γ_n . Furthermore, the effects of p-wave capture cannot be ignored. Both effects serve to lessen the spin and parity discrimination of this method as the neutron energy increases. These effects are illustrated in Fig. 5. It

Fig. 5. Intensities for population of final states as a function of neutron energy.

is clear that the separate effects of the neutron strength functions S_0 and S_1 and the photon strength functions $S(E1)$ and $S(M1)$ must be considered.

The use of both iron and scandium filtering, with their different s- and p-wave admixtures, can result in reliable parity information. Such information is displayed in Fig. 6, for the classical case of $^{167}\text{Er}(n,\gamma)^{168}\text{Er}$.¹⁴ A firm parity identification is provided over an excitation range of 2 MeV or more. The failure to discriminate at high excitation energy is almost certainly attributable to the failure to resolve closely-spaced transitions.

Occasionally, the ability of resonance-averaging in identifying all states within a spin-parity range (completeness) has been questioned. In particular, Hamilton¹⁵ cites a number of states in ^{146}Nd (levels at 1518, 1769, 1906, 2046, and 2168 keV) with suitable spin and parity, which were not reported in an earlier ^{10}B filtered experiment at Argonne by Bushnell et al.¹⁶ The absence of those states in an averaged spectrum would clearly violate the premise of resonance-averaging and render its usefulness questionable.

The ^{146}Nd spectrum was checked at the 2 keV scandium beam available at the Brookhaven HFBR. Figure 7 shows the appropriate energy region of the spectrum, and the arrows indicate transitions not reported by Bushnell. Aside from the weak 5799 keV transition, all the states cited by Hamilton appear clearly in the spectrum. These observations emphasize the fact that

Fig. 6. Ratio of 2 and 24 keV populations.

while high-quality averaged spectra are required to support the "completeness" claim, there is no evidence here that the method of resonance averaging is inadequate in identifying a complete level set. In fact we go further: there is evidence that resonance averaging is as reliable as any other method of spin-parity determination, including that of nuclear polarization, provided only that it be properly applied. In this case "proper application" means simply a careful analysis of the data coupled with a proper fluctuation analysis.

Fig. 7. A portion of the 2 keV ^{146}Nd spectrum (Ref. 17).

Table I
Relative RMS Fluctuations, σ/m , for ^{168}Er

J_f	2 keV				24 keV			
	s waves		s+p waves		s waves		s+p waves	
	calc.	$2/\sqrt{\nu}$	calc.	$2/\sqrt{\nu}$	calc.	$2/\sqrt{\nu}$	calc.	$2/\sqrt{\nu}$
2^-	.194	.200	.197	.141	.119	.133	.109	.080
3^-	.135	.137	.135	.098	.081	.092	.077	.054
4^-	.133	.137	.133	.098	.078	.092	.073	.054
5^-	.188	.189	.187	.134	.109	.127	.101	.073
2^+	.194	.203	.171	.141	.119	.133	.077	.080
3^+	.135	.133	.116	.098	.082	.092	.056	.054
4^+	.133	.139	.120	.098	.080	.092	.053	.054
5^+	.188	.188	.161	.134	.109	.127	.074	.073

Fluctuations

The relative dispersions (σ/m) for resonance-averaged cross sections may be directly evaluated from the Monte Carlo Code RACA and compared to data. Table I summarizes such a calculation for the ^{168}Er case.

Qualitatively the calculated dispersions may be understood in terms of the assumed Porter-Thomas dispersions of neutron and radiative models. Neglecting the correlations arising in the neutron and total widths, the expected relative dispersion becomes $2/\sqrt{\nu}$, which is what is obtained from the product of two random variables, each obeying a χ -square distribution with ν degrees of freedom; ν in this case represents the number of resonances in the averaging interval. Table I compares the Monte-Carlo calculation with the quantity $2/\sqrt{\nu}$, and shows that the naive expectation is remarkably close to the calculated result.

Experimental observation in the case of $^{167}\text{Er}(n,\gamma)^{168}\text{Er}$ at 2 keV, for 3^- and 4^- capturing states gives a relative standard deviation of 0.137, in good agreement with the table. These fluctuations, when compared to the mean intensity for populating states of various spin and parity (Fig. 8) determine the sensitivity of the method. In the case of 2 keV ^{167}Er capture, the sensitivity allows us to distinguish parities, and the $(3^\pm, 4^\pm)$ spin groups from the $(2^\pm, 5^\pm)$ spin groups, over 2 MeV range of excitation.

Fig. 8. Resonance-averaged spectrum for ^{168}Er .

Entrance Channel Effects

Now we are in a position to turn the method around and inquire: are the data indicative of any violations of the assumptions a) to f) above?

An extreme, but highly instructive example of how the simple population patterns of Fig. 2 can be altered by entrance channel effects is afforded by the example of ^{240}Pu ,¹⁸ whose resonance-averaged 2 keV intensities are displayed in Fig. 9. A clear grouping into odd and even parity bands is clearly evident, but the expected spin grouping is completely absent. (The 0^+ and 1^+ resonances should populate final states 0^- , 1^- , 2^- in the ratios 1:2:1 by E1 transitions, and 0^+ , 1^+ , 2^+ states by M1 transitions in a similar pattern.)

^{240}Pu is an exception to the general rule because the target nucleus ^{239}Pu is fissile. It is known experimentally, and expected from the channel theory of fission, that the fission widths are strongly spin dependent.

Fig. 9. Resonance-averaged spectrum for ^{240}Pu (Ref. 18).

Fig. 10. Calculated intensity distributions for ^{240}Pu (Ref. 18).

For ^{239}Pu it is found that $\langle \Gamma_F(J=0) \rangle / \langle \Gamma_F(J=1) \rangle = 65$.¹⁹ The large J=0 fission widths result in large total widths for J=0 resonances, and since,

$$\sigma_{n,\gamma} = \sigma_c \Gamma_\gamma / \Gamma,$$

the radiative capture for J=0 resonances is suppressed. The relative probability for final state population, Fig. 10, shows only two groupings for dipole transitions, with similar populations of states 0, 1, and 2.

This example is a good one for illustrating several other features of averaged spectra. Perhaps the most important is the apparently different energy dependences of the positive and negative parity population. Referring first to the latter states, it is obvious that the dominant multipole in the population is E1 (there is a small correction for M1's following p-wave neutron capture). The Brink-Axel hypothesis implies that strengths of these E1 transitions vary with excitation energy in the same way as the photoexcitation cross section. Parameterization of the photoexcitation cross section by the Lorentzian form,

$$\sigma_a = \sigma_0 \{ E^2 \Gamma^2 / [(\Delta E^2)^2 + \Gamma^2 E^2] \} \text{ where } \Delta E^2 = E_0^2 - E_\gamma^2$$

and allowing for the split in the giant resonance caused by nuclear deformation, permits us to calculate cross sections at low nuclear excitation. The Brink-Axel hypothesis relates the photon strength function to the photoabsorption cross section,

$$\langle \Gamma_\gamma \rangle / D = (3\pi^2 \hbar^2 c^2 / E_\gamma^2) \langle \sigma_a \rangle,$$

$$f_{E1} = \langle \Gamma_\gamma \rangle / D E^3,$$

and f_{E1} is shown plotted as the solid line in Fig. 9. Because the intensities have been normalized to the absolutely determined photon strengths of reference 18, the data may be compared absolutely. It can be seen from the figure that the giant resonance tail well reproduces the energy variation of the intensities, but the intensity observed is about 65% of that expected

from the resonance extrapolation. This is in agreement with the observations of McCullagh, Stelts, and Chrien,²⁰ based on a large sample of discrete resonance data. The recent review of Raman²¹ confirms the conclusion that the Lorentzian extrapolation of the dipole resonance overpredicts the observed photon strengths for (n,γ) reactions. Donald and Maureen Gardner²² have suggested several possible explanations for this overprediction, and support McCullagh et al. in their suggestion for an energy variation in the width of the Lorentzian expression.

Returning to Fig. 9, it is apparent that the slope of the positive parity state population is different from that of negative states. The E1 and M1 matrix elements may vary differently, but superimposed on this variation is the effect of p-wave capture on the population of these positive parity states. The effective photon strength function must be written as the weighted average of two components: one corresponding to s-wave capture followed by M1 radiation, the other to p-wave capture followed by E1's. The Monte Carlo code "RACA" indicates that about 35% of the population is due to p-wave. The assumption of an energy-independent $f(M1) \equiv \Gamma(M1)/DE_\gamma^3$, leads to the calculated band shown on the figure.

The M1 variation shown here suggests an increasing divergence between E1's and M1's as excitation energy increases. Lone²³ and, more recently, Kopecky²⁴ have revived an old suggestion that collective M1 strength may be concentrated in a giant resonance at an excitation given by the spin-orbit partner splittings of the shell model.

Such an M1 giant resonance is strikingly illustrated by boron filtered beam data on ¹⁰⁶Pd (Fig. 11). Here the positive parity state populations seem to be turning over about a broad maximum near 8 MeV. Bohr and Mottelson²⁵ give an approximate energy for the spin-flip strength at about one-half the E1 giant resonance energy, or $E_0 \approx 41 A^{-1/3}$. This energy would place an M1 giant resonance maximum ranging from 9 MeV for A=100 to 6.6 MeV for A=240.

Kopecky²⁴ has collected a set of nine resonance-averaged spectra ranging from ⁹⁶Mo to ²³⁹U, from which the exponent n in the power-law dependence $I_\gamma(M1) \approx E_\gamma^n$ may be derived. The exponent n may be related to an assumed giant resonance energy, E_0 , and width Γ . The normalization of the strength function is taken from discrete resonance data.

Fig. 11. Resonance-averaged spectrum for ^{106}Pd .

Table II

M1 Strengths Calculated on the Giant Resonance Assumption $S(M1) = \Sigma EB(M1)$

Nucleus	$E_{\gamma M1}$ [MeV]	$f(M1)$ [10^{-8} MeV^{-3}]	$S(M1)$ [$\mu^2_0 \text{ MeV}$]	
^{106}Pd	7.5	1.2(3)	220(55)	$E_0 \approx 8.5 \text{ MeV}, \Gamma \approx 4 \text{ MeV}$
^{168}Er	6.2	2.7(5)	780(144)	$E_0 \approx 8.5, \Gamma \approx 6 \text{ MeV}$
^{176}Lu	5.8	1.8(5)	580(160)	$E_0 \approx 8.5, \Gamma \approx 6 \text{ MeV}$
^{233}Th	4.2	4.0(8)	690(140)	$E_0 \approx 6 \text{ MeV}, \Gamma \approx 6-8 \text{ MeV}$
^{239}U	4.1	3.0(6)	520(105)	$E_0 \approx 6 \text{ MeV}, \Gamma \approx 6-8 \text{ MeV}$

Non-statistical Effects

As has been previously stated, the basis for the application of the averaging method to nuclear structure problems is the statistical model for resonance decay. Are the present data sufficient to test this assumption?

Sufficiently precise M1 data does not yet exist to pin down these M1 giant resonance parameters with any great exactitude, but the data are certainly suggestive of a giant resonance interpretation. Table II shows summed M1 strength for 5 nuclides, derived from the measured M1 strength function and the giant resonance interpretation. These are in reasonable agreement with shell model calculations.

Clearly, the success obtained for spin and parity determinations by this method implies that initial and final state correlations cannot be large.

Table I shows that a departure of an intensity fluctuation from the average value by two or three standard deviations will mask non-statistical effects which are as large as 60% of the mean--a very large effect. It follows then that averaging can only exclude the largest effects and will not be sensitive to effects at, say, the 30% level.

Nevertheless, there have been very large effects reported. One such effect is the report of Stefanon et al.^{26,27} of the possible dependence of primary capture γ -ray strength on the K quantum number of the final state in ^{174}Yb . Stefanon found that for resonances over the lowest 200 eV over threshold, the ratio $I(K=2^+)/I(K=0) \geq 3.5$, when the intensities were corrected by an E_γ^5 reduction factor.

Recently, ^{174}Yb has been re-examined with the 2 keV scandium filter at the Brookhaven High Flux Beam Reactor with the specific intention of examining such non-statistical effects. At the present time, only preliminary data are available from this experiment. Even preliminary data, however, are quite sufficient to show that the original claim is not supportable.

Transitions to $K=0^+$ final states at 1561, 1715, 1958, 2123, 2171, and 2336 keV were compared to $K=2^+$ final states at 1634 and 1805 keV. Only well-separated transitions are included in these sets. A ratio $I(2^+)/I(0^+) = 1.39 \pm 0.20$ was found, which is within averaging statistics.

Thus, we can conclude that K-dependent effects, if present, must be at a 20% level or smaller.

Using resonance-averaging to confirm initial state correlations such as, for example, correlations between neutron and radiative widths would appear not to be possible. There is, however, an interesting way to modify the incident neutron spectrum in the filter. To introduce this idea, let me first quote from an exchange between Lowell Bollinger and myself at the 1966 Argonne Slow Neutron Capture γ -ray Conference, p. 530, in reference to boron filtering.

Chrien: "...there may be also an off-resonant component. If so, it would influence your results..."

Bollinger: "What you say is undoubtedly true. In fact it may turn out to be one of the more interesting things to try in the future. It may be possible to look for a difference...when capture at the resonances is somehow inhibited."

Fig. 12. Off-resonance (2 keV) spectrum for ^{60}Co (above), compared to thermal capture (below).

Off-resonance capture has recently been demonstrated at 2 keV at Brookhaven.²⁸ For samples of relatively small mass number, the level spacing can be large enough so that no resonances appear in the averaging window. Such a case is $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ which has no s or p-wave resonances near 2 keV. Despite the unfavorable ratio of $\sigma(n,\gamma)/\sigma(n,n) \approx 130/2000$, the spectral quality is remarkably good (see Fig. 12) from a sample of 9.9 gms/cm^2 . It is interesting to note that the intensities differ significantly from thermal capture, even though the same resonance tails contribute.

Having made the point that off-resonance capture can be measured at 2 keV, it is evident that for most samples, the spectrum is dominated by the resonances. Let us suppose, however, that a resonance filter of the same composition as the target is placed in the beam. To a first approximation, the resonance contribution is thus removed and we are left only with the off-

resonance contribution. We are then free to examine final state correlations and expect to see the effects of direct neutron capture enhanced to those states with significant single-particle character.

Furthermore, by varying the thickness of the resonance absorber, it may be possible to alter the effects of the Porter-Thomas averaging so that, for example, a thin absorber removes mainly the large resonances, selectively.

An experiment to test the correlations observed by F. Becvar¹¹ in $^{173}\text{Yb}(n,\gamma)^{174}\text{Yb}$ using this variation of the "self-indication" method is in progress at the BNL HFBR. A wide range of thicknesses will be studied, and the effects on the averaging spectrum will be observed. It will be interesting to see if this method is useful for direct capture studies.

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