A review of currently-used techniques to measure neutron capture cross sections is presented. Measurements involving use of total absorption and Moxon-Rae detectors are based on low-resolution detection of the prompt γ-ray cascades following neutron captures. In certain energy ranges activation methods are convenient and useful. High resolution γ-ray measurements with germanium detectors can give information on the parameters of resonance capture states. The use of these techniques is described.

I. Introduction

Neutron capture reactions are important in a wide range of nuclear applications from stellar nucleosynthesis to reactors. These reactions provide a means of populating states of many nuclides and hence are also important in determining nuclear structure and providing insight into capture reaction mechanisms. As knowledge concerning neutron interactions has developed a variety of techniques for capture studies have been made available to the experimenter. Some of these are quite specific as to energy range, source type, or nuclear species, others are generally applicable to many types of sources and samples.

In this review a description of some of the more useful techniques will be given in the hope of acquainting the non-specialist with activity in this field, and to impart some appreciation to the user of cross section information about the limitations and expected precision of capture cross section measurements. For the purposes of the present discussion, the term capture will be taken to indicate radiative capture.

The most commonly-used methods are based on direct detection of prompt photons emitted after capture with low resolution devices. These prompt detection methods are suitable for use with pulsed source, time-of-flight experiments. The use of high resolution techniques relevant to spin assignments and the systematic behavior of capture resonances will also be discussed.

II. Direct Detection Methods

The capture of neutrons in non-fissile targets is followed by the emission of electromagnetic radiation to states of the product nucleus. The spectral character of this radiation is quite complex. From first order perturbation theory, the electric dipole portion of a multipole expansion of this radiation may be expressed as a width amplitude in the following terms:

\[ \gamma = \frac{16 \pi}{9} \cdot \frac{1}{\sqrt{\gamma}} \cdot \left( \frac{\mathcal{G}}{2} \right)^{\frac{1}{2}} \cdot \gamma \]

The complexity of the resonance wave function \( \psi \) leads to a distribution of \( \gamma \) which is approximately Gaussian. The widths follow therefore approximately a chi-square distribution with one degree of freedom, similar to the distribution law for neutron widths. The angular momentum selection rules introduce an addition variability. The spectra from resonance to resonance display marked differences because of these factors, as is illustrated in Fig. 1 showing the spectra from the first three resonances of a typical heavy odd-A target, \(^{173}\text{Yb}\).

The primary transition is followed by a cascade of secondary radiation leading ultimately to the ground state. In a heavy nucleus a γ-ray multiplicity of three to four is typical.

![Fig. 1. Examples of high resolution γ-ray spectra recorded from several resonances of \(^{173}\text{Yb}\).](image)

An ideal direct detection technique must exhibit an insensitivity to the spectral variability. This insensitivity can be accomplished by several means, which we shall discuss in some detail. We note that any γ-cascade proceeding from the initial state must have the energies of the individual members sum to the available energy for the reaction:

\[ E_{\text{available}} = E_B + E_n \]

where: \( E_B \) is the neutron separation energy (usually 5-8 MeV) and \( E_n \) the center of mass energy for the incident neutron.

The two major detection techniques most commonly employed are the "total absorption" and the "Moxon-Rae" types.

A. Total Absorption Detection

The principle of this method is simple: one collects, as far as practical, all of the prompt γ-rays following capture to produce a single pulse, one for each capture event. This is accomplished by making the detector subtend 4π solid angle and large enough so that all the γ-rays in the de-excitation cascade are absorbed in the detector. In practice this ideal is never achieved, since a γ-ray of 8 MeV has an absorption mean length of about 41 cm in a liquid scintillator. Fortunately γ-ray multiplicities usually range between 3 and 4 photons per capture, and a liquid scintillation tank of about 1 meter in diameter is practical to construct with efficiencies of 50% or more.
Liquid scintillator tanks of this size range are in operation at many laboratories. An example which serves to illustrate many of the features of such devices is a detector used at ORELA called "ORELAST", shown in Fig. 2. ORELAST is 1.56 meters in diameter and contains 3000 liters of NL-224 (1,2,4 trimethyl benzene) poisoned with trimethylborate to inhibit neutron capture by hydrogen. The tank is viewed by 32 5-inch phototubes and is coated with an epoxy-based titanium-oxide reflector. The detector is pierced by a 7 inch diameter through-tube fabricated from 0.015 inch aluminum and it contains a 5 foot liner of 6LiH, 2.5 cm thick. Such a detector has a good signal to noise ratio. Figure 3 shows the observed count rates from the ORELAST from a 25 mil thick 238U sample. The tank can be subdivided for coincidence operation; the upper curve represents events detected in one of the two halves of the tank, the bottom curve is the coincidence rate. The improvement in signal to noise ratio is about 5 for coincidence operation.

Modern capture tanks are relatively fast in response. The time resolution of ORELAST is about 5.7 ns, which is now typical for tank operation. Due to the large size of the capture tank detector, however, a large background, typically several hundred counts/sec, exists with a bias of from 1-2 MeV applied to the tank. The total tank efficiency may be written as the product of two factors:

$$\epsilon = \epsilon_c \epsilon_b,$$

where $\epsilon_c$ is the cascade efficiency and $\epsilon_b$ is the spectrum fraction determined by the detection bias level.

Block and Hockenbury have calculated the cascade efficiency for a 1.25 meter diameter tank for cascades of γ-rays from medium-A nuclides, based on known thermal capture spectra. The efficiencies they deduce range from 0.85 ± 0.02 (for 60Ni, $E_g = 7.82$ MeV) to 0.98 ± 0.01 (for 50Cr, $E_g = 9.27$ MeV). The variation is evidently caused by the differences in spectra for these nuclides. The spectrum fraction $\epsilon_b$ can be estimated from extrapolation below the lowest possible bias which can be set—usually 0.5 MeV. Typical tank operation under running conditions, however, requires a bias level of about 2 MeV, at which the spectrum fraction is typically 70%. The estimated error of the extrapolation process is about 5% in the overall efficiency. The low energy bias of the tank is not altogether a disadvantage. It can be used effectively to suppress γ-rays due to inelastic neutron scattering.

Because of their large volume and high detection efficiency, capture tanks are sensitive to a number of background sources. Most of these backgrounds are in principle capable of subtraction. Table I, taken from a report of the Karlsruhe group, by Spencer and Beer lists the various types of background encountered.

<table>
<thead>
<tr>
<th>Source</th>
<th>Time Dependent</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Tube Noise and Natural Radioactivity</td>
<td>No</td>
</tr>
<tr>
<td>(2) Sample Activation</td>
<td>No</td>
</tr>
<tr>
<td>(3) Accelerator Room Background</td>
<td>No</td>
</tr>
<tr>
<td>(4) Capture in Sample Holder</td>
<td>Yes</td>
</tr>
<tr>
<td>(5) Scattered neutrons moderated in tank and captured in tank or sample</td>
<td>No</td>
</tr>
<tr>
<td>(6) Overlap Neutrons</td>
<td>Yes</td>
</tr>
<tr>
<td>(7) Sample-scattered neutrons promptly captured in the tank</td>
<td>Yes</td>
</tr>
<tr>
<td>(8) Rescattered neutrons captured in sample</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Most of these backgrounds are determinable by either 1) use of resonance "notched" filters introduced in the beam, which remove all neutrons whose energies are properly related to time-of-flight in a pulsed neutron experiment, or 2) by background runs with dummy samples. The use of a 6Li or equivalent liner is important in preventing scattered neutrons from entering the tank, or being rescattered to the sample. The suppression of the last two types of the table, (7) and (8) is particularly important, as they are not susceptible to correction by the notched-filter technique. Hockenbury has estimated the sensitivity of the 1.25 meter RPI tank to scattered neutrons at less than $10^{-5}$ at 80 keV. The Karlsruhe group has likewise estimated a sensitivity of 2 to 3 parts in $10^{-5}$ at 300 to 500 keV. It is especially important to ensure a low prompt neutron sensitivity in view of the large scattering to
capture ratio at higher neutron energies. An example of the need to suppress this kind of background arises in the interesting correlations between total radiation widths and capture widths that have been reported by the RPI group. These correlations are important to establish because of their implications for nuclear reaction theory and for the prediction of average capture cross sections.

Multiple scattering corrections in the sample yield are readily calculable with modern high-speed computing techniques, and they are discussed in a later section.

B. Moxon-Rae Detectors

For many applications the large size, high background, and timing abilities of the scintillation tank detectors are disadvantages. The Moxon-Rae detector was developed to overcome these deficiencies, providing a small detector with good timing at the expense of detector efficiency, which is reduced to a few percent, compared to the 70% of the tank detector.

The idea is to construct a detector whose efficiency is proportional to photon energy. If the detector subtends a reasonably small solid angle at the sample position, the probability of detection of more than one member of the photon cascade is small and thus to a good approximation,

\[ e \propto \sum_{i=1}^{V} E_{\gamma i}; e_i = kE_{\gamma i} \]

\[ e \propto \sum_{i=1}^{V} E_{\gamma i} = kE_{\text{total}} \]

The detection efficiency is thus independent of the \( \gamma \)-ray cascade and dependent only on the total energy available in the reaction.

The idea developed by Moxon and Rae is shown schematically in Fig. 4. The photons from the capture sample are transformed to electrons by a graphite converter surrounding the sample. The emergent electrons are converted to light in thin sheets of plastic scintillator attached to photomultipliers. Since the electron range increases roughly linearly with photon energy, the number of electrons emerging from the graphite converter surface is approximately proportional to photon energy; hence detector efficiency is also proportional to photon energy.

The constant of proportionality relating efficiency to photon energy has been studied by a number of experimenters; the most recent work is that of Iyengar, Tal and Jhingan shown in Fig. 5. These data show the typical behavior of \( k \): it rises rapidly from zero to a relatively constant value from below 1 MeV up to 12 MeV. The overall efficiency of the converter increases with Z; high Z elements tend to reach a plateau value at quite low values of energy and to rise slowly with energy, while low Z values reach a maximum near 2 MeV and then fall off with increasing energy. The data suggest that the addition of a material such as B\( _{2}\)O\( _{3}\) to the carbon converter should give an optimum response function; in practice about 9% (atomic) of the converter is bismuth.

The Moxon-Rae detector, while offering efficiencies of only a few percent is simple to construct and fast in response. It can be operated at relatively low bias levels at reasonable background rates. Because of these virtues it has been used extensively at time-of-flight facilities for capture measurements.

A higher-efficiency version of this detector type has been developed by Weigmann, Carraro and Bockhoff at Geel. The device is shown schematically in Fig. 6. It consists of a series of thick plastic scintillators arrayed in a sandwich whose layers are alternately viewed by a pair of photomultipliers. A coincidence requirement on the phototubes requires the converted electron to travel in at least 2 scintillators, thus providing the essential property of the Moxon-Rae detector. A boron-loaded plastic sheet between scintillation elements reduces the effect of proton capture of neutrons. The advantage

![Fig. 5. The Moxon-Rae efficiency per unit photon efficiency, \( k \), for a number of converter materials (ref. 8).](image)

![Fig. 4. A schematic view of the Moxon-Rae detector and its response to photons of different energies.](image)
of this detector is that it offers high efficiency--
10% at 8 MeV--in a relatively small and simple
detector.

![Diagram of detector]

Fig. 6. The high efficiency Moxon-Rae detector
developed at Geel.

An elegant generalization of the Moxon-Rae de-
tector has been developed by Macklin and Gibbons,
based on a suggested attributed to Maier-Leibnitz. 11
The detector output is multiplied by a weighting factor,
calculated to transform the response of an arbitrary
detector--in practice a plastic scintillator--so that
the energy proportionality is achieved. If the
response function giving a pulse height within the
range $E$ and $E+dE$ is $P(E)dE$, this condition calls for
a weighting function $w$ satisfying the following
relation:

$$
\int w(E)P(E)dE = E.
$$

The pulse height distributions to be expected
from an incident photon of energy $E_{\gamma}$ were calculated
by Macklin and Gibbons 12 for right circular cylinders
of plastic and liquid scintillators for
energies up to 10 MeV in 50 keV steps. The inter-
action is dominated by Compton scattering, but the
small pair production cross section and the resulting
Compton interactions of the annihilation quanta were
included, as were the various wall effects. The
weight function is conveniently introduced by digital
computer processing of the raw spectrum. Macklin has
used this method in conjunction with a liquid sci-
tillator, NE-226, based on hexafluorobenzene, ($\rho=1.6$)
which is relatively insensitive to fast neutrons.
Figure 7 shows the two fluorocarbon scintillators,
4 cm thick by 10 cm diameter, mounted on 5-in photo-
tubes. The overall efficiency, at a bias level of
150 keV is about 15% per capture and the time reso-
lution is less than two nanoseconds. A multi-
parameter detection scheme is used, and a detector
file is incremented at each event; the increment
being determined by the weight function.

![Diagram of fluorocarbon detector]

Fig. 7. The fluorocarbon detector developed at ORNL.

It is interesting to note, however, the relative
insensitivity of the measured capture cross sections
to the form of the weighting function used in this
type of detector. This relative insensitivity partly
results from the use of a $\gamma$-detector with no full
energy peak. Figure 8 shows the experimental results
from the average pulse height weighting factor as a
function of neutron energy for indium and tantalum.

Fig. 8. The average weighting factor of the Macklin-
Gibbons detector as a function of neutron energy for
indium and tantalum (ref. 11).

Shown is the ratio of the weighted counts to those
for the unweighted spectrum, with an electronic bias
corresponding to 40 keV. As the neutron energy in-
creases, the capture process changes from predominant-
ly $S$-wave to predominantly $P$ and $D$-wave, with corres-
ponding parity reversals and spin changes for the
compound levels. From these data there is observed
little effect from the use of a weighting function,
even though there must be a considerable change in
at least the initial portions of the $\gamma$-cascades
resulting from capture. Another point of interest
is the behavior of the average weighting function
with neutron binding energy, Fig. 9. Above 7 MeV,
the plateau of Fig. 9 implies a multiplicity apparent-
ly proportional to total cascade energy; below 7 MeV
the linear rise is what is expected if the multi-
plicity is constant, leading to an average photon
energy proportional to total energy release.

The low bias achievable in this method makes it
sensitive (and thus useful) for inelastic neutron
$\gamma$-ray detection. In this case some attention must
be paid to the anisotropic character of the radiation.
For multipoles up to $l=2$, or quadrupole
\[ \Psi(\theta) = 1 + aP_2(\cos\theta) + bP_4(\cos\theta). \]

Note that $P_2$ is a function of $\cos^2\theta$; at $\theta = 90^\circ$ this approaches a minimum. Figure 10 shows that for volumes exceeding 46 liters, the $P_2$ correction can be made zero, and the $P_4$ corrections are relatively small ($\approx 5\%$). While the use of hydrogenous scintillators is unacceptable because of their neutron sensitivity, deuterated liquid scintillators offer somewhat lower neutron sensitivity than do fluorocarbons, to improve light collection and to reduce pulse height dependence on source position.

### III. Analysis of Capture Yields

The extraction of cross sections and resonance parameters from capture yields is appreciably more complicated than the corresponding analysis of total cross section data. The relation between yields and cross sections may be written, ignoring resolution corrections:

\[ Y(E_n) = \left[ \sum_{\Delta E} \left( \sigma_{\Delta E}(E_n) / \sigma_{\Delta E} \right) dE_n \right] \times \left( 1 + \frac{f_m}{\epsilon} \right) / \epsilon \]

where $\sigma_{\Delta E}$, $\sigma_{\Delta Y}$ are the total and partial Doppler-broadened cross sections and $f_m$ the multiple scattering and self absorption corrections, $\epsilon$ the detection efficiency.

In the thin sample approximation, for $l=0$:

\[ Y_0 \epsilon(E_n) = A_0 = 2\pi \lambda^2 g \Gamma_0 \epsilon \Gamma / \Gamma. \]

The principal problems encountered in reducing yields to cross section information is the determination of the flux $\Psi$, the detector efficiency $\epsilon$, and especially where $\Gamma_n \gg \Gamma_y$, the correction for multiple scattered neutrons. At low energies, where on an isolated resonance $\Gamma_y \gg \Gamma_n$, a thick sample will show a saturated count rate at the resonance maximum. The saturated level fixes the product $\epsilon \Psi$, and it remains only to establish the energy variation of $\Psi$ (and possibly $\epsilon$) over the energy range of the experiment. This is conventionally done with a beam monitor, usually $^6$Li$(n,\alpha)$, $^{10}$B$(n,\alpha)$ or a hydrogen recoil counter.

Figure 11 illustrates the normalization technique using the saturated resonance method as applied by de Saussure, et al. at Oak Ridge. The data are compared to the ENDF/B-III resonance parameters for the $^{238}$U $6.67$ eV resonance. deSaussure estimates that the normalization error in this instance can be no larger than $2\%$.
The multiple scattering term, $f_m$, can be expanded in terms of orders ranging from single up to several scatterings before capture. The terms are complicated functions of resonance parameters and sample geometry, particularly at higher energies, where the loss of energy upon scattering can be larger than the resonance width. They can be adequately treated only by extensive Monte Carlo computations. Fortunately several reliable codes are available and in common use among various experimental laboratories.

Closed-form analytical expressions have been developed at BNL,14 and San Diego,15 which solve the multiple scattering corrections to second order for the near thermal region ($c_p > c_q$) and for infinite slab geometry. For the resolved resonance region, codes have been developed at BNL,16 San Diego,17 RPI,18 and Harwell,19 and those codes have been interchanged and checked for reliability. In the unresolved resonance region, one must have recourse to statistical simulations of the cross sections underlying the unresolved structure region, using the Wigner level distributions and the Porter-Thomas width distribution. Bogart20 has discussed the effect of these calculations on spherical shell transmission results, while Frohner21 has applied these ideas to capture cross sections derived from white-source time-of-flight measurements. These corrections allow reasonable accuracies of about 1% in the resolved resonance region and 2 to 3% in the unresolved region.

IV. Supplementary Capture Techniques

Certain capture techniques are useful only for specific nuclides for selected energy regions using steady state neutron sources, or in specialized circumstances. They are important, however, in establishing useful normalization points or standards for the direct methods.

Indirect methods of high precision and sensitivity are the "danger coefficient" and "pile oscillator" techniques.22 These methods refer to the effects on reactivity by introducing an absorber into a critical assembly. In the latter case, the sample is introduced periodically to improve sensitivity and to reduce the effects of secular reactivity variations due to barometric changes. Mass spectrometry has also been employed to deduce the number of neutrons occurring in a sample placed in a high reactor flux. These methods suffer from the heterogeneous nature of the energy distribution of a reactor flux, and are not discussed further here.

A. Spherical Shell Transmission

An absolute method of absorption cross section is afforded by the spherical shell transmission technique.22 The sample is arranged in a shell around either the source or detector and the number of neutrons reaching the detector is recorded by an energy insensitive neutron detector. In this geometry in-scattering exactly compensates out-scattering and only absorption is measured. In principle the method is absolute; no knowledge of neutron source strength or detector efficiency is needed, and in this regard it is analogous to a transmission measurement taken in a geometry where scattering events do not contribute.

It is of course impractical to use and construct spherical shells from most materials and for most neutron sources; they have been most often used with antimony-beryllium sources. Furthermore, in practice it has been shown that multiple scattering effects and self-shielding effects related to resonance structure introduce sizeable correction factors in sphere data.

Frohner21 has reanalyzed shell transmission data to take account of resonance structure in a Monte Carlo approximation. The value for $\sigma_0$ on gold at 24 keV reported by Schmidt and Cook23 was changed from 532 ± 60 mb to 650 ± 35 mb when structural effects were included. This example demonstrates that the precision of shell transmission results is not so high as formerly believed. Nevertheless the method provides an alternate measurement of capture free of questions of source strength or detector efficiency.

B. Activation

Some nuclides, after neutron absorption, produce daughters which decay subsequently by $\beta$-emission with characteristic half lives. The $\beta$ or $\gamma$ radiation accompanying this decay can be counted either during or after irradiation and the intensity may be rated to the number of captures through knowledge of the decay scheme and half lives. By using modern high-resolution solid state detectors, the characteristic radiations can usually be easily reported and recorded, even for isotopic mixtures. Efficiencies and source strengths are such that relatively thin samples requiring only modest corrections for $\gamma$ ray and neutron absorptions (1 to 10%) are useful.

This method may be applied with a well known standard so that flux and efficiency corrections need not be known. An example is that of Fig. 12, showing the 12 keV $\gamma$-ray (the $2^n - 0^n$ transition in $^{198}$Au) following the 2.7 day beta decay of $^{198}$Au, and the 417 keV $\gamma$-ray (a $4^n - 2^n$ transition in $^{116}$In). These spectra were obtained by activating gold and indium with the 24.3 keV neutron beam produced through an iron filter at the BNL High Flux Reactor.24

![Fig. 12. Gamma decays from gold and indium foils after activation with 24.3 keV neutrons from an iron filter in HFBR.](image)

Only the relative detector efficiency between 417 and 412 keV need be known, with appropriate branching ratios, half lives and small corrections for sample absorption effects, to deduce the cross section ratio between indium and gold. An alternate technique involves comparison between a measurement at thermal and the energy in question. This requires a knowledge of the thermal cross sections for the standard and the sample, but avoids knowledge of flux and efficiencies.

In any activation measurements it is essential...
to know the energy distributions of the incident neutron flux, and, in particular, to guard against the interaction of neutrons degraded in energy by scattering processes. The ratio of cross sections, for a straight $1/\nu$ absorber, is 1000 between thermal and 25 keV, for example, and in many cases the thermal region is dominated by a resonance leading to cross sections even higher. The historical tendency of activation cross sections to decrease as measurements are made with improved sources and techniques testifies to the influence of this effect. However, at high neutron energies (> 1 MeV) and for small cross sections, the activation method is extremely effective. The specific nature of the activity discriminates against inelastic scattering competition, and the activity can be counted under conditions of low background.

It is only recently, however, that MeV activation cross section measurements have properly taken account of the influences of secondary and degraded neutrons on the sample. Kantele and Valkonen have pointed out the influence of secondary neutrons produced in the tritium target head for 14 MeV activation work, and they have stressed the importance of extrapolating to zero sample thickness to provide reliable cross sections. Following this work, Rigaud, et al., 26 did systematic studies of capture at 16 MeV on 51y, 103Rh, 127I, and 139La. They show that the apparent cross sections depend largely on the geometry, and the mass and material of the target heads. Cross sections ranging from 2 to 7 mb for 127I and from 0.5 to 1 mb for 103Rh, for example, were obtained by variations in the above parameters with resulting modification of the secondary neutron spectra. The apparent cross section increases as the mass of the target backing material increases, for nuclides far from magic neutron numbers. Rigaud, et al. conclude that even with the use of an AF target backing, corrections of up to 50% for 103Rh were necessary. The results of their studies (Fig. 13) allow Rigaud to conclude that (n,\gamma) cross sections near 1 MeV are in the range 1.0 ± 0.5 mb, independent of neutron number, in contrast to previous measurements (triangles in Fig. 13), which gave up to 20 mb from samples away from magic neutron numbers. Vuletin, Kullas, and Cindro have confirmed the importance of secondary neutron reactions such as (n,2n) in activation studies, and they have shown that with proper corrections, the long-standing discrepancy between activation results and those obtained by direct integration of unfolded spectra for plastic activation electron pair detectors is removed. These recent measurements have eliminated the disagreement between the observed cross sections and those predicted by the Clement, Lane, and Rook model of semi-direct capture in the 14 MeV region, as indicated in Fig. 13.

### V. High Resolution Capture Studies

The study of electromagnetic transitions to individual final states has given us much detailed information on the nuclear structure of nuclides formed in the (n,\gamma) reaction, and on the nature of the (n,\gamma) reaction mechanism. This area is beyond the scope of the present review. High resolution techniques, however, can be interpreted also to provide information about individual capture states, such as their spins and parities, and on their average properties such as strength functions and level spacings. Those aspects are of direct interest to the applications of capture cross sections.

In a number of cases, especially in light nuclides with well known level schemes mapped out in excitation up to the region of the neutron binding energy, it is possible to integrate partial cross sections directly to obtain the total capture. At Los Alamos, for example, Jurney has used the Omega West thermal capture \gamma-ray facility with a detector consisting of a Ge(Li) detector and an optically divided NaI annulus to measure partial cross sections. The annulus is operated in an anti-coincidence mode for Compton suppression up to 3 MeV \gamma-energy, and in a pair spectrometer mode in the 2-7 MeV range. Normalization is provided by observing the 2.2 MeV hydrogen capture line. Cross sections for additive capture by \(^{16}\)O, \(^{6}\)Li and \(^{7}\)Li have been derived with quoted accuracies of about 10%.

The selection rules for electromagnetic transitions have long been used to establish resonance spins, and this technique is straightforwardly applied to high-energy primary \gamma rays populating states of known spin. Significant information is also available in the low energy portion of the \gamma-spectrum.

It has long been established that the population of low-lying states by \gamma-ray cascades following capture shows a strong spin dependence. Following a suggestion by Hulsenga and Vandenbosch, and elaborated by Poonitz, a plausible explanation for this spin dependence can be based on the argument that the population of final states depends simply on the number of possible routes available for \gamma-cascades of a given multipole order and multiplicity to reach a given final state. The subsequent decay rate of the state is then largely a function of the difference in spins between the compound nucleus capturing state and the level in question. For a large difference the effect is large, since for a given cascade multiplicity, the number of possible de-excitation sequences decreases rapidly with the net spin change between initial and final states. For the assignment of resonance spins, it is apparent that absolute decay rates need not be measured; it suffices to examine the ratios of decay rates of final states with known spin, since the ratios are highly spin dependent.

The technique has been exploited as a simple and effective method of resonance spin determinations, Corvi, Stefanon, Cöcev, and Glachobbe et Geel have demonstrated this most remarkably in a measurement on the spin of \(^{235}\)U. They studied the de-excitation of the 6° member (160.6 keV) of the \gamma rotational band compared to the de-excitation of the 2° level at
687 keV, which emits a 642 keV γ-ray to the first excited state. Although several fission and background lines lie near the 160.6 keV peak, Fig. 15 shows a varying ratio for the 160.6 line compared to the 642 keV monitor line, depending on resonance spin. As expected the 6® level is more heavily populated for the J=4 resonance. The 16 resonant spins assigned by Corvi et al. were later confirmed by a much more elaborate polarized neutron experiment carried on by Keyworth et al. at Oak Ridge.

Recently similar methods have been extended to the unresolved resonance region. Of particular interest in this regard is the question of possible intermediate structure in the neutron strength functions in the various channel spin states. A novel method using these high resolution methods has recently been used by Coceva and his collaborators at Geel.

Consider two low-lying levels a and b, with \( J_a \geq I + 1/2 \) and \( J_b \leq I - 1/2 \), where I is the target spin. Let \( \sigma^+ \) be the probability that a γ-cascade from an \( I+1/2 \) level populates a, \( \sigma^- \) be the probability of population from an \( I-1/2 \) state, and similarly for \( \sigma_b \). Further define \( R^+ = \sigma_a^+ / \sigma_b^- \), \( R^- = \sigma_a^- / \sigma_b^+ \), and \( R_b = \sigma_b^- / \sigma_b^+ \) (Fig. 16). The average ratio, in a given interval containing many resonances, between the populations of levels a and b can be related to the \( I+1/2 \) and \( I-1/2 \) capture rates by

\[
X = \frac{R^-}{R_b} \frac{R^+}{R_b}
\]

where \( X = \sigma(I+1/2) / \sigma(I-1/2) \).

The values of \( R_b \), \( R^+ \) and \( R^- \) are determined from isolated resonances. From X one can thus derive the spin dependent strength functions \( S^+_\sigma \) and \( S^-\sigma \).

**Fig. 15.** Portions of the low-energy γ-ray spectra following neutron capture in \(^{235}\text{U}\). The de-excitation of the 6® member of the g.s. rotational band results in a peak at 160.6 keV.

**Fig. 17.** The population ratios for spin 5 levels (at 330 and 348 keV) and spin 3 levels (at 171 and 482 keV) in \(^{166}\text{Ho}\).
Measurements of high energy primary transitions can be used to determine level density parameters, such as the spin cut-off parameter $\sigma$:

$$\sigma(J) = (2J+1) \exp\left[- (J+\frac{1}{2})^2 / \sigma^2 \right].$$

A direct way to determine $\sigma$ is to deduce it from $D(I+1/2)$ and $D(I-1/2)$ by simply counting levels. An alternate way, which is insensitive to missed levels, is to make use of the expectation that the photon strength function is spin independent:

$$S_J = \frac{\Gamma_{\gamma J}(J)}{\Gamma_{\gamma J}(J)} = \frac{\Gamma_{\gamma I}(I+1/2)}{\Gamma_{\gamma I}(I-1/2)} \approx \frac{D(I+1/2)}{D(I-1/2)}.$$

Coceva has tested this method for 30 resonances in $^{115}$In, 16 $^{114}$In and 16 $^{115}$In, and for $\gamma$-rays to 41 low-lying states of $^{116}$In. The results were averaged separately for $E1$ and $M1$ transitions and are summarized in Table II.

<table>
<thead>
<tr>
<th>$\sigma$</th>
<th>$\frac{S_0^+}{S_0^-}$</th>
<th>$\frac{\Gamma_{\gamma I}(I+1/2)}{\Gamma_{\gamma I}(I-1/2)}$</th>
<th>$D(I+1/2)/D(I-1/2)$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.80</td>
</tr>
</tbody>
</table>

From this table a value of $3.6 \pm 0.4$ is deduced, which is in good agreement with typical values for $A \geq 100$ as obtained from direct spacing measurements.

From the several illustrations given above it can be seen that high-resolution $\gamma$-ray spectroscopy is capable of providing useful supplementary information for interpreting capture cross section measurements.

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References

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