Essentially monoenergetic neutrons with keV energies can be obtained from a reactor by using suitable filters. To date, prompt γ-ray spectra have been measured using 24-, 2-, and 1-keV neutrons, obtained through Fe+Al+S, Sc+Ti and $^6$Li filters, respectively. Two features of these data are of note to reactor shielding. First, the radiative capture spectra from higher Z nuclei usually result from an average over many resonance states. Hence statistical fluctuations in the primary γ-ray intensities, to which the corresponding thermal neutron capture spectra are subject, are averaged out. Second, such data provide information on the dependence of radiative capture spectra on neutron energy. The data shows that at 24 keV there is a significant p-wave contribution to these spectra, even for those mass regions where the ratio of the p-to-s wave strength function is close to a minimum. This occurs because the smallness of the relative penetrability at 24 keV, 0.04<(kR)2<0.08 for 100<A<240, is compensated for by the branching ratio Γp/Γ which is now much larger for p-wave than for s-wave resonances.

\[ \Gamma(\gamma) \propto \frac{1}{E} \exp\left(-kR\sqrt{E}\right) \]

(1)

where \( k \) is a constant. A $^6$Li filter whose thickness is such as to peak the neutron energy distribution at 1 keV has been installed in the HI channel of the High Flux Beam Reactor at Brookhaven National Laboratory. The flux properties of this facility are summarized in Table 1. As can be seen from this table a major disadvantage of this type of filter is that there also exists an appreciable flux distribution of 2 keV background neutrons. This, of course, is to be expected since in eq. 1 when \( E \gg k^2 \), \( \Gamma(\gamma) \propto 1/E^2 \) that is, identical to the unfiltered neutron energy distribution. In practical terms, since the external beam contains a large flux of high energy neutrons, for which the \( Ge(Li) \gamma \)-ray detector from, and appreciable radiation damage of the \( Ge(Li) \gamma \)-ray detector can occur.

A recently developed, and for most applications a more satisfactory, method of obtaining external beams of keV-energy neutrons from a reactor is to use thick filters of materials which have "deep" interference minima in their total neutron interaction cross sections. By use of suitable combinations of two or more different materials in the filter it is usually possible to suppress the transmission of neutrons with energies corresponding to all but one of these minima.

In this manner an intense beam of essentially monoenergetic neutrons, with energies corresponding to that of the selected transmission minima is obtained. In the first such facility developed, a beam of 1.95 keV neutrons was obtained through a thick Sc filter located in a beam channel of the Materials Testing Reactor.

![Image of Table 1](https://example.com/table1.jpg)

**TABLE 1. Filter Parameters. Fluxes and backgrounds for filter combinations available at the Tailored-Beam Facility.**

<table>
<thead>
<tr>
<th>Filter</th>
<th>Available Flux (n/cm²/sec)</th>
<th>Thermal Background (n/cm²/sec)</th>
<th>Eγ (n/cm²/sec)</th>
<th>γ's (mr/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}$Fe</td>
<td>$1.0 \times 10^6$</td>
<td>300</td>
<td>$1.4 \times 10^3$</td>
<td>6</td>
</tr>
<tr>
<td>$^5$Al</td>
<td>$3.56 \times 10^6$</td>
<td>$5 \times 10^6$</td>
<td>500</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>$^5$S</td>
<td>$1.2 \times 10^6$</td>
<td>$5 \times 10^6$</td>
<td>500</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>$^{38}$Co</td>
<td>$1.5 \times 10^6$</td>
<td>$5 \times 10^6$</td>
<td>500</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>$^{105}$Pb</td>
<td>$1.0 \times 10^6$</td>
<td>$5 \times 10^6$</td>
<td>500</td>
<td>$3 \times 10^6$</td>
</tr>
</tbody>
</table>

In order to assess γ-ray production in a fast reactor, and thereby estimate the shielding requirements, it is necessary to know how the prompt γ-ray spectrum varies with neutron capture energy. These prompt capture γ-rays will constitute much of the "hard" component of the reactor photon spectrum and will therefore have the most stringent shielding requirements. Reliable prediction of the neutron energy dependence of the capture γ-ray spectrum requires an understanding of the reaction mechanisms involved. Of crucial importance are (1) the magnitude of the contributions from neutron capture with 1, 0, and (2) whether there are appreciable departures from the statistical model of compound nucleus states. Either of these effects can significantly alter the photon spectrum from that obtained from thermal neutron capture.

Nuclear research reactors can be used as a source of keV neutrons, with sufficient intensities to allow detailed studies of reaction mechanisms over a wide range of neutron energies. The simplest experimental scheme for doing this is to insert a thick filter of a material having a 1/v neutron cross section dependence on neutron energy. The data shows that at 24 keV there is a significant p-wave contribution to these spectra, even for those mass regions where the ratio of the p-to-s wave strength function is close to a minimum. This occurs because the smallness of the relative penetrability at 24 keV, 0.04<(kR)2<0.08 for 100<A<240, is compensated for by the branching ratio Γp/Γ which is now much larger for p-wave than for s-wave resonances.

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A recently developed, and for most applications a more satisfactory, method of obtaining external beams of keV-energy neutrons from a reactor is to use thick filters of materials which have "deep" interference minima in their total neutron interaction cross sections. By use of suitable combinations of two or more different materials in the filter it is usually possible to suppress the transmission of neutrons with energies corresponding to all but one of these minima.

In this manner an intense beam of essentially monoenergetic neutrons, with energies corresponding to that of the selected transmission minima is obtained. In the first such facility developed, a beam of 1.95 keV neutrons was obtained through a thick Sc filter located in a beam channel of the Materials Testing Reactor. The use of this facility for neutron capture γ-ray spectroscopy has been described in ref. 3. Subsequently, a 24 keV neutron beam was developed on the MTR using a filter combination of Fe+Al+Sc. A versatile 24-keV filtered neutron beam facility, in which varying lengths of Fe and Al can be used, has subsequently been installed in the HI channel of the HFBR.

![Image of Figure 1](https://example.com/figure1.jpg)

**Figure 1** shows the 24-keV flux profile for two filter combinations containing 9- and 27-in of Fe.
NEUTRON FLUX FOR FILTERED BEAM

Thus, the 24-keV neutron energy distribution will have a FWHM of 1.1-2.0 keV depending upon the thickness of the Fe in the filter. The purity of the 24-keV neutron beam has been measured with a hydrogen-filled proportional counter. Neutron spectra were obtained from these data by differentiation, using a code developed by Bennett, et al. An example of these data is given in Fig. 2, which illustrates the effectiveness of the Al in reducing the leakage through the higher energy Fe "windows." For the 9-in Fe plus 14-in Al filter the higher energy neutron components are < 0.1% of the 24-keV neutron flux. The background from thermal neutrons and reactor-produced γ rays are also low, as can be seen from Table 1.

Advantages of filtered neutron beams from reactor sources for studying neutron capture reaction mechanisms in the keV-neutron region can briefly be summarized as:

1. There are several neutron energies which are available using filtered neutron beams.
2. High fluxes (> 10^6 neutrons/cm^2-sec) of essentially monoenergetic neutrons can be obtained.
3. Because of the finite energy spread inherent in the filtered neutrons, the primary capture γ-ray transitions (i.e., those de-exciting the capturing state) generally result from the decay of many compound nucleus states, and the normal statistical fluctuations in their intensities tend to be averaged out.
4. The resultant energy shift of the primary γ-ray transitions compared to the energies measured in thermal-neutron capture provide a unique discrimination between primary and secondary transitions.

An example of the significant variation in the capture spectra obtained with thermal, 1- and 24-keV neutrons is illustrated in Fig. 3 for Mn. The Fe-filter spectrum is dominated by the 23.7 keV resonance while the Al-filter spectrum is influenced by the 337-, 1098- and 2375-eV resonances.

Fig. 1. Calculated flux through Fe+Al+S filters containing 9- and 27-in Fe.

Fig. 2. Fast neutron spectra transmitted through Fe+Al+S filter arrangements as measured with a hydrogen-filled proportional counter. The two curves illustrate the effectiveness of Al in reducing the high-energy neutron components relative to that of the 24-keV neutron group.

Fig. 3. Manganese prompt γ-ray spectra from capture of thermal, 1- and 24-keV neutrons.

The 24-keV neutron beam facility has proven to be particularly valuable in assessing both, the importance of p-wave capture (compared to s-wave capture) in this
neutron energy region and, the changes in the photon spectrum which can be attributed to p-wave capture.
Initial measurements have centered on the Gd isotopes; principally because of the paucity of information on
the prompt γ rays resulting from neutron capture in the even-mass Gd isotopes, and some anticipated interesting nuclear structure effects to be found from these data. In this mass region the s-wave strength function is at near a maximum while the p-wave strength function is near a minimum. Even so, in the photon spectrum resulting from capture of 24-keV neutrons in $^{154}$Gd, which represents then an average over 130 resonance states thereby averaging out the statistical fluctuations in the primary γ-ray transition intensities, and which is shown in Fig. 4, final states with $I^\pi = 1/2^+$, $3/2^+$ and $5/2^+$ are populated with comparable intensities to those having $I^\pi = 1/2^-$ and $3/2^-$. (This is illustrated quantitatively in the plot of reduced transition intensities shown in Fig. 5.) This is in contrast to the situation expected for s-wave capture alone where the El transitions to negative parity states would be expected to have intensities 5-10 times greater than the M1 transitions to the positive parity states, and final states with $I^\pi = 5/2^-$ would be even more weakly populated. Thus we conclude that in $^{154}$Gd, $\ell=0$ and $\ell=1$ neutron capture are comparable at 24 keV. This observation is consistent with our expectation. Although the relative

![Gamma-Ray Energy (keV)](image1)

![Gamma-Ray Energy (keV)](image2)

**Fig. 5.** Plot of reduced transition intensities $(I_γE_γ)$ for primary γ rays from capture of 24-keV neutrons in $^{154}$Gd.

**Fig. 4.** High-energy portion of the spectrum of γ-rays from 24-keV neutron capture in $^{154}$Gd.
penetralities between $l=0$ and $l=1$ neutrons at 24 keV are only $0.04<(kR)^2<0.08$ for $100<A<240$, they are compensated somewhat by the branching ratio $\Gamma_y/\Gamma$ which is often much larger for $l=1$ resonances. The expression for the ratio of $p$- to $s$-wave capture, ignoring the fluctuation correlation factor is

$$\frac{\sigma_p}{\sigma_s} = \frac{3S_1}{S_0} \frac{\langle \sigma_p(\Omega) \rangle}{\langle \sigma_s(\Omega) \rangle} (kR)^2 \quad (2)$$

In the case of 24-keV neutron capture in $^{154}$Gd this ratio is $\sim 0.5$, assuming values of $S_0 = 2.0 \times 10^{-4}$ and $S_1 = 1.0 \times 10^{-4}$. In considering the relative $p$- to $s$-wave capture ratio as a function of neutron energy, $E_n$, we can note from eq. 2 that

$$\frac{\sigma_p}{\sigma_s} \propto E_n \quad \text{when} \quad \langle \sigma_p(\Omega) \rangle \ll \langle \sigma_s \rangle$$

and that

$$\frac{\sigma_p}{\sigma_s} \propto E_n^{3/2} \quad \text{when} \quad \langle \sigma_p(\Omega) \rangle \gg \langle \sigma_s \rangle.$$

A final example of the importance of $p$-wave capture at 24 keV is provided by the data on $^{156}$Gd(n,$\gamma$) reaction, where the photon spectra resulting from 1- and 24-keV neutron capture are compared in Fig. 6.

Using the above estimate for the relative $p$- to $s$-wave capture cross sections with values of $S_0 = 1.8 \times 10^{-6}$ and $S_1 = 1.0 \times 10^{-6}$ we calculate that $Q_1/Q_0$ are $\sim 1.0$ and $0.2$ for 24- and 1-keV neutron capture, respectively. The relative contribution of $p$-wave capture to the two spectra shown in Fig. 6 is dramatically illustrated by the 5297 keV peak which results from a primary transition to a final state in $^{157}$Gd having $I^\pi = 5/2^+$. The relative $p$- to $s$-wave capture ratio as a function of neutron energy, $E_n$, we can note from eq. 2 that

$$\frac{\langle \sigma_p(\Omega) \rangle}{\langle \sigma_s(\Omega) \rangle} \propto E_n \quad \text{when} \quad \langle \sigma_p(\Omega) \rangle \ll \langle \sigma_s \rangle$$

$$\frac{\langle \sigma_p(\Omega) \rangle}{\langle \sigma_s(\Omega) \rangle} \propto E_n^{3/2} \quad \text{when} \quad \langle \sigma_p(\Omega) \rangle \gg \langle \sigma_s \rangle.$$

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