Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research A 562 (2006) 401–406

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Generating a multi-line neutron beam using an electron Linac and a U-filter

R. Moreh[a,b,*], R.C. Block[b], Y. Danon[b]

[a]*Physics Department, Ben-Gurion University of the Negev, Beer-Sheva, Israel*
[b]*Gaerttner LINAC Laboratory, Rensselaer Polytechnic Institute, Troy, New York 12180, USA*

Received 3 January 2006; received in revised form 20 February 2006; accepted 21 February 2006
Available online 20 March 2006

Abstract

A neutron source having ~30 discrete energy lines in the range 34–6200 eV is produced by using a ^{238}U filter in conjunction with an electron linear accelerator. The characteristics of this neutron source are discussed and possible uses and applications are given.

PACS: 29.25.Dz; 29.30.Hs; 28.20.Cz

Keywords: Neutrons; Uranium filtered beams; monochromatic neutrons; Cross sections

1. Introduction

Pulsed neutron beams of discrete energies can be generated by using an electron linear accelerator in combination with a ^{238}U filter. Such beams have many interesting and useful characteristics when compared with the steady-state filtered neutron beams obtained using nuclear reactors [1–4]. The filter materials used in conjuction with nuclear reactors are scandium (producing 2.03 keV neutron beams with a width $\Delta E \sim 1.3$ keV), iron (for $E_n = 24.3$ keV, $\Delta E \sim 2.1$ keV), and silicon (for $E_n = 54$ keV, $\Delta E \sim 1.1$ keV and $E_n = 148$ keV, $\Delta E \sim 16$ keV). Other materials such as argon, sulfur, and chromium are also used as filters. Moreover, combinations of two or more materials were employed [1] for improving the purity and the monochromatic character of the resulting neutron beam. As an example, the addition of aluminum and sulfur to the iron filter reduces [1] the relative number of neutrons with energies higher than 24 keV. A review of filtered n–beam facilities was published by Block and Brugger [5].

Filtered beams were used for a variety of studies ranging from measurements of average total cross-section and average (n,γ) cross-sections [1], to applications in neutron radiography, radiobiological studies and cancer treatment [6].

The filter materials have narrow energy "windows" in their total cross-sections, which allow neutrons of specific energies to pass through while those with different energies are removed from the beam. These energy windows correspond to deep minima in the total neutron cross-section [7,8] in the nuclei of the filter and are created by the destructive interference between the nuclear resonance scattering of neutrons and potential scattering. The dips or minima in the total cross-sections are more pronounced in mono-isotopic filters with even–even nuclei. This is because the resonance levels formed by neutron capture in such nuclei have only a single channel spin and the destructive interference may cause a drastic reduction of the scattering cross-section. Iron is nearly mono-isotopic because ^{56}Fe has high natural abundance (91.8%) and has deep minima at several energies such as 24.3, 82.1, 137, 308, 642 and 938 keV.It was thus widely used in reactors as a filter for producing the 24.3 keV line. In effect, the iron filter converts a white neutron spectrum to a neutron beam with several discrete energies. Another example of an

*Corresponding author. Physics Department, Ben-Gurion University of the Negev, Beer-Sheva, Israel. Tel.: +972 8 6461569; fax: 972 6472810.
E-mail address: moreh@bgumail.bgu.ac.il (R. Moreh).

0168-9002/$ - see front matter
doi:10.1016/j.nima.2006.02.160

even–even nucleus which can be used as a neutron filter is depleted U (99.8% ^{238}U) as it is mono-isotopic and reveals a large number of deep minima in its total neutron cross-section [9]. In even–odd isotopes, e.g. ^{45}Sc or ^{51}V, more than a single channel spin is involved, and the destructive interference can occur only in one channel spin at a time. Hence the resulting interference effect is not as strong as in even–even mono-isotopic materials.

Most of the filtered n-beam facilities were installed in conjunction with nuclear reactors.

One important advantage in using neutron TOF beams having discrete energies is the high signal-to-noise ratio of each mono-energetic line, which enables one to perform n-scattering studies with better accuracy than that obtained with normal TOF measurements.

In the present work, we focus our attention on studying a ^{238}U filtered n-beam where the neutrons are generated using an electron linear accelerator. In all previous studies [7,8,10,11] involving electron Linacs, iron was used as a filter. The main advantage of using a Linac is the high neutron fluxes produced at higher energies. In addition, the pulsing makes it easy to measure the neutron energies via time of flight (TOF). Thus when using an iron filter, several discrete neutron energies are generated not only at 24.3 keV but also at much higher energies up to 982 keV. This is to be contrasted with the case of nuclear reactors where only the line at 24.3 keV can effectively be utilized. In fact, such a multi-line neutron source with an Fe filter in conjunction with an electron linear accelerator has already been used. A precise determination of the total neutron cross-section of hydrogen [8] and of deuterium [10,11] was made using this method. It was also employed to investigate the minima in the total cross-section of iron, yielding accurate values of the corresponding resonance parameters [7].

In the literature, the use of a U filter was proposed [12] in conjunction with a nuclear reactor. Some suggestions were also given about using secondary filters or arrays of filters and scatterers for producing a range of filtered beam energies. It was concluded that it is very difficult to produce pure quasi-monoenergetic beams (between 100 and 2541 eV) using a U filter except at 186 eV. Here the contamination was calculated to be around a few percent. In an earlier paper [13], however, the purity of the beam at 186 eV actually obtained using U in combination with secondary filters of Se, Mn, and Ge, was reported to be 70%.

In the present work, we describe an experimental facility based on a ^{238}U-filter in conjunction with the Gaerttner electron linear accelerator. It was installed at Rensselaer Polytechnic Institute and was employed for producing a multi-line neutron source in the range between 64 and 6165 eV. The applications of this source are described in detail below.

2. Experimental arrangement

The neutron source is generated by an electron linear accelerator via a two-step process. First, bremsstrahlung is produced by the electron beam striking a stack of ten water-cooled Ta plates (5 cm × 5 cm, with thicknesses ranging from 1.6 to 6.4 mm). Second, the neutrons are obtained by the ^{181}Ta(γ, n) reaction. The Ta plate thicknesses were chosen to produce approximately equal energy deposit in each plate to facilitate the water cooling. The total Ta thickness was chosen to maximize the neutron production and minimize neutron absorption. The electron energy was around 50 MeV and was produced by the Gaerttner Electron Linear Accelerator of the Rensselaer Polytechnic Institute (RPI), operated at a pulse repetition rate of 225 Hz. The obtainable electron current was 50 μA and the pulse width could be varied between 56 and 1000 ns. The neutron beam was then passed through stacked sheets of metallic ^{238}U (99.8%), 98 mm thick, which served as a neutron filter, producing several discrete neutron lines of high intensity in the energy range 34 eV to around 6.2 keV. The experimental arrangement is shown schematically in Fig. 1.

3. Direct beam

An important feature in the U-filtered beam discussed here is that most of the lines are highly mono-energetic with $dE/E \sim 10^{-3}$, which makes it an ideal choice for performing precise absorption and scattering measurements at discrete energies. The filter was placed at a distance of 15 m from the water-cooled Ta photo–neutron source, and the n-energies were determined by measuring the TOF along 25.5 m path. Fig. 2 shows the neutron TOF spectrum produced after passing through the 98 mm thick ^{238}U filter. In a sense, the U filter converts a white neutron spectrum to a multi-line spectrum with sharply defined energies. The apparent large width of the low-energy lines is created by the longer TOF of neutrons at such energies. Note the high monochromaticity of the strong intensity neutron lines obtained and the high signal-to-noise ratio. The notches appearing in some of the peaks are created by some weak s- and p-wave resonances, and by ^{235}U resonances. The energies of the ^{238}U-filtered neutron lines are listed in Table 1 together with relative intensities and line widths.

In carrying out the above measurement, no attempt was made to optimize the thickness of the U absorber. Since we

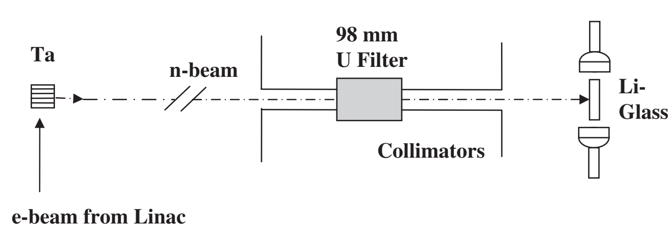

Fig. 1. Schematic view of the layout of the U-filter measurement. The Ta plates are water cooled and stacked within an aluminum container (1 mm thick). The distance between the Ta target and the Li-glass n-detector is 25.5 m.

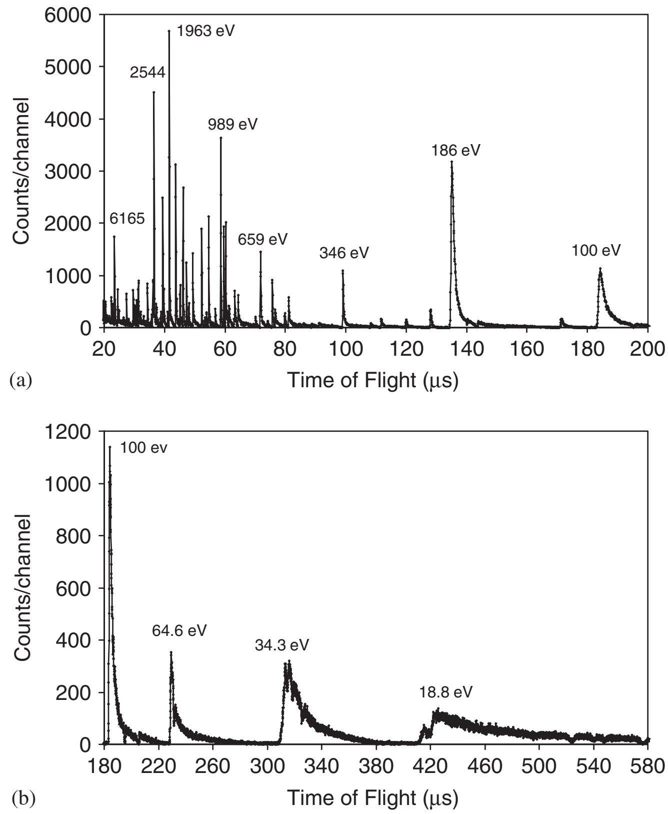

Fig. 2. (a). TOF spectrum of the direct beam of neutrons in the range 20–200 μs obtained by using a 98 mm ^{238}U filter (99.8%). The flight path is 25.5 m. Note that the energy peaks displayed here (in eV units) correspond to the minima in the ^{238}U total n-cross-section and not to peaks of the n-resonances of ^{238}U. The width of each time channel is 64 ns.The running time was 4 h. The notches in the lines are due to weak s- and p-wave resonances and ^{235}U resonances. (b) Same as (a) but for the time range 180–580 μs.

Table 1
Transmission peak energies, widths and transmitted peak intensities of filtered neutrons deduced from the data of Ref. [9] by using a ^{238}U filter, 98 mm thick

Energy (eV)	FWHM (eV)	Transmission	Relative area
34.3	2.79	0.12	1.59
64.6	1.36	0.08	0.45
100.3	2.42	0.27	1.00
186.2	3.36	0.54	1.35
346.2	1.29	0.25	0.13
517.0	1.20	0.12	0.06
593.5	1.11	0.21	0.08
659.5	1.41	0.33	0.11
935.2	1.67	0.42	0.11
956.6	1.76	0.46	0.12
988.6	2.53	0.63	0.20
1138.0	1.85	0.48	0.12
1243.0	1.63	0.43	0.10
1392.0	1.77	0.40	0.09
1520.4	1.88	0.41	0.09
1594.9	2.94	0.45	0.15
1778.6	2.51	0.71	0.16
1962.9	5.83	0.86	0.29
2183.0	2.60	0.62	0.10
2543.4	5.01	0.81	0.21
3276.7	1.73	0.19	0.16
3433.2	2.24	0.38	0.08
6164.5	4.16	0.65	0.09

The relative areas were obtained from the measured TOF spectrum of Fig. 2, and normalized to that of the 100.3 eV line, where the actual area of this line collected in a 4 h run was 50700 counts.

are producing neutron lines between 34 and 6 keV, there is no optimum filter thickness for the whole energy region. The only requirement was to use a U thickness which could reduce the gamma flash intensity to a level tolerable by the neutron detector and have a negligible interference with the scattering measurements. We just selected a thickness that is a compromise between counting statistics and sharpness of the neutron lines.

In fact, in a recent application [14], a U-filter of smaller thickness (7.5 cm) was used in order to get higher counting statistics for a given length of running time. In such a case, it was necessary to make trade-offs between the counting statistics, the signal to background ratio and the sharpness of the resulting neutron lines.

4. Theoretical background

4.1. Intensity of transmitted lines

In order to calculate the transmission through the filter we used the ENDF/B-6.8 cross-section library for ^{238}U and the processing code NJOY [15] that accounts for the effect of Doppler broadening. We assumed the U-filter temperature to be 300 K. The transmission through the filter is given by

$$T(E) = \exp(-N\sigma_t(E)) \tag{1}$$

where N is the filter thickness in units of atom/b and $\sigma_t(E)$ the total cross-section in units of b/atom. The count rate at a given TOF channel i of energy E_i can be calculated from the relation

$$R_i = \phi(E_i)T(E_i)\eta(E_i)\frac{\mathrm{d}E}{\mathrm{d}t}(E_i) \tag{2}$$

where $\phi(E_i) = \alpha E_i^{-0.65}$ gives the neutron flux variation with energy (determined in a separate experiment using a Pb filter); $\eta(E_i) = \beta E_i^{-0.5}$ is the Li-glass detector efficiency at energy E_i and $\mathrm{d}E/\mathrm{d}t(E_i) = \gamma E_i^{3/2}$ is the transformation factor from TOF to energy (where α, β and γ are constants). In order to compare the calculated spectrum with experiment, the results were normalized to the measured peak intensity of the 186.2 eV line. The results are displayed in Fig. 3 which reveals a very good agreement between the measured and calculated spectrum of the transmitted direct beam below and at the 186.2 eV line. The comparison also shows the excellent signal-to-background ratio obtained at the peaks and also indicates that the ENDF/B-6.8 data for ^{238}U in the interference minima is accurate. Note that the above calculation is applicable only for peaks in which the Linac pulse width is negligible compared to the TOF at the particular neutron energy. A similar comparison at much higher neutron energies is more complicated because of resolution broadening due to the LINAC pulse width, the TOF channel width and the neutron time dependent emission from the neutron producing target.

To get some insight on the location and magnitude of the transmitted peak and its relation to the resonance parameters, we represent the s-wave resonance cross-section using a simple Breit–Wigner formula [16]

$$\sigma_t(x) = \frac{\sigma_0}{x^2+1}\left[1 + 2x\frac{R}{\lambdabar}\right] + \sigma_{\text{pot}} \tag{3}$$

where R is the effective nuclear radius, $\lambdabar$ the reduced de Broglie wavelength of the neutron, $x = 2(E - E_0)/\Gamma$, where E_0 is the resonance energy and Γ is the full-width at half-maximum of the resonance. The total cross-section at the resonance peak, obtained by taking $x = 0$ and neglecting σ_{pot}, is given by $\sigma_0 = 4\pi\lambdabar_0^2 g\Gamma_n(E_0)/\Gamma$ where g is a statistical factor determined by the spin of the nucleus, $\lambdabar_0$ is the reduced neutron wavelength at the resonance energy and Γ_n is the neutron width. Using Eq. (2) and assuming that near the resonance $\lambda \approx \lambda_0$, the neutron energy at the minimum of the interference cross-section can be found:

$$E_{\min} = E_0 - \frac{\lambdabar_0}{R}\frac{\Gamma}{2} \tag{4}$$

and the corresponding total cross-section at the interference minima is given by

$$\sigma_t^{\min} = \sigma_{\text{pot}} - \frac{\sigma_0}{\left(\lambdabar_0/R\right)^2 + 1}. \tag{5}$$

Since R is constant and $\lambdabar \propto 1/\sqrt{E}$, the minimum energy is closer to the resonance energy E_0 at high energies and is also dependent on the resonance width. The minimum cross-section $\sigma_t^{\min}$ is a very strong function of the resonance peak strength σ_0 and is smaller than the potential scattering. Both the energy and cross section magnitude at the interference minima are also functions of the temperature and the experimental resolution. The calculated transmitted intensities through the 98 mm ^{238}U filter were used to generate the line energies, relative intensities and the FWHM widths in ^{238}U. No resolution broadening effects were included in the calculation. The results for some of the strong intensity lines are listed in Table 1.

4.2. Temperature effect

The temperature affects the width of the resonance that will in turn change the location and magnitude of the cross-section minima. A calculation demonstrating the effect of the temperature on transmission through the 98 mm ^{238}U filter is given in Fig. 4 for the case of the 2543 eV filtered line at few temperatures ($T = 0$, 300, 600, 1000 K).

The results of this calculation indicates that as the filter temperature increases, the transmission peaks shift to the left and the total area under the peak is decreased, however, the FWHM of the peak remains unchanged.

It is important to note that in calculating the width of the lines versus temperature, one have to account for the vibrational motion of the U-atoms in the metallic lattice. This may be done by using the effective temperature T_e of the U-atoms; it may be evaluated, from a knowledge of the phonon density of states $g(v)$, using the Lamb relation [17]:

$$T_e = \frac{1}{k}\int_0^\infty hvg(v)\left[\frac{1}{e^{hv/kT} - 1} + \frac{1}{2}\right]dv \tag{6}$$

where k is the Boltzmann constant and $g(v)$ is usually measured by inelastic neutron scattering, and normalized

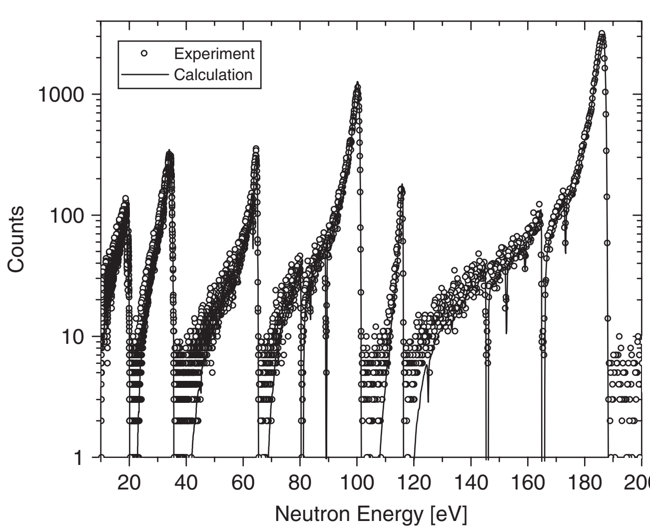

Fig. 3. Comparison of the measured and calculated direct beam transmitted through 98 mm of ^{238}U-filter. The effect of the other isotopes, such as ^{235}U, was ignored.

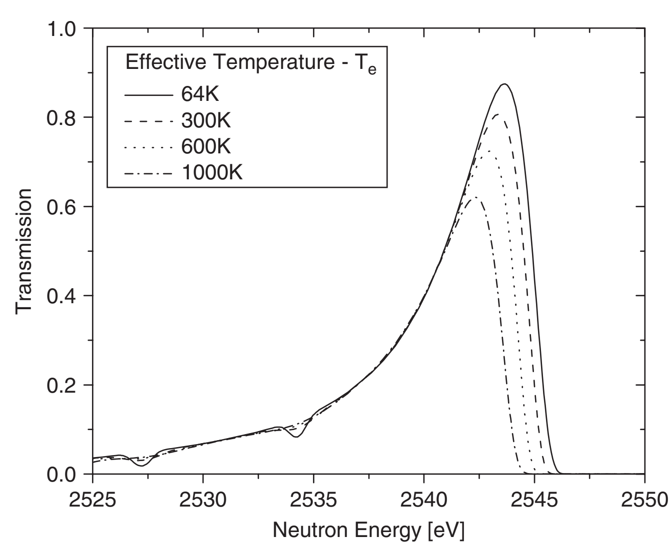

Fig. 4. Calculation of the peak intensity at the minima of the 2543 eV line (calculated in transmission through 98 mm of ^{238}U) for different filter temperatures. Note that at $T = 0$ K, the effective temperature $T_e = 64$ K (see text).

so that $\int_0^\infty g(v)\mathrm{d}v = 1$. A very good estimate of the value of T_e at 0 K, is obtained by using the literature values [18] of $g(v)$ measured at a low temperature such as 50 K and carrying out a numerical integration. The result obtained using Eq. (6) is $T_e = 64$ K. This is the actual value used in calculating the shape of the transmitted line at 0 K (shown in Fig. 4 as $T_e = 64$ K). At higher temperatures, such as 300 K, the effect of the lattice binding in U can be neglected because the atomic vibrational energies are relatively low, hence T_e at $T = 300$ K is slightly higher but nearly equal to T.

Note also that the neutron line widths of the filtered beams depend on the thickness of the filter, becoming narrower with increasing thickness.

5. Scattering measurements

It is of interest to note that the U-filter may also be utilized in scattering measurements. This is done in a manner similar to another arrangement in which an iron filter 20 cm long was employed [19]. This experimental setup is illustrated in Fig. 5 where a thin polyethylene sample (CH_2) is used to scatter neutrons emitted by a Ta target. The neutrons are then passed through a ^{238}U filter, hence the final outgoing n-energies are identical to those given in Table 1. In Fig. 5, the Ta photoneutron source is not visible to the n-detector. This experimental mode was recently employed [14] to carry out a comparative study of the scattering intensities from two different scatterers (CH_2 and C) whereby the final neutron energies are the same for the two samples. A typical TOF spectrum of neutrons scattered at 45° from a polyethylene sample is given in Fig. 6. Note the high signal-to-noise ratio of the resulting TOF spectrum which makes it possible to determine the intensity of each line with good accuracy.

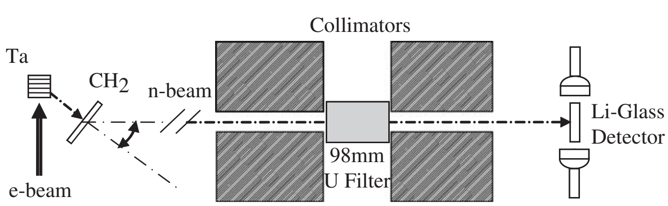

Fig. 5. Schematic view of the layout of the scattering experiment. The distance between the Ta target and the ^{6}Li-glass n-detector is 25.5 m.

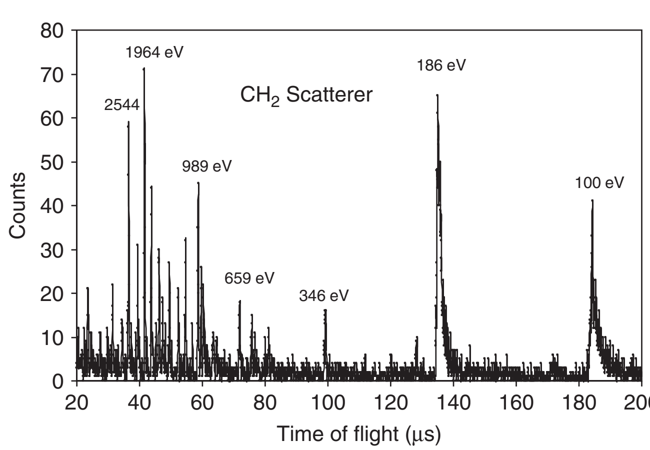

Fig. 6. TOF spectrum of neutrons scattered from a 1.1 mm sample of polyethylene (CH_2) and passed through a 98 mm of ^{238}U filter. The running time is 1.5 h. The energies of the stronger neutron lines are indicated.

6. Conclusions

In conclusion, a multi-line neutron beam with sharply defined energies was produced. It can be used for total cross-section measurements and in scattering measurements. The sharpness of the neutron energy lines may be varied by changing the thickness of the U-filter. The effect of varying the temperature of the U-filter on the resulting neutron lines is also discussed. The high sensitivity of the filtered neutron beam TOF spectrum to the position of the minima in the cross section can be used to test the current cross section libraries and provide indications of any inaccuracies in the neutron resonance parameters of the filter material.

Acknowledgements

We would like to thank J. Westhead, L. Prince and M. Gray, for technical support and for operating the Linac.

References

[1] R.C. Greenwood, R.E. Chrien, Nucl. Instr. and Meth. 138 (1976) 125.
[2] C.A. Perks, K.G. Harrison, R. Birch, H.J. Delafield, Radia. Prot. Dosim. 15 (1986) 31.
[3] G. Constantine, L.J. Baker, N.P. Taylor, Nucl. Instr. and Meth. A 250 (1986) 565.
[4] I.G. Schroder, R.B. Schwartz, E.D. McGarry, in: R.A. Schrack, C.D. Bowman, (Eds.), Nuclear Cross Section and Technology, NBS Special publication, vol. 425, 1975, p. 89
[5] R.C. Block, R.M. Brugger, in: S. Cierjacks (Ed.), Neutron Sources for Basic Physics and Application, vol. 3, Pergamon Press, Oxford, 1983 Chapter 8.
[6] R.F. Barth, A.H. Soloway, R.G. Fairchild, Cancer Res. 50 (1990) 1061.
[7] K.A. Alfieri, R.C. Block, P.J. Turinsky, Nucl. Sci. Eng. 51 (1973) 25.
[8] Y. Fujita, K. Kobayashi, T. Oosaki, R.C. Block, Nucl. Phys. 258 (1976) 1.
[9] P.F. Rose, C.L. Dunford, ENDF-102 data format and procedures for the evaluated nuclear data file ENDF-6, BNL-NCS-44945, Rev. 2, Brookhaven National Laboratory, (1997) www.nndc.bnl.gov
[10] P. Stoler, N.N. Kaushal, F. Green, Phys. Rev. C 8 (1973) 1539.
[11] P. Stoler, N.N. Kaushal, F. Green, E. Harms, L. Laroze, Phys. Rev. Lett. 29 (1972) 1745.
[12] A.J. Mill, Nucl. Sci. Eng. 85 (1983) 127.
[13] R.B. Royer, R.M. Brugger, Nucl. Instr. and Meth. 145 (1977) 245.

[14] R. Moreh, R.C. Block, Y. Danon, M. Neuman, Phys. Rev Lett. 96 (2006) 055302.
[15] R.E. MacFarlane, D.W. Muir, The NJOY Nulcear Data Processing System, Version 91 (LA-12740-M), 1994.
[16] G. Bell, S. Glasstone, Nuclear Reactor Theory, Robert E. Krieger Publishing Company (1970).
[17] W.E. Lamb, Phys. Rev. 55 (1939) 190.
[18] M.E. Manley, et al., Phys. Rev Lett. 86 (2001) 3076.
[19] R. Moreh, R.C. Block, Y. Danon, M. Neuman, Phys. Rev. Lett. 94 (2005) 185301.