GENERATION OF INTERMEDIATE NEUTRONS USING DIFFERENT FILTER SYSTEMS

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ABSTRACT

Neutrons in the Intermediate energy range are of great importance in many fields of science and technology. A survey is made on the conventional sources of Intermediate energy neutrons. The phenomena of neutron windows is discussed thoroughly. A proposed technique for using a combination between resonance scattering materials and transmission filters in producing neutrons in the Intermediate and Epithermal energy range is presented. A set of scat-filter combinations are suggested to produce neutrons of specified energies.

NOMENCLATURE

$\sigma_n\gamma$	radiative capture cross-section,
σ_{nn}	elastic scattering cross-section,
σ_s	total p-wave multi-level cross-section,
I	target spin quantum number,
l	orbital angular momentum quantum number of the neutron,
J	compound nucleus spin quantum number,
g	statistical weight factor $g = \dfrac{2J+1}{2(2I+1)}$,
k_n	neutron wave number $k_n = 1/\lambda$,
R	potential scattering radius,
E_0, E_λ	resonance energy (of level λ),
$\Gamma, \Gamma\lambda$	total width of level (λ),
$2\Gamma_\gamma, \Gamma_{\lambda\gamma}$	radiation width (of level λ),
Γ_n, Γ_n	neutron width (of level λ),
A	target nucleus mass divided by the neutron mass,
2π	Plank's constant,
K	Boltzmann's constant,
T	Sample temperature.

INTRODUCTION

Neutrons generated in nuclear reactors or by the use of nuclear interactions have a wide range of energy. This energy range is usually classified into three main ranges; thermal range (10^{-3} to 1ev), Intermediate range (1ev to several Kev) and fast range (> 500 kev). Neutrons in the intermediate range have a great importance since they are greatly needed in the field of science and technology, for example [1]:

i. Calibration and development of health physics instruments,
ii. Radiological experiments,
iii. Calibration of spectrometry systems,
iv. Radiotherapy
v. Neutron radiography,
vi. Studies of molecular and nuclear structures.

The generation of neutron beams in Intermediate energy range has been carried out by various methods. These methods are [1,2,3]:

1. Crystal Monochromators according to Bragg's law is only useful for producing neutrons of energy less than 10-100 ev. For energies higher than that, the yield becomes very small since yields decrease with increasing energy.
2. Nuclear interactions such as (P,n) reactions with Li7, V51, Cu 64. Neutron yield increases as the energy decreases below 10-20 Kev,
3. Neutron radioactive sources produce neutrons of limited energies and are accompanied by intense gamma radiation.
4. Resonance scattering of neutrons using materials of high primary resonance peak at the intermediate range. These neutrons are, however, accompanied by either significant gamma contamination or by neutrons scattered by secondary resonances, or by both.

5. Neutron filters (called transmission filters), which allow neutrons of a specified energy to be transmitted with a high transmission factor. This has the advantage of reducing the gamma rays, but neutron transmission through secondary windows can cause problems.

The present work introduces a new technique for the generation of Intermediate energy neutrons. This technique is mainly dependent on the phenomena of "neutron windows". This phenomena is based on the fact that "In an ideal transmission filter, there exists a narrow band of energy where the transmission of neutrons reaches hundred percent (neutron window), while the transmission elsewhere is zero". In practice, there will be some transmission outside the window (secondary window) and always some attenuation through it. To overcome the problem of secondary window, we make use of a second filter or resonance scatterer combined with the original filter.

GENERAL THEORY OF NEUTRON WINDOWS

To understand the phenomena of neutron windows, we examine the Breit-Wigner formula [4] for the capture cross section for a single isolated resonance;

$$\sigma_{n\gamma}(E) = \frac{\pi\lambda^2 g\Gamma_n\Gamma_\gamma}{(E-E_o)^2+\Gamma^2/4} \qquad (1)$$

and the scattering cross-section has a somewhat different form:

$$\sigma_{nn}(E) = \frac{\pi\lambda^2 g\Gamma_n^2}{(E-E_o)^2+\Gamma^2/4} + 4\pi R^2 + \frac{4\pi\lambda R' g\Gamma_n(E-E_o)}{(E-E_o)^2+\Gamma^2/4} \qquad (2)$$

The first term describes pure resonance scattering and is similar to Equation (1). The second term describes pure potential scattering. The third term describes the interference between potential and resonance scattering. For $E < E_o$ it is negative, i.e. the interference is destructive. Therefore, potential scattering and resonance scattering can virtually cancel each other and the scattering cross section falls to a minimum value and it is this property of resonance reaction which is referred to as neutron windows. Corbett [1] pointed out in 1975 that the cross section in the minimum can be very low for doubly even isotopes, i.e the nucleus has an even number of protons and even number of neutrons.

CALCULATION OF NEUTRON WINDOW CR SECTION

The minimum cross section occurs at the window en (E_{min}) defined by $d\sigma/dE = 0$. Then from Equation

$$E_{min} = E_o - \frac{\Gamma}{2R}$$

From Equation (2) and Equation (3), we get;

$$\sigma_{min} = 4\pi R^2\left[1 - \frac{g\Gamma_n/\Gamma}{1+(R/\lambda)^2}\right] \qquad ($$

where $E_{min} - E_o \approx \Gamma/2$

However, for most isotopes, the nearby resonances in isotope and impurities in the sample will complicate calculation. It should be noted that if the resonanc another isotope coincides with the position of the win it may obliterate this minimum and yield the iso ineffective as a filter. In such cases, more accu calculations of the window cross section are needed, ta into account particularly the effect of probable impurit

MULTI-ISOTOPE, MULTI-LEVEL FORMULA

The total cross section for a particular isotope is ta to be sum of the s-wave cross section (σ_o) and th wave cross section (σ_p).

The p-wave cross section is sufficiently accura calculated as the sum of the p-wave potential scatte plus a sum over Doppler broadened resonances.

$$\sigma_p(E) = 12\pi\lambda^2\sin^2(K_nR' - \arctan K_nR') + \sum_\lambda 4\pi\lambda^2 g\Gamma_{\lambda n}\frac{0.8863}{\Delta}e^{-\left(\frac{e-E_\lambda}{\Delta}\right)^2}$$

where $\Delta^2 = \left(\frac{4KTE_\lambda}{A}\right) + \Gamma_n^2/\ln 16$

The S-wave cross section is that given by the R-ma formalism (Lane and Thomas, 1958). However, as the reactions likely for the energy range and isotopes under consideration are elastic and radiative capture, the formula needed is much simplified.

$$\sigma_s(E) = 2\pi\lambda^2 \sum_{J=|I-1/2|}^{J=I+1/2} g(1-\Re(U(J))) \qquad (6)$$

U(J) is the collision matrix given by

$$U(J) = e^{-ik_nR'} \left\{ \frac{1-\frac{i}{2}\sum_{\lambda} \frac{\Gamma_{\lambda n}}{E_\lambda - E - i\Gamma_{\lambda/2}}}{1+\frac{1}{2}\sum_{\lambda} \frac{\Gamma_{\lambda n}}{E_\lambda - E - iF_{\lambda\gamma}/2}} \right\} \qquad (7)$$

The sum in Equation (6) is over all levels λ of spin J. Where the sum in Equation (7) is over the two spin states I+1/2, |I-1/2|.

The elastic scattering cross section is given by

$$\sigma_{nn} = \pi\lambda^2 \sum_{J=|I-1/2|}^{J=1+1/2} g\,|1-U(J)|^2 \qquad (8)$$

The capture cross section is calculated from

$$\sigma_{n\gamma} = \gamma_s(E) - \sigma_{nn}(E) \qquad (9)$$

The contributions from up to six isotopes within a sample may then be summed and the total cross section is calculated from the formula

$$\sigma_{TOTAL} = \sum_{h=1}^{m} (\sigma_s + \sigma_p)H(h) \qquad (10)$$

where the sum is over m isotopes of fractional abundance H(h).

The multi-isotope, multi-level formula can generate accurate cross sections predictions from resonance data. The accuracy is mainly limited by the accuracy of resonance data.

A computer code, XSEC, [5] was constructed to calculate the total cross section from resonance data.

Measurements have recently been made on the transmission of neutrons through thick single isotopes in order to confirm the existence and characteristics of the principal windows in each isotope, and also to identify other windows, some of which are difficult or impossible to predict theoretically. The first measurements were made [6] on samples of Ni-58 and Ni-60. Further such measurements started by then on w-148 and Zn-64 samples. These measurements confirm the existence of the principle windows in Ni-58 and Ni-60 cross sections which had been theoretically predicted [5]. The agreement between theory and experiment is shown in Figure (1) for Ni-58 and Figure (2) for Ni-60.

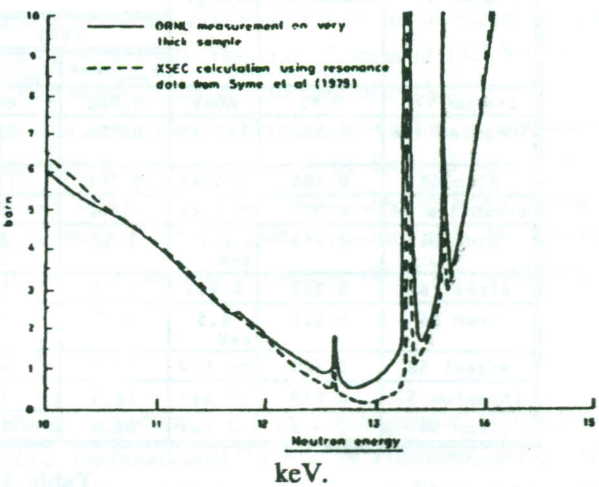

Figure 1. The cross-section of Nickel-58 in the region of the 13 keV window.

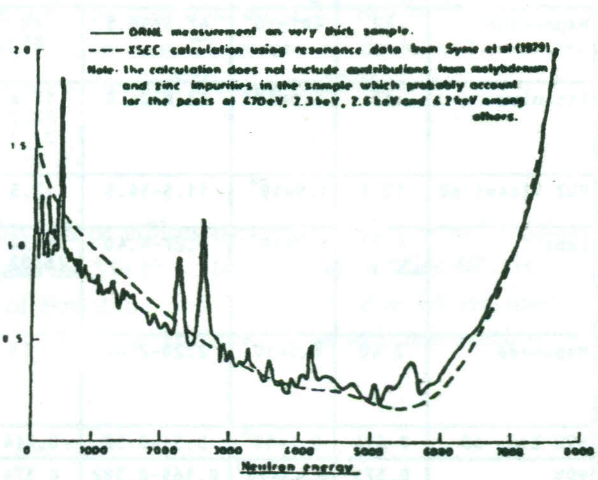

Figure 2. The cross-section of Nickel-60 in the region of the 5keV window.

Table 1. Natural elements for filter material.

Filter Marerial	Atomic Weight of Predominant Isotop	Abundance of Predominant Isotope	Window Energy E_{min}/keV	Energy (E_{min}) and Cross-section (σ_{min}) at Minimum for Entriclment of Predominant Isotope to:							
				100%		99.9%		99%		Nat. Abund.	
				E_{min}/keV	σ_{min}/fm_2	E_{min}/keV	σ_{min}/fm	E_{min}/keV	σ_{min}/fm	E_{min}/keV	σ_{min}/fm
Scandium	45	100%	2	-	-	-	-	-	-	2.3	6.3
Iron	56	91.72	24	24.4	0.9	24.4	1.9	24.4	9.6	24.4	46
Aluminium	27	100%	25	-	-	-	-	-	-	25.3	54
Sulphur	32	95%	73	73	0.3	73	0.5	73	2.3	73	11
Silicon	28	92.2%	120	122	0.7	122	2.9	123	22	125	180
Calcium	40	96.7%	120	123	0.5	123	1.4	123	10	122	29

Table 2. Enriched Single Isotopes for Filter Material.

Filter Material	Natural Abundance	Window Energy	Energy (E_{min}) and Cross-section (σ_{min}) at Minimum for Enrichments to:							
			100%		99.9%		99%		95%	
			E_{min}/keV	σ_{min}/fm^2	E_{min}/keV	σ_{min}/fm^2	E_{min}/keV	σ_{min}/fm^2	E_{min}/keV	σ_{min}/fm^2
Erbium 170	0.15	60eV	0.062	66	0.0585	68	0.0585	77	-	-
Tungsten 184	0.307	160 eV	0.156	33	0.153 0.159	41 43	0.152 0.159	51 53	0.151 0.160	72 91
Zinc 68	0.186	400 eV	0.398	17	0.398	17	0.398	23	0.398	44
Strontium 86	0.099	500 eV	0.502	30	0.503	31	0.503	36	0.503	59
Zinc 64	0.489	2.2 keV	2.17	3	2.17	3	2.16	10	2.15	33
Nickel 60	0.262	4 keV	4.25	1	4.0	7	3.25	34	2.75	127
Iron 54	0.058	4.5 keV	4.5	3	4.5	3	4.5	9	4.5	36
Nickel 58	0.679	14 keV	13.7	4	13.7	18	13.7	131	-	-
Chromium 52	0.838	47 keV	46.5	1	46.5	1	46.5	7	46.5	34
Iron 54	0.058	48 keV	48.0	1	48.0	2	48.0	7	48.0	38

Table 3. Resonance Scatterers.

Scatterer	Peak Cross-section (σ_o) and Peak Energy (E_o)		half-Height Energies (E) E/keV	Rcsonance Energies (E_o). Scattering widths (Γ_n) and Reesponsible Isotope			Other Scattering Peaks	Remarks
	E_o/keV	σ_o/fm^2		E_o/keV	Γ_n/eV	Isotope		
Magnesium	82	401×10^3	47.5-90.5	80 83	1200 1500	^{25}Mg ^{24}Mg (p-wave)	Smaller peaks at 20keV, 280 MeV and 450keV with peak cross-sections ≈ 100 fm^2	Cross-sectior elsewhere ger 150-300 fm^2
Titanium	18	1.1×10^4	13.8-24.0	17.6 22.2 22.8	8700 650 630	^{48}Ti ^{48}Ti ^{49}Ti	4000-5000 fm^2 cross-section peaks at 40keV and 50 keV.	Cross-sectior elsewhere ≤ 5 except at the energies
90Z Nickel-60	12.6	1.9×10^4	11.5-14.5	12.5	26.60	^{60}Mi	Smaller peaks at 29 and 65 keV plus other minor ones.	Cross-sectior elsewhere ≈ 5
Cobalt	4.33	3.7×10^4	4.27-4.40	4.32 5.02	110 650	^{59}Co ^{59}Co	Cross-section high in 4-6 keV region plus several other peaks at higher energies. Large resonance peak at 132 eV.	
Maganese	2.40	6.5×10^4	2.20-2.60	2.38	400	^{55}Mn	10^5 fm^2 peaks at 330 eV and 1.1 keV. Smaller peaks at 7.2 keV, 8.9 keV 17.8 keV and 18 keV.	Several narr peaks at high energies.
99% Zinc-68	0.514	5.1×10^5	0.51-0.52	0.514	8.7	^{68}Zn	Large peak at 18.8 keV.	
90% Neodymium-144	0.375	6.45×10^5	0.365-0.382	0.374	16.2	^{144}Nd	Peaks at 734 eV, 1.277 keV and 1.628 keV but not so high.	

APPROPRIATE FILTER-SCATTERER SYSTEMS

An examination of the cross sections calculated by XSEC, was made to search for materials having neutron windows in the Intermediate energy range. Sixteen materials potentially useful in filter systems have been identified. Of these 16 materials, six are useful in their elemental form; there are shown in Table (1). For most of these materials, the effect of enriching the predominant isotope to 99 % and 99.9 % abundance is also shown Table (2) shows materials useful as filters in the form of enriched isotopes. This list of isotopes and energy windows have been selected on a basis of being well spread in energy as well as on cost and likely ease of enrichment. Many of the proposed filter systems discussed below need to be used in conjunction with a resonance scatterer. A list of possible scatterers is presented in Table (3).

The following is a description of combinations of filters and scatterers for specified Epithermal and Intermediate energies.

a) 120 Kev

The successful combination at this energy consists of a filter of mainly "Silicon" with a little "Calcium" both in their natural elemental form. The secondary windows in both elements do not coincide. The thickness of materials is 80 cm of Silicon plus 20 cm of Calcium. The transmission at 122 Kev is equal to 44 % with half-width of ± 7 Kev. The contamination to such a beam would be from:

i. Gamma rays due to the low mass of filter.

ii. 50 Kev neutrons due to window in Silicon at this energy.

b) 75 Kev

"Sulphur" has a window at this energy. A suitable scatterer is "Magnesium", it has two broad scattering peaks in two of its isotopes at 80 Kev. The thickness of materials is 150 cm of Sulphur and 2 cm of Magnesium. The transmission at 75 Kev is equal to 44 % with half-width of ± 6 Kev. The main contamination is from 20 Kev neutrons due to scattering peak of Magnesium at this energy.

c) 47 Kev

"Iron -54" and "Chromium -52" are used as two filters with coincident windows. The thickness of materials used is 20 cm of Iron -54 and 50 cm of Chromium -52. The transmission at 47 Kev is 26% with half-width of ± 1250 Ev. The contamination is due to several other windows in both filters which do not coincide up to at least 200 Kev.

d) 14 Kev

" Nickel -58" is used as a filter in conjunction with a scatterer of either "Titanium" or "Nickel -60". The thickness of the materials used is 30 cm of Nickel -58 with 5 mm of Nickel -60. The transmission at 13.7 Kev is 6% with half-width of 200 Ev. In case of Nickel -58 - Nickel - 60 combination system, there are several other windows in Nickel -58; for example: at 56-61 Kev, 83 Kev, 104-107 Kev, 122-125 Kev, 139 Kev and 153-158 Kev resonance peak in Nickel -60. So that, Titanium may be a better scatterer to be used as the source of 14 Kev neutrons.

e) 2.2 Kev

Natural "Scandium" filter and "Manganese" scatterer are effective combination at this energy. However, using "Zinc" in combination with Scandium as a filter system may either remove the necessity of a scatterer or improve even further the purity of the 2 Kev source. The thickness of the materials used is 70 cm of Scandium and 15 cm of Zinc -64. The transmission at 2.2 Kev is 71 % with half-width of 0.15 Kev. There are no coincident windows in both Scandium and Zinc up to 30 Kev.

f) 500 Ev

This source utilises the 502 Ev window in "Strontium - 86" and the 514 Ev scattering peak in "Zinc-68". About 140 cm of Strontium and 0.3 mm of Zinc-64 are used. The transmission at 510 Ev is 36% with half-width of ± 10 Ev.

g) 160 Ev

"Tungsten -184" has a successful window at 160 Ev. At higher energies, no windows are found. Hence, it would not seem necessary to utilize a resonance scatterer with this filter. A 60 cm of Tungsten -184 has a transmission at 150 Ev of 26 % with half-width of ± 10 Ev.

h) 60 Ev

"Erbium -170", like Tungsten -184 has a successful window at 60 Ev with no other windows found at higher energies. The neutron transmission from 60 cm of Erbium -170 at 60 Ev is 17% with half-width of 8 Ev. Due to several resonances in Erbium -168, the transmission in the window may have several dips in it.

CONCLUSION

By the use of filter-scatterer combination system, it is possible to construct successful neutron sources in the Epithermal and Intermediate energy range. The amount of materials which are suggested are not necessarily the optimum values. Since there is an inaccuracy in measuring the cross section values of there materials.

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