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R. FULFARO

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INSTITUTO DE ENERGIA ATÔMICA
Caixa Postal 11049 (Pinheiros)
CIDADE UNIVERSITÁRIA "ARMANDO DE SALLES OLIVEIRA"
SÃO PAULO — BRASIL

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R. Fulfaro

Divisão de Física Nuclear
Instituto de Energia Atômica
São Paulo - Brasil

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ABSTRACT

In order to reduce the neutron second order contamination effect in a resonance measurement a technique which makes use of a Tellurium filter was developed and the Iridium resonance at E_0= 0.654 eV was chosen as standard.

Tellurium has the necessary properties for a good filter since its neutron cross section is low and constant near the energy E_0 and has a resonance near the energy $4E_0$.

Calculation of the second order contamination effect from (111) planes of an Aluminium single crystal was made for the Iridium resonance affected by Doppler broadening and instrumental resolution.

The efficiency of the Tellurium filter was calculated as a function of neutron energy and an expected curve for the Iridium resonance was obtained; the agreement with the experimental points measured with filtered beam evidentiates that the utilization of this type of filter permits to perform accurate nuclear resonance measurements in this energy range.

I. INTRODUCTION

Crystal spectrometer have proved particularly effective in the determination of parameters for neutron resonance, from the total cross section measurements in the region below 10 eV. The higher order contamination in the reflected beam arises as a problem in evaluating crystal spectrometer data.

The principle of operation of the instrument is based on the Bragg condition for elastic scattering.

$$n \lambda_0 = 2 d \sin \theta_B \tag{1}$$

Not only neutrons with wavelength λ_0 but also neutrons with wavelength $\lambda_0/2$, $\lambda_0/3$, etc will be diffracted at the Bragg angle θ_B. These higher order neutrons give a contamination in the first order monochromatic beam.

Order contamination can be assumed negligible when a total neutron cross section curve with a 1/v energy dependence is measured in the wavelength region below the peak of the thermal neutron spectrum[7].

Gold is frequently used as a standard when a neutron wavelength determination is necessary for cross section measurements and also for measuring neutron flux[1]. In particular, for the IEA crystal spectrometer, this well known curve can be measured correctly over the wavelength interval from 0.3 to 1.2Å (0.91 to 0.057 eV), without use of any method to avoid the problem of higher order contamination.

However, even in this energy range a small order contamination can be particularly serious in the study of a nuclear resonance[2,3].

The second order contamination effect on the Iridium resonance measurement at E_0= 0.654 eV (0.353Å) was previously studied[3]. In the present work the main purpose is to show how this effect can be reduced by a technique developed which makes use of a tellurium filter.

II. EFFECT OF ORDER CONTAMINATION IN TRANSMISSION MEASUREMENTS

The total cross section at each energy is obtained by measuring the transmission of the specimen with monochromatic neutrons (i.e. n= 1). The cross section can be computed from the relationship

$$T = e^{-N\sigma 1} \tag{2}$$

where N is the number of atoms per cm^2 of the sample.

Having higher order contamination, the experimentally observed transmission at each energy is given by

$$T_{obs} = \frac{i}{I} \tag{3}$$

where the incident intensity I is a sum of intensities of all orders.

$$I = \sum_{n=1}^{m} I_n \tag{4}$$

Similarly for the intensity i transmited by the sample.

$$I = \sum_{n=1}^{m} i_n \tag{5}$$

The transmission T_n at each wavelength λ/n is given by

$$T_n = \frac{i_n}{I_n} = e^{-N\sigma_n} \tag{6}$$

where σ_n is the cross section at the λ/n wavelength.

From equations (3) and (6), T_{obs} becomes

$$T_{obs} = \sum_{n=1}^{m} \frac{I_n}{I} T_n \tag{7}$$

Defining $f_n = I_n/I$ as the ratio between each higher order intensity and the total intensity incident in the sample, one can rewrite eq. (7) in the form:

$$T_{obs} = \sum_{n=1}^{m} f_n T_n \tag{8}$$

Using a well known total cross section curve σ_1 as standard, the transmissions T_n can be calculated. Hence, having the f_n values previously determinated, one can obtain the contaminated experimental cross section curve that will be observed. It is given by the equation

$$\sigma_m = \frac{1}{N} \ell n \left(\sum_{n=1}^{m} f_n T_n \right)^{-1} \tag{9}$$

Calculation of the higher order contamination (f_n) needs calculation of the crystal reflectivity[4]. However, in the lower wavelength range some approximations can be made in order to determine the contamination.

For the case of a nuclear resonance measurement near to 1 eV (0.286 Å), only the second order contamination is considered, since the reflectivity for orders higher than the second decreases rapidly at this energy range.

Therefore, when a well known curve σ_1 is measured, the observed total cross section will be give by

$$\sigma_m = \frac{1}{N} \ell n (f_1 T_1 + f_2 T_2)^{-1} \tag{10}$$

Defining $k = I_2/I_1$ the σ_m becomes

$$\sigma_m = \sigma_1 + \frac{1}{N} \ell n \left[\frac{1+k}{1 + k \exp N(\sigma_1 - \sigma_2)} \right] \tag{11}$$

An aluminum Al(111) crystal was used as monochromator for the experiences in the present work; the k value for this crystal was previously determined[3]

$$k = \frac{(\epsilon \phi R' \Delta E)_2}{(\epsilon \phi R' \Delta E)_1} \tag{12}$$

where the subscripts refer to the order. The crystal reflectivity is $R' = R\, e^{-2M}$ with e^{-2M} being the Debye Waller factor.

The detector efficiency ϵ for the k determination was assumed proportional to $E^{-1/2}$ and the energy dependence of the product ϕR was obtained experimentally, and is given by $\phi R \propto E^{-2.7}$. When two orders are compared $(\Delta E)_2/(\Delta E)_1$ is constant. Taking into account that e^{-2M} depends only of the order and for any order $M_n = n^2 M_1$, the $k = 0.037$ value was obtained.

The parameters of the Iridium resonance at $E_0 = 0.654$ eV were previously determined with good accuracy[5] and this is one reason why this resonance was chosen for this study. This fact permits the calculation of the total cross section standard curve σ_1. For Iridium the cross section $\sigma_2 = 25$ barns is constant[5] at the energy range 4E(or$\lambda/2$).

III. TOTAL CROSS SECTION STANDARD CURVE σ_1

This matter was object of study in reference (3) and will be briefly related in this section.

Using the one level Breit-Wigner formula the Iridium resonance curve ($E_0 = 0.654$ eV) was calculated, adding also the contributions from all resonances appearing in the target material. The resulting curve, A, is shown in fig. 1.

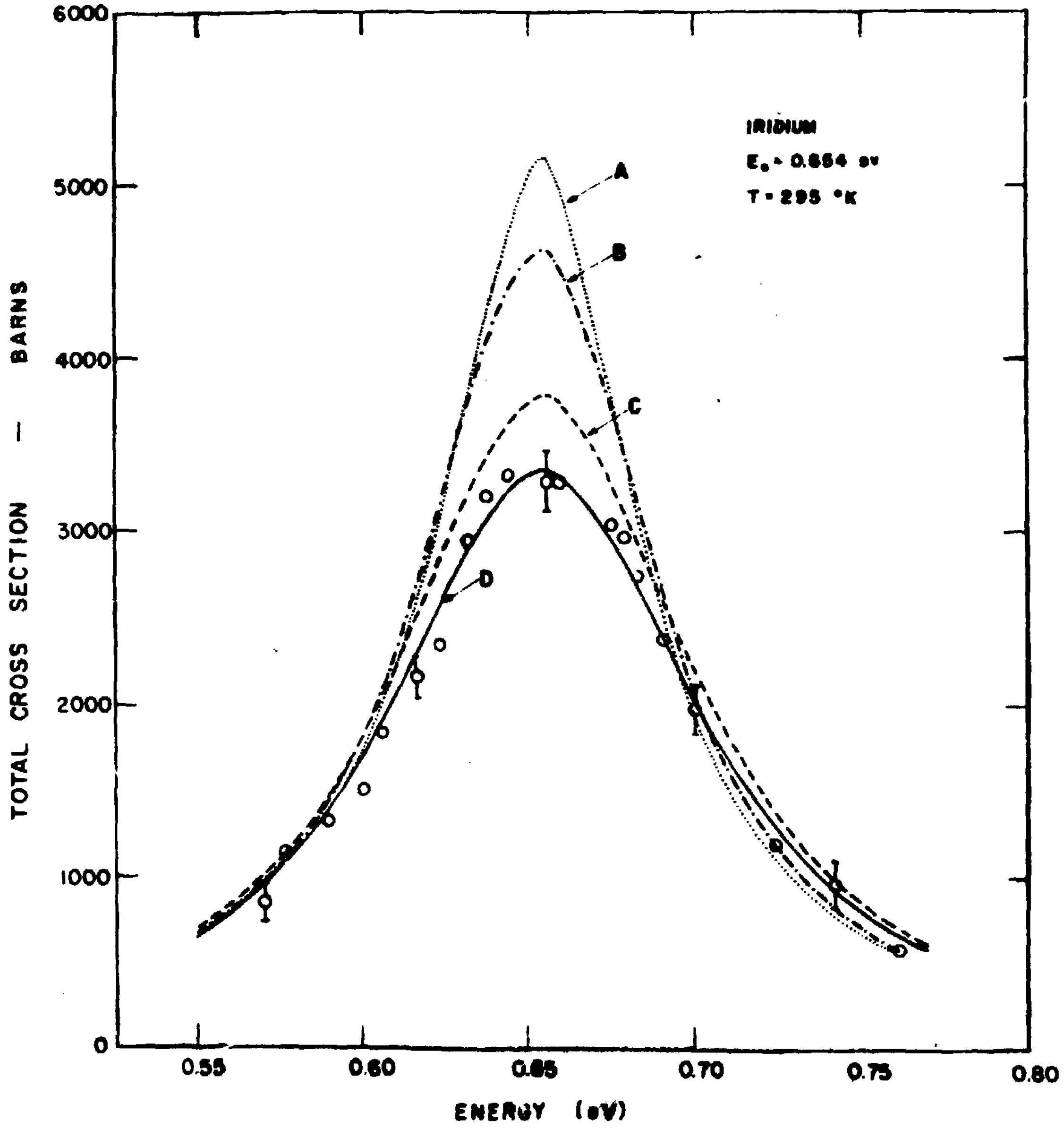

Fig. 1
Total cross section of Iridium as a function of neutron energy at room temperature. *Curve A is the theoretical Breit-Wigner shape. Curve B results from Doppler effect.* Curve C includes the effect of the spectrometer resolution function. Curve D is obtained taking into account the second order neutron contamination from the (111) planes of an Al crystal.

For the resonance Doppler broadening, resulting from the thermal motion of the target nuclei the theory elaborated by Lamb[6] for a solid specimen was used. By this theory the effect of lattice binding on the shape of a resonance is considered merely substituting the real specimen temperature T by an effective temperature T_{eff} as defined by Lamb. For Iridium $T_{eff}= 1.04$ T. The resulting Doppler broadening curve σ_B, is the curve B in fig. 1.

The instrumental resolution will cause the measured transmission T_1 to differ from the true transmission $T_B= e^{-N\sigma B}$ as follows:

$$T_1 = \frac{\int_0^\infty T_B(E)\ R(E'-E)\,dE'}{\int_0^\infty R(E'-E)\,dE'} \tag{13}$$

where

$$R(E'-E) = A(E')^{-3.2} \exp - \left[\frac{4\ell n2}{(\Delta E)^2} (E'-E)^2 \right] \tag{14}$$

The term $(E')^{-3.2}$ takes into account the reactor spectral distribution, the crystal reflectivity, and the 1/v variation of the detector efficiency. The full width at half maximum of the energy distribution of the reflected neutron beam, is given by

$$\Delta E = 4\,d \cos\theta\,(0.286)^{-1}\,E^{3/2}\,\Delta\theta \tag{15}$$

where $\Delta\theta$ is a function of crystal mosaic spread and the collimators. For the IEA crystal spectrometer and Al(111) crystal $\Delta\theta= 10$ min.

In fig. 1, the C curve represents the total cross section σ_1 calculated by eq. (13).

With the σ_1 values the contaminated cross section σ_m can be calculated by eq. (11). The value σ_m for Iridium are represented by the D curve in fig. 1. The total neutron cross section, for an Iridium sample with N= 3.97 x 10^{-4} atoms/barn, was measured over the energy interval from 0.55 eV to 0.80 eV; the experimental points are in agreement with the expected curve D.

IV. TELLURIUM FILTER

In order to supress higher order contaminations one desires a filter having the following properties: high transmission for neutrons with the desired wavelength λ and low transmission for the undesired higher order neutrons with wavelength λ/2, λ/3, etc.

For any order the intensity transmited by a filter is given by

$$I'_n = I_n\,t_n \tag{16}$$

where I_n is the incident intensity and t_n is the transmission of the filter.

$$t_n = \exp\cdot(N\sigma e) \tag{17}$$

with N being the number of molecules per cm^3, e the thickness and σ the total cross section of the filter.

Therefore the total intensity of the filtered beam is

$$I' = \sum_{n=1}^{m} I'_n \qquad (18)$$

The eq. (18) can be rewritten in the form

$$\frac{I'}{I'_1} = 1 + \sum_{n=2}^{m} \frac{I'_n}{I'_1} = 1 + \sum_{n=2}^{m} C_n \qquad (19)$$

with C_n representing the ratio between each filtered intensity of higher order and the filtered intensity of first order

$$C_n = \frac{I'_n}{I'_1} = \frac{I_n}{I_1}\,\frac{t_n}{t_1} = \frac{f_n}{f_1}\,\frac{t_n}{t_1} \qquad (20)$$

From eq. (19) one can note that a filter is as much efficient as much the ratio I'/I'_1 is brought near to unity, or as much the C_n sum is brought near to zero.

At the present work only the second order contamination is significant.

$$C_2 = \frac{I_2}{I_1}\,\frac{t_2}{t_1} = k\,\frac{t_2}{t_1} \qquad (21)$$

where t_1 and t_2 are the transmissions through the filter for neutrons with energy E and 4E respectively.

A technique for elimination of the second order contamination effect in the Iridium resonance at E_0= 0.654 eV was developed by use of a tellurium filter. Tellurium has the necessary properties for a good filter, i.e., its cross section is low and constant, σ= 6.0 barns, in the energy range from 0.6 eV to 0.7 eV, being practically transparent to neutrons with these energies; absorbs neutrons in the energy range of the second order because it has a resonance in this region, which cross section varies from 400 barns to 15 barns from 2.4 eV to 2.8 eV respectively[5].

When the filter is used the cross section σ_m is calculated by the eq.(11), with k substituting C_2. The filter is as much efficient as much the D curve approaches the C curve in fig. 1; or by the eq.(21) as much as the ratio t_2/t_1 minimizes the k value.

The tellurium filter has a cilindrical form and is obtained from a powder compactation made by the Nuclear Metallurgy Division of the IEA. The obtained density ρ= 4.5 g/cm^3 is 72% of the metal density and the filter dimensions (4 cm diameter and 2.5 cm thickness) is due to the matrix used in the compactation process.

The number of atoms per cm^3, $N = \rho N_0/A$, calculated with A= 127.6, is equal to N= 2.127 x 10^{22}. The ratio between transmissions is written in the form $t_2/t_1 = \exp - [N\,e\,(\sigma_2 - \sigma_1)]$ with the cross sections values obtained from reference (5).

By substituting the values in eq. (21), one can write C_2 in the form:

$$C_2 = 0.037 \exp\left[-0.0532\,(\sigma_1 - \sigma_2)\right] \qquad (22)$$

By the above equation the C_2 values were calculated in the energy interval from 0.6 to 0.7 eV and are plotted in fig. 2. One can note from the figure that in 0.65 eV, near the Iridium

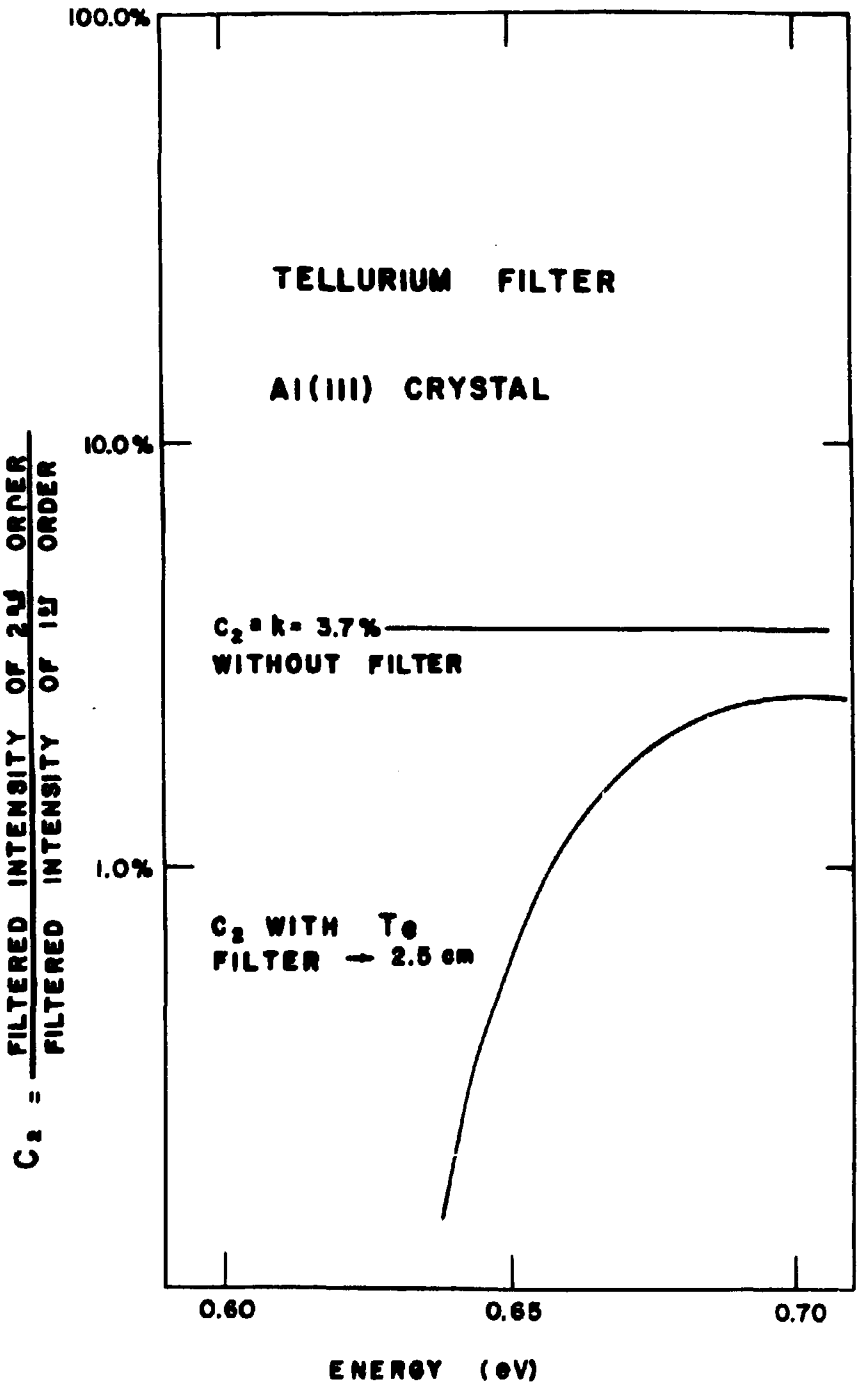

Fig. 2
Ratio between intensities filtered through 2.5 cm Tellurium filter. At the energy of the resonance peak, $E_0 \simeq 0.654$ eV, the contamination is smaller than 1.0%.

resonance peak, the ratio C_2 is smaller than 1.0%. Hence, the ratio between the second and the first order intensities which was 3.7% (the k value) is now appreciably reduced for the Al(111) crystal reflections in this,energy range.

In fig. (3) is indicated by E the curve that must be measured when the Tellurium filter is used, i.e., the result of eq.(11) calculation with k substituted by C_2. In this figure are also shown the previously discussed curves C and D.

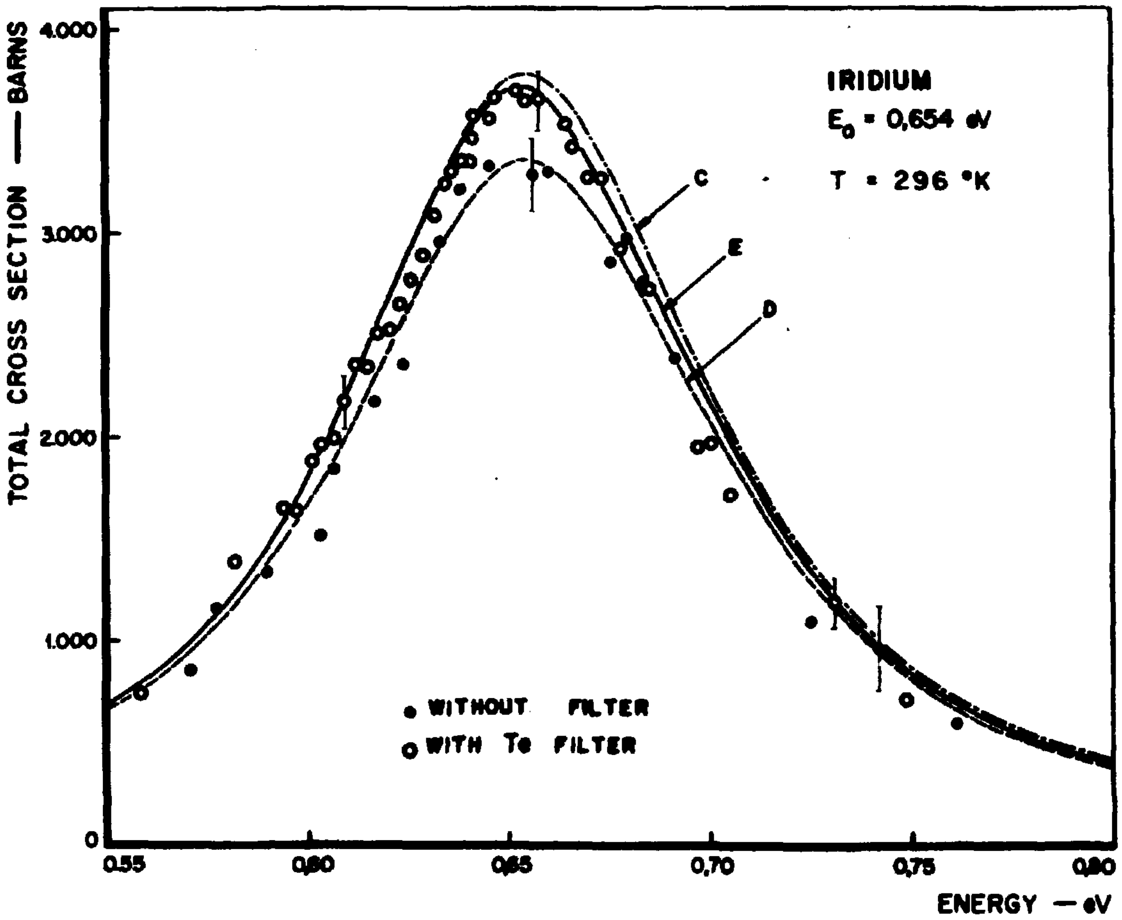

Fig. 3
Total cross section of Iridium for neutron beam filtered through Tellurium. The waited curve is E; C and D are the same of fig. 1.

Using the neutron beam filtered through Tellurium, the Iridium total neutron cross section was measured again. The experimental points are plotted in fig. (3) showing good agreement with the waited curve E, what indicates the accuracy of the filter calculation.

One can note from the figure that second order contamination is not completely eliminated by using this filter thickness. If this ideal condition occurs the E curve must be coincident with the C curve. For the reduction of the remaining contamination in E= 0.7 eV to a quantity smaller than 1.0%, 10 cm of compacted powder Tellurium would be necessary.

Results shown in the present paper evidenciate that the utilization of this type of filter is a method that can resolve the second order contamination problem. By this method and using an optimized filter thickness it is possible to perform accurate nuclear resonance measurements in this energy range.

RESUMO

Com o objetivo de reduzir o efeito de contaminação de nêutrons de segunda ordem na medida de uma ressonância foi desenvolvida uma técnica que utiliza um filtro de Telúrio e escolhida a ressonância do Irídio em $E_0 = 0.654$ eV como padrão.

O Telúrio possui as propriedades necessárias a um bom filtro, uma vez que sua secção de choque para nêutrons é baixa e constante próximo à energia E_0 e possui uma ressonância na região de energia próximo a $4E_0$.

O cálculo do efeito de contaminação de segunda ordem dos planos (111) de uma monocristal de Alumínio foi feita para a ressonância do Irídio afetada pelo alargamento Doppler e resolução instrumental.

A eficiência do filtro de Telúrio foi calculada em função da energia do nêutron obtendo-se uma curva esperada para a ressonância do Irídio; a concordância dos pontos experimentais medidos com o feixe filtrado evidencia que a utilização dêsse tipo de filtro é um método que permite efetuar medidas precisas de ressonâncias nucleares nesta região de energias.

RÉSUMÉ

Ayant pour but la réduction de l'effet de la contamination de neutrons de deuxième ordre dans le mesure d'une résonance, une technique qui utilise um filtra de Tellure a été developpée. La résonance de l'Iridium pour $E_0 = 0.654$ eV a été choisie comme standard.

Le Tellure possède les propriétés necessaires à un bon filtre, parce que sa section efficace pour les neutrons est baisse et constante au voisinage de l'énergie E_0 et il y a une résonance en la région d'énergie voisine à $4E_0$.

Le calcul de l'effet de contamination de deuxième ordre pour les plans (111) d'un cristal d'Aluminium a été effectivé pour la résonance d'Iridium affectée par l'élergissement Doppler et la résolution instrumentale.

L'efficacité du filtre de Tellure a été calculée en fonction de l'energie du neutron et une courbe espérée pour la résonance de l'Iridium a été obtenue; l'accord des points expérimentaux mesurés avec le faisceau filtré montre que l'utilisation de ce type de filtre est une méthode qui permet d'effectuer des mesures précises de résonances nucléaires en cette région d'énergie.

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