The use of resonance detectors for the investigation of neutron spectra in fast-neutron reactors

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The possibility of the investigation of the low energy portion of the neutron spectra in reflecting fast reactors by activated resonance detectors is considered.

Absorber difference and "1/v absorption" methods are illustrated by an example of the measurement of the flux distribution of resonance neutrons with energies of 4.9 ev (Au$^{197}$) and 2.95 kev (Na$^{23}$) in the reflecting reactors BR-1 and BR-5. It is shown that the neutron spectrum region from one to several thousand electron volts can be studied in adequate detail with the aid of the set of detectors described.

The resonance detector method has been used with success for many years for the investigation of neutron spectra in intermediate- and thermal-neutron reactors. The use of thin foils or layers of material having strong isolated resonance activation cross sections as detectors permits the determination of neutron fluxes, at energies corresponding to the resonance maximums [1].

The resonance detector method can also be useful for the study of comparatively soft spectra arising in fast neutron reflecting reactors. However, in this case, the contribution of the primary, usually the strongest, resonance to the detector activation can prove to be comparable with the resonances at high and lower energies. Therefore, it is necessary to use special methods to separate the activity induced by the neutrons which correspond to the resonance energy.

One of such methods is the absorber difference method. If the detector foil is covered on both sides during irradiation by layers of the same material which is thin in all neutron energy regions except in the neighborhood of the resonance at $E = E_0$, then the portion of the total activity due to the resonance neutrons will be decreased, because of the screening, in comparison with the case when the detector foil was irradiated without screening layers (filters).

It can be shown that the difference of the absolute magnitude of the saturation activity $\Delta A$, which refers to unit volume of the detector foils without filters and with filters of thickness $t$, when irradiated in identical isotropic neutron fluxes, can be represented by the following expression:

$$\Delta A = \psi (E_0) \frac{\pi}{2} \Gamma \Sigma_o a \eta$$

$$+ 2t \int \left[ \Sigma_a (E) \Sigma_c (E) \left\{ 1 - \frac{1}{2} \right\} \right] \psi (E) dE. \quad (1)$$

Here $\psi (E)$ is the neutron flux with energy $E$; $\Gamma$ is the radiation width; $\Sigma_0 a$ is the activation cross section at the resonance maximum; $\Sigma_a$ and $\Sigma_c$ are the activation cross sections of the isotope being irradiated and the total absorption cross section of the detector respectively (all macroscopic cross sections).

The first term in formula (1) is dependent on the screening of the resonance neutrons which is characterized by the factor $\eta$. The second term, to a first approximation, takes into account the absorption of the neutrons which lie outside the resonance being studied (the integration is carried out over all of the energy region except the
neighborhood of the resonance). It is assumed that, for these neutrons, $\Sigma_{ct} \ll 1$, and that the detector thickness can be neglected in comparison with the filter thickness. From relation (1) it is obvious that with $\Sigma_{ct} \gg \Sigma_{c}(E)$ it is always possible to make the second term negligibly small in comparison with the first. Thus, by measuring the activity difference $\Delta A$ and knowing the resonance parameters and the dependence of the absorption factor $\eta$ on them, it is possible to determine the flux of resonance neutrons.

The absorption factor $\eta$ can be calculated easily with the aid of the Gurevich-Pomeranchuk resonance absorption theory (see for example [2]) in the limiting cases of narrow ($\Gamma \ll \xi E_{0}$) and broad ($\Gamma \gg \xi E_{0}$) isolated resonances and also for isolated absorption resonances ($\Gamma \approx \Gamma_{\gamma}$). We will, for convenience, introduce the parameters $\beta = \Sigma_{ct}$, $\beta_{o} = \Sigma_{ct}^{o}$; the relation of the filter thickness $t$ and the detector thickness $t_{o}$ to the "drawing-out" length of neutrons from the resonance region is $E_{0} \approx t_{o}$ which corresponds to its maximum. It is obvious that

$$\Sigma_{ct} = \begin{cases} \Sigma_{o} & \text{for } \Gamma \ll \xi E_{0} \\ \Sigma_{o} \frac{\Gamma_{\gamma}}{\Gamma} & \text{for } \Gamma \gg \xi E_{0} \text{ and } \Gamma \approx \Gamma_{\gamma}. \end{cases} \quad (2)$$

Then the factor $\eta(\beta, \beta_{o})$ in Eq. (1) will be determined by the relation

$$\eta(\beta, \beta_{o}) = F(\beta, \beta_{o}) - F(\beta, \beta_{o}) = f(\beta_{o}) - f(\beta + \beta_{o}) - \beta f(\beta)$$

$$= \frac{f(\beta_{o}) - f(\beta + \beta_{o}) - \beta f(\beta)}{\beta_{o}} \quad (3)$$

where

$$F(\beta, \beta_{o}) = \frac{(\beta + \beta_{o}) f(\beta + \beta_{o}) - \beta f(\beta)}{\beta_{o}} \quad (4)$$

is the factor which takes into account both the self-screening of the detector and the screening by its filters.

$$f(\beta) = \int_{0}^{t} e^{-\beta \mu} \left[ I_{0} \left( \frac{\beta}{2\mu} \right) + I_{1} \left( \frac{\beta}{2\mu} \right) \right] d\mu \quad (5)$$

is the function which describes the self-screening of the resonance neutrons in a plane layer of thickness $t$ [2]; $I_{0}$ and $I_{1}$ are Bessel functions of order zero and one, with imaginary argument. From formula (4) it is obvious that the factor $F(\beta, \beta_{o})$ is proportional to the difference between the activities of layers of thickness $\beta + \beta_{o}$ and $\beta$. The values $\eta(\beta, \beta_{o})$ can be calculated from tables of functions of $f(\beta)$ given in [2]. However, in practice, one has to deal mostly with the case $\beta \gg \beta_{o}$ when the calculation of the difference between the close values of $f(\beta + \beta_{o})$ and $f(\beta)$ can lead to a significant error in the value of $\eta$. In this case one should use for $\eta(\beta, \beta_{o})$ the formula which is obtained by a Taylor's series expansion of $f(\beta + \beta_{o})$ and which is correct to third-order terms in $\beta^{2}$:

$$\eta(\beta, \beta_{o}) = f(\beta_{o}) - f(\beta) \left( 2 + \frac{\beta_{o}}{\beta} \right)$$

$$+ \frac{e^{-\beta}}{\beta} \left[ \left( \beta + \beta_{o} - \frac{\beta_{o}^{2}}{12} + \frac{\beta_{o}^{3}}{192} \right) I_{0} \left( \frac{\beta}{2} \right) \right.$$  

$$\left. + \left( \beta + \beta_{o} + \frac{\beta_{o}^{2}}{12} - \frac{\beta_{o}^{3}}{192} \right) I_{1} \left( \frac{\beta}{2} \right) \right]. \quad (6)$$

Values of the function $\eta(\beta, \beta_{o})$ for certain $\beta$ and $\beta_{o}$ calculated from formula (6) are given in Table 1. The interference resonance and potential scattering has been neglected in the calculation of $\eta(\beta, \beta_{o})$. When $\Gamma \approx \xi E_{0}$ and $\Gamma_{\gamma} \gg \Gamma_{\gamma}$, the calculation is difficult and consequently must be carried out separately, by numerical methods, for each specific resonance.

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