Use of keV-energy ion beams in inducing neutron resonance reactions: Effective cross-sections

Bency John*
Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA
** email: bjohn@barc.gov.in*

Introduction

One facet of slow neutron reactions that is only rarely reported is the resonance-absorptions in mono-directionally moving target materials. Available reports in this field[1,2] deals with material velocities below some threshold such that the relative velocities in neutron-material motion remained below discrete-resonance values. Reports on effective cross-section calculations for higher relative velocities, especially above the 1/*v* region where the discrete-resonances are found, are very sparse[2].

Advances in plasma and ion-beam technologies would let high flux, high velocity ion flow in a controlled manner, and therefore, there can arise a renewed scope for discrete-resonance reactions with ion-beam as the moving 'material'. In this suggestion, there will be disadvantages due very low reactant density compared to a typical solid reactant. These disadvantages may be compensated to some extent by high reaction cross-section available at a selected discrete-resonance, and a possibility for online separation of transmuted-isotopes; the latter facilitated by use of ion-beams. In the present work a scheme for the effective cross-section calculation for ion-beam thermal-neutron reactions has been worked out and the scheme has been applied for discrete-resonance region in two important reactions, namely, neutron-capture by ^{238}U and ^{239}U nuclei as examples[3].

Effective cross-section

Theoretical considerations for the effective cross-section calculation for any one type of ion-beam thermal-neutron reaction are the following. Assume a parallel beam of mono-energetic particles with lab velocity $\vec{v}$ colliding with target particles whose velocities $\vec{u}$ are distributed in such a way that $p(\vec{u})d^3u$ is the fraction with velocities in a small three dimensional region d^3u around $\vec{u}$. If ρ_1 and ρ_2 are the densities of beam and target particles, respectively, the number of reactions occurring per unit time and unit volume is given by

$$\rho_1\rho_2\int d^3u\ p(\vec{u})\ |\vec{v}-\vec{u}|\ \ \sigma_{tb}(|\vec{v}-\vec{u}|)\ =\ \rho_1\rho_2 v\bar{\sigma}(v) \quad ....(1)$$

where $\bar{\sigma}(v)$ is the effective cross-section for incident particles with speed *v*. The cross-section appearing on LHS of Eq.(1) is the cross-section for the two-body neutron-nucleus interaction of the given type, for a given relative speed $|\vec{v}-\vec{u}|$. Assuming that target particles have Maxwell-Boltzmann distribution of velocities, one finds the exact ideal gas expression for the effective cross-section[4] as

$$\bar{\sigma}(v) = \frac{1}{\pi^{1/2}}\int_0^{\infty}\frac{dw}{uT}\frac{w^2}{v^2}\left(\exp\left(-\frac{(v-w)^2}{uT^2}\right)-\exp\left(-\frac{(v+w)^2}{uT^2}\right)\right)\sigma_{tb}(w) \quad ....(2)$$

where $\vec{w}=\vec{v}-\vec{u}$ is the relative velocity.

The two-body neutron-nucleus cross-section $\sigma_{tb}(w)$ can not be obtained from measured neutron data directly, because measured data give integrated cross-sections between neutrons of given speed and target nuclei that have a distribution of speeds. An alternative is to use the Breit-Wigner single level *s*-wave expression whenever one deals with a isolated *s*-wave resonance or a series of such resonances [2,5]. Values of the resonances parameters of interest can be obtained from published data tables, for example from the NNDC data base[6].

Using the resonances parameters from the NNDC data base, the effective cross-sections were calculated for the first large s-wave resonance in ^{238}U+n and ^{239}U+n capture reactions and the results are presented in Fig.1 as a function of ion lab energy (calculated from *v* of U ions) in the range from 10 eV to 3×10^3 eV.

Plots of the resonance peaks obtained using the resonances parameters are given in Fig.2 for reference. Projectiles of ^{238}U of energy 1570 eV, when incident on a thermal neutron column (of T=293 K), have maximum cross-section of 580 b to induce the neutron capture resonance that occur in normal ^{238}U(n,γ) reaction at incident neutron energy of 6.67 eV. Similarly, projectiles of ^{239}U

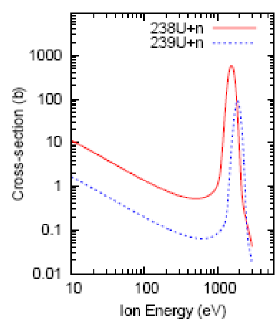

Fig. 1 Effective cross-sections as a function of ion energy, calculated for ion-beam thermal-neutron reactions 238U+n (continuous line) and 239U+n (dashed line).

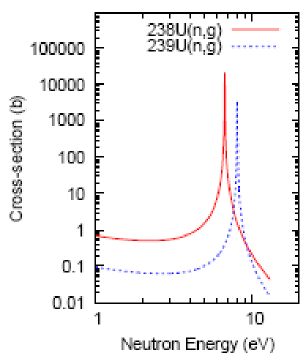

Fig. 2 Capture cross-sections as a function of neutron energy, calculated using the Breit-Wigner formula for ^{238}U(n,γ) (continuous line) and ^{239}U(n,γ) (dashed line) reactions.

of energy 1890 eV have maximum cross-section of 92 b to induce the neutron capture resonance that occur in normal ^{239}U(n,γ) reaction at incident neutron energy of 8.01 eV. Broadening of the peaks (FWHM of 325 eV and 365 eV, respectively for ^{238}U+n and ^{239}U+n capture reactions) and lowering of the peak cross-sections are very large in Fig.1 and this is because neutron thermal velocities are relatively very large and cause large Doppler effects.

The results suggest that by controlling the ion energy, the relative speeds can be matched to a chosen resonance value. Besides, the use of moving ions can facilitate for online transmutation-isotope-separation, for example, in 238U+n reaction, after the neutron capture, the compound nuclei (239U) formed can be separated from primary beam almost immediately after their formation, using well established electromagnetic mass-separation methods. The primary beam can be re-circulated while the separated 239U can be implanted on suitable substrates or re-accelerated for applications.

Summary

In this work a new concept of ion-beam thermal-neutron interaction for inducing neutron resonance reactions has been discussed. A scheme for effective cross-section calculation in such reactions has been presented. The effective cross-sections for the first large s-wave resonances in ^{238}U+n and ^{239}U+n capture-reactions, induced by ion-beams of ^{238}U and ^{239}U, respectively, when incident on a thermal neutron column, have been calculated. It has also been pointed out that use of ion-beams in this manner will facilitate online-separation of the transmuted-isotopes.

References

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