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THE CROSS SECTION OF INELASTIC NEUTRON ACCELERATION FOR INDIUM ISOMERS

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Abstract: The cross sections of inelastic neutron acceleration have been obtained from the excitation curves for ^{113m}In and ^{115m}In using the principle of detailed balance, and have been calculated theoretically. The average energy transferred to the neutron in a single collision is positive below 0.25 MeV and both isomers are not the usual moderators, but are the "accelerators" of neutrons.

If a neutron collides with an excited nucleus, the inelastic neutron acceleration (INNA) in which the neutron carries away the excitation energy [2]) is possible with an observable cross section. The inversely populated medium containing mainly long-lived nuclei (isomers) can in principle act as a neutron accelerator due to the multiple INNA reactions [3]). To verify this possibility it is necessary to know the energy dependence of the acceleration and slowing down cross sections for various isomers.

The INNA cross section $\sigma_{m\to 0}(E)$ can be obtained from the experimental cross section of the inverse reaction, i.e. the excitation of the isomeric level by neutrons $\sigma_{0\to m}(E)$:

$$\sigma_{m\to 0}(E_1) = \frac{2I_0+1}{2I_m+1}\frac{E_2}{E_1}\sigma_{0\to m}(E_2),$$

$$\frac{A}{A+1}E_1 = \frac{A}{A+1}E_2 - \varepsilon_m, \tag{1}$$

where I_m and I_0 are the spins of the isomeric and the ground states respectively; ε_m is the isomeric level energy, and E_1 and E_2 are the neutron energies in the lab system for the direct and inverse reaction, respectively.

To determine $\sigma_{m\to 0}(E)$ at low energies one should measure $\sigma_{0\to m}(E)$ near the threshold. These experiments require good energy resolution since $\sigma_{0\to m}(E)$ is small in magnitude and increases quickly with energy. If the measured quantity is the total amount of the isomer formed, then in order to exclude the population of the isomeric level through the higher levels the energy of the incident neutron should not exceed the corresponding threshold.

Recently Santry and Butler [1]) have carried out measurements satisfying the

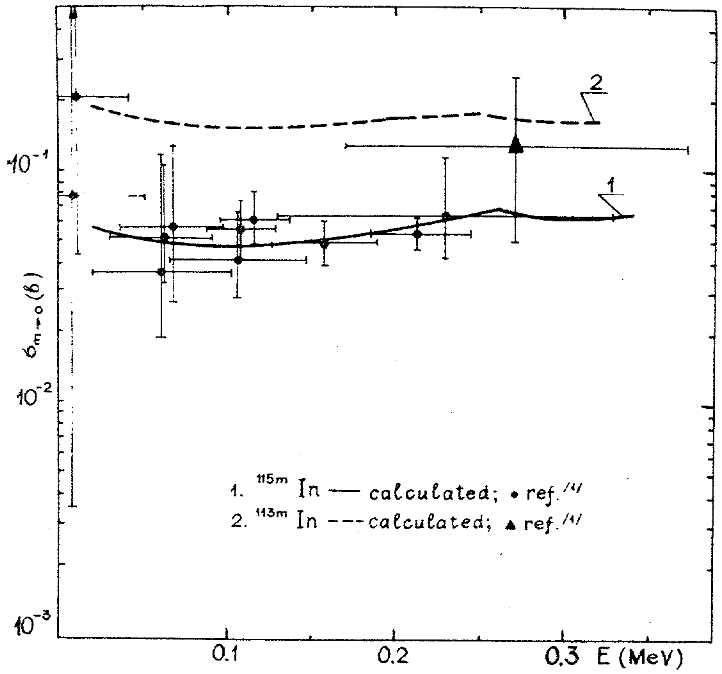

Fig. 1. The cross section of inelastic neutron acceleration on indium isomers.

above requirements on ^{115m}In [$\varepsilon_m = 0.336$ MeV, $I_0 = \frac{9}{2}^+$, $I_m = \frac{1}{2}^-$, $\tau_m = 6.5$ h, ref. [12])]. The acceleration cross section $\sigma_{m\to 0}(E)$ calculated from the Santry and Butler data using (1) is shown in fig. 1. The energy resolution in their experiments was 0.02–0.04 MeV, so that their low-energy results give in fact the lower limit to the acceleration cross section. Fig. 1 demonstrates that in the incident neutron energy range 0.1–0.25 MeV, $\sigma_{m\to 0}(E)$ is of the order of 0.05 b.

The cross section $\sigma_{m\to 0}(E)$ can be also calculated using the optical model with the help of the Hauser-Feshbach formulae [taking into account the Moldauer width fluctuation correction [4])].

The result of such a calculation is shown in fig. 1 for a spherical potential with the following parameters:

$$U(r) = -Vf(x_1) + \frac{\lambda_\pi^2}{a_1 r} V_{\text{s.o.}} \frac{\mathrm{d}}{\mathrm{d}x_1} f(x_1)\boldsymbol{l}\cdot\boldsymbol{\sigma} + 4iW \frac{\mathrm{d}}{\mathrm{d}x_2} f(x_2);$$

$$x_i = (r - r_{0i}A^{\frac{1}{3}})/a_i; \qquad f(x_i) = (1+e^{x_i})^{-1}; \qquad (2)$$

$$r_{01} = 1.24 \text{ fm}; \quad r_{02} = 1.26 \text{ fm}; \quad a_1 = 0.62 \text{ fm}; \quad a_2 = 0.58 \text{ fm};$$

$$V = 49.5 \text{ MeV}; \quad V_{\text{s.o.}} = 6.2 \text{ MeV}; \quad W = 1.4 \text{ MeV}.$$

Almost the same potential has been used by Lagrange for the calculation of ^{89}Y and ^{93}Nb cross sections [5]). Lagrange obtained the parameters of the potential by fitting the strength functions for s- and p-neutrons (S_0 and S_1), the potential scattering radius R' and the total cross section $\sigma_t(E)$ (SPRT method). Following the idea of the SPRT method we have varied the imaginary part of the optical potential to fit the experimental value of $S_0 = (0.26 \pm 0.03) \times 10^{-4}$ for ^{115}In [ref. [6]]. The calculated total cross section coincides with experiment [7]) to 10% accuracy. The radiative capture has not been taken into account owing to its small influence on the inelastic acceleration.

The calculated and the experimental values of $\sigma_{m\to 0}(E)$ coincide to an accuracy of 20%. A more accurate calculation of $\sigma_{m\to 0}(E)$ will be reasonable only after a refinement of experimental data, and first of all after improvement in the energy resolution.

Knowing the cross sections $\sigma_{m\to 0}(E)$, $\sigma_t(E)$ and the average cosine of the scattering angle $\bar{\mu}(E)$ one can calculate the average energy $\langle \Delta E \rangle$ transferred to the neutron by the isomer. Here, $\langle \Delta E \rangle$ is the difference between the average energy transferred to the neutron inelastically $\langle \Delta E \rangle_{in}$ and the recoil energy $\langle \Delta E \rangle_r$ where [3])

$$\langle \Delta E \rangle_{in} = \frac{A}{A+1}\left(\frac{\sigma_{m\to 0}}{\sigma_t}\varepsilon_m - \sum_{i=2}\frac{\sigma_{m\to i}}{\sigma_t}\varepsilon_i\right),$$

$$\langle \Delta E \rangle_r = \frac{2AE}{(A+1)^2}(1-\bar{\mu}), \qquad (3)$$

$$\langle \Delta E \rangle = \langle \Delta E \rangle_{in} - \langle \Delta E \rangle_r .$$

Here $\sigma_{m\to i}$ is the cross section for the slowing down on higher levels. The values of $\langle \Delta E \rangle_{in}$ and $\langle \Delta E \rangle_r$ calculated using the experimental data on σ_t [ref. [7]]] and $\bar{\mu}$

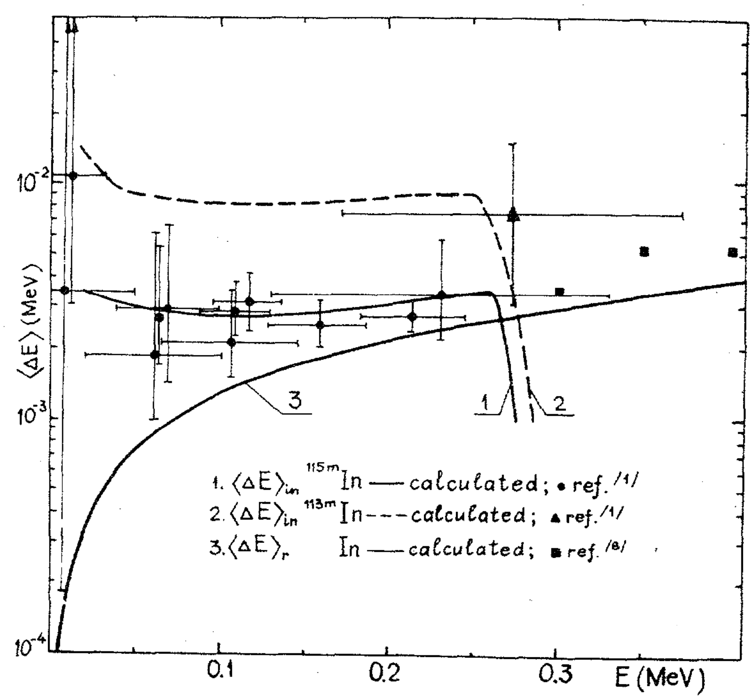

Fig. 2. The average energy transferred to the neutron by the isomer in a single collision.

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[ref. [8]] for ^{115}In, as well as those calculated using the optical model, are shown together in fig. 2. It can be seen from fig. 2 that above the threshold of the next level [$\varepsilon_2 = 0.26$ MeV, $I_2 = \frac{5}{2}^-$, ref. [12]], $\langle \Delta E \rangle_{\text{in}}$ decreases rapidly. Fig. 2 demonstrates that in the energy interval 0.02–0.25 MeV, $\langle \Delta E \rangle$ is positive, i.e. the isomeric nucleus $^{115\text{m}}$In is the neutron "accelerator" (and not a moderator as the usual nuclei in the ground state are).

The very fact that there exist isomeric nuclei which act as neutron accelerators had been demonstrated earlier theoretically for $^{85\text{m}}$Kr and $^{87\text{m}}$Sr [ref. [9]] (which are M4 isomers as well as $^{115\text{m}}$In). In the energy region considered the main contribution to $\sigma_{\text{m}\to 0}(E)$ is due to the p-wave in the entrance channel and the d-wave in the exit channel [9]), and ($k^2 = 2mE/\hbar^2$)

$$\sigma_{\text{m}\to 0}(E) \approx \tfrac{5}{4}\pi k^{-2} T_{2,\frac{5}{2}}(E+\varepsilon_{\text{m}}), \tag{4}$$

where $T_{2,\frac{5}{2}}(E+\varepsilon_{\text{m}})$ is the transmission coefficient for d-neutrons with total angular momentum $\frac{5}{2}$. The value of $T_{2,\frac{5}{2}}(E+\varepsilon_{\text{m}})$ is proportional to the strength function $S_{2,\frac{5}{2}}$. The latter should follow the A-dependence of the S_0 because their maxima are located near one another. This is due to the proximity of the values of A for which the $s_{\frac{1}{2}}$ and $d_{\frac{5}{2}}$ neutron single particle states coincide with the binding energy [10]). Thus for small S_0 the value of $S_{2,\frac{5}{2}}$ (and hence of $\sigma_{\text{m}\to 0}$) will be also small. For $^{87\text{m}}$Sr [$\varepsilon_{\text{m}} = 0.388$ MeV, ref. [13]], S_0 equals $(0.26 \pm 0.06) \times 10^{-4}$ [ref. [6]] and is close to that for $^{115\text{m}}$In, so that the values of $\sigma_{\text{m}\to 0}(E)$ for $^{87\text{m}}$Sr and $^{115\text{m}}$In should be also close to each other. These values are about three times less than those calculated in ref. [9]), where the imaginary part of the optical potential had been taken from ref. [11]) and had not been fitted by the SPRT method. The conclusion that $^{87\text{m}}$Sr is a neutron accelerator still holds, though the boundary of the region where $\langle \Delta E \rangle > 0$ decreases to 0.1 MeV.

From the previous considerations it is clear that for the nuclei with large S_0, the cross section of the INNA reaction should be several times greater than for those with small S_0. Let us consider for example $^{113\text{m}}$In [$\varepsilon_{\text{m}} = 0.392$ MeV, $I_{\text{m}} = \frac{1}{2}^-$, $I_0 = \frac{9}{2}^+$, $\tau_{\text{m}} = 2.7$ h, ref. [12]] for which $S_0 = (0.85 \pm 0.20) \times 10^{-4}$ [ref. [6]]. The fit gives $W = 5.3$ MeV instead of 1.4 MeV for $^{115\text{m}}$In. For such a value of W, $\sigma_{\text{m}\to 0}(E)$ and $\langle \Delta E \rangle_{\text{in}}$ exceed the corresponding values for $^{115\text{m}}$In by a factor of more than two (see figs. 1 and 2).

Thus, the existence of nuclei which are neutron accelerators ($\langle \Delta E \rangle > 0$) in the energy range 0.02–0.25 MeV among M4 isomers can be considered established.

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