Neutron cross sections of the isomeric nuclei Kr^{85m}, Sr^{87m}, and Nb^{91m}

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(Submitted June 20, 1975)
Yad. Fiz. **23**, 1186–1189 (June 1976)

Inelastic neutron acceleration and retardation cross sections are calculated in the Hauser-Feshbach formalism. In the 0.02–2-MeV range the acceleration cross section is on the order of tenths of a barn. For the Sr^{87m} nucleus the mean energy given to a neutron in a single collision is positive up to 0.5 MeV. Thus, the isomeric nucleus acts not as a moderator but as an accelerator of neutrons.

PACS numbers: 28.20.Cz, 28.20.Lh, 27.50.+e, 27.60.+j

It was shown earlier[1] that in an inversely populated isomeric medium, neutron energies can be considerably greater than the isomer excitation energy, ε_m, owing to multiple inelastic scattering. For the calculation of neutron spectra in real systems it is necessary to know the energy dependence of neutron inelastic acceleration and retardation cross sections for specific isomers.

In the present paper we calculate these cross sections in the 0.02–2-MeV range using the Hauser–Feshbach formalism[2] with allowance for the Moldauer correction for fluctuations in the neutron widths.[3] The calculations are performed for the near-magic nuclei Kr^{85m} ($\varepsilon_m = 0.305$ MeV, $\tau = 6.4$ hr[4]), Sr^{87m} ($\varepsilon_m = 0.388$ MeV, $\tau = 4.1$ hr[5]), and Nb^{91m} ($\varepsilon_m = 0.104$ MeV, $\tau = 90$ days[6]), which undergo an $M4$ transition between $I_m = \frac{1}{2}^-$ and $I_g^\pi = \frac{9}{2}^+$ levels. For M transitions the acceleration reaction proceeds with a neutron spin flip, owing to which it is necessary to transfer to the nucleus one less unit of angular momentum than for E transitions of the same multipolarity.[7] The choice of near-magic nuclei is connected with the low level density, which raises the energy of the first post-isomeric level and also decreases the competition of radiative capture and inelastic excitation of higher-lying levels. The lower spin of the isomeric level increases the statistical factor $g = (2J+1)/2(2I_m+1)$ for the cross section for formation of a compound nucleus with spin J ($I_m < J < I_g$).

In the calculations we have used the penetrabilities $T_{lj}(E)$ ($j = l \pm \frac{1}{2}$, l is the orbital angular momentum of the neutron) calculated for an optical potential of the Woods–Saxon type with surface absorption and spin-orbit coupling with the parameters taken from Perey and Perey.[8] Radiative capture was not considered because it is small. The use of another potential, the parameters of which were chosen to describe the total and differential neutron scattering cross sections for Nb^{93},[9] gives an acceleration cross section differing only by several percent from the cross sections calculated with the potential from Perey and Perey.[8] On the other hand, the cross sections for inelastic excitation of the levels of Nb^{93} (including also levels with a large spin difference $\Delta I = 3$), calculated with the potential from Perey and Perey, agree satisfactorily with the experimental data.[9]

The calculated cross section for inelastic acceleration of neutrons by isomers $\sigma_g(E)$ is on the order of tenths of a barn (Fig. 1). In the energy region near $0.5\,\varepsilon_m$ the cross section $\sigma_g(E)$ has a dip. In this region the main contribution to the cross section comes from the p wave in the entrance channel and the d wave in the exit channel; thus, in the Hauser–Feshbach model ($k^2 = 2mE/\hbar^2$)

$$\sigma_g(E) \sim \frac{5}{4} k^{-2} T_{1,3/2}(E) \frac{T_{2,5/2}(E+\varepsilon_m)}{T_{1,3/2}(E) + T_{2,5/2}(E+\varepsilon_m)} \sim \frac{5}{4} k^{-2} T_{2,5/2}(E+\varepsilon_m). \quad (1)$$

Since $T_{lj} \sim k^{2l+1}$, $\sigma_g(0.5\,\varepsilon_m) \sim \varepsilon_m^{3/2}$, and as the energy of the isomeric transition decreases, the minimum cross section falls off. The Moldauer correction does not qualitatively change this result. According to (1) for $E \ll \varepsilon_m$ we find $\sigma_g(E) \sim E^{-1}$, but for energies on the order of 10 keV and below the cross section should have a resonance structure, so the approximation of the optical model is inapplicable. At very small energies the main contribution comes from the s wave in the entrance channel and the f wave in the exit channel, so that the acceleration cross section is subject to a "$1/v$" law.

To the right of the dip with increasing energy there is a rise in $\sigma_g(E)$ due to both the growth of $T_{2,3/2}(E+\varepsilon_m)$ and the larger contribution of waves with higher angular momenta. For $E \gg \varepsilon_m$ the inelastic acceleration cross sections ought to be comparable for nuclei with similar A; however, the competition of opening channels for the excitation of higher-lying levels restricts any further growth of $\sigma_g(E)$. Near the threshold for excitation of the i-th level there should be found in $\sigma_g(E)$ near-threshold singularities.[10] In the Hauser–Feshbach model for $E < \varepsilon_i$ there are no near-threshold singularities, and for $E > \varepsilon_i$ in the denominator of fractions like (1), proportional to the decay probability of the compound nucleus over all channels, there appears the ad-

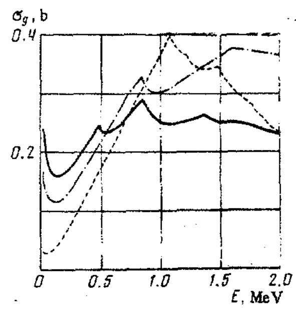

FIG. 1. Inelastic neutron acceleration cross section $\sigma_g(E)$ for the isomers Kr^{85m} (dash-dot curve), Sr^{87m} (solid curve), and Nb^{91m} (dashed curve).

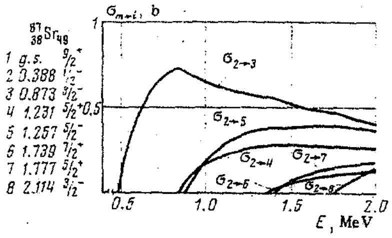

FIG. 2. Level diagram for Sr^{87} and cross sections for neutron excitation from the isomeric state $\sigma_{m\to i}(E)$.

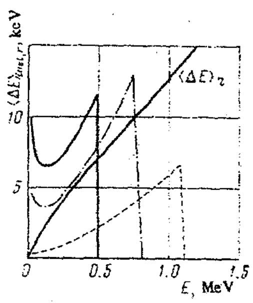

FIG. 3. Mean energy $\langle\Delta E\rangle_{\rm inel}$ transferred to a neutron in an inelastic collision with the isomers Kr^{85m} (dash dot curve), Sr^{87m} (solid curve), and Nb^{91m} (dashed curve); $\langle\Delta E\rangle_r$ is the mean recoil energy for Sr^{87m}.

ditional term $T_{l',j'}(E-\varepsilon_i)\sim(E-\varepsilon_i)^{l'+1/2}$. For the i-th level with spin-parity I_i^{π} the compound nucleus is always found with a spin J_1, for which $l'=0$, which gives square-root singularity, making a more appreciable change in $\sigma_g(E,J_1)$ near threshold. The contribution, however, from $\sigma_g(E,J_1)$ to $\sigma_g(E)$ can turn out to be small, so that the change in $\sigma_g(E)$ will be determined by the values of $l'>0$, not exerting any influence immediately in the vicinity of the threshold. Levels with different I_i^{π} give different post-threshold behavior for the cross section. In turn, the excitation cross section for the i-th level $\sigma_{m\to i}(E)$ is itself also determined by the values of I_i^{π}. Fig. 2 shows the assumed level diagram[5] and the calculated inelastic neutron retardation cross section $\sigma_{m\to i}(E)$ (in the lab frame) for Sr^{87m}.

Knowing the cross sections, we can calculate[1] the mean energy transferred by an isomer to a neutron at rest in a single collision, $\langle\Delta E\rangle$:

$$\langle\Delta E\rangle=\frac{A}{A+1}\left\{\frac{\sigma_s}{\sigma_t}\varepsilon_m-\sum_i\frac{\sigma_{m\to i}}{\sigma_t}\varepsilon_i-\frac{2E}{A+1}(1-\bar{\mu})\right\}. \quad (2)$$

Here $\sigma_t(E)$ is the total scattering cross section, and $\bar{\mu}$ is the mean cosine. Assuming the scattering through the compound nucleus to be spherically symmetric, we can find $\bar{\mu}$ (and σ_t) in the optical-model approximation. In Fig. 3 we show the energy loss due to recoil $\langle\Delta E\rangle_r=2E(1-\bar{\mu})A/(A+1)$ for Sr^{87m}, and also the mean energy transferred to the neutron by purely inelastic means $\langle\Delta E\rangle_{\rm inel}=\langle\Delta E\rangle-\langle\Delta E\rangle_r$ (the first two terms of Eq. (2)) for all three isomers. For Nb^{91m} in the energy range in question $\langle\Delta E\rangle_{\rm inel}<\langle\Delta E\rangle_r$ and $\langle\Delta E\rangle<0$; i.e., the isomer Nb^{91m} is a typical moderator of neutrons. For Sr^{87m} with $E<0.5$ MeV the mean energy given to the neutron is positive ($\langle\Delta E\rangle_{\rm inel}>\langle\Delta E\rangle_r$), so up to $E\sim0.5$ MeV Sr^{87m} is no longer a moderator but an accelerator of neutrons. Above the point of intersection of the curves of $\langle\Delta E\rangle_{\rm inel}$ and $\langle\Delta E\rangle_r$ as the result of inelastic retardation in post-isomeric levels the mean energy given to a neutron becomes negative, abruptly increasing in absolute value. For Kr^{85m} up to $E=0.76$ MeV $\langle\Delta E\rangle>0$, but in the range 0.2–0.6-MeV this assertion lies within the limits of accuracy of the calculation.

In conclusion it should be noted that the appearance of new information on the number, spins, and parities of the levels as well as on the behavior of the strength functions of s, p, and especially d neutrons can change the calculated cross sections somewhat. Nevertheless, this will hardly affect the fact that neutron accelerators exist over a fairly wide energy range.

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Translated by E. Aronson