Acceleration of thermal neutrons by ^{152m}Eu isomeric nuclei

I. A. Kondurov, E. M. Korotkikh, and Yu. V. Petrov
B. P. Konstantinov Institute of Nuclear Physics, USSR Academy of Sciences

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Acceleration of thermal neutrons by isomers was observed for the first time. For ^{152m}Eu the cross section for inelastic acceleration is: $\sigma_{in} = 0.28 \pm 0.06$ b.

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An inelastic scattering reaction with a noticeable cross section, in which the excitation energy is transferred to the scattered neutron, is possible as a result of the interaction of neutrons with nuclei in the excited state.[1] Thus, for ^{113m}In and ^{115m}In isomers with a lifetime of several hours[2] the calculations based on the optical model and the recalculation of experimental data for the back reaction give a value of about 0.1 b for the cross section of inelastic acceleration in the energy region of ~0.1 MeV.[3] So far, however, a direct reaction of neutron acceleration could not be observed, in spite of several attempts.[4–6] Below we present the results of measurements in which acceleration of thermal neutrons by a ^{152m}Eu nucleus was observed (M3 transition, $I^{\pi}_{m} = 0^-$, $I^{\pi}_{g} = 3^-$, $E_m = 48.5$ keV, $\tau_m = 13.42 \pm 0.07$ h).[2]

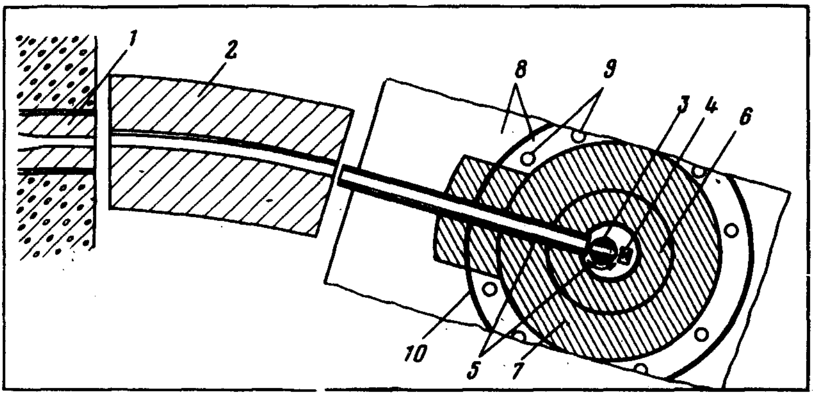

FIG. 1. Experimental setup: 1, reactor channel; 2, logarithmic neutron pipe[7]; 3, rotating boron shutter; 4, target; 5, boron shield; 6, removable γ-ray shield; 7, lead shield; 8, plastic moderator; 9, neutron counters; 10, cadmium shield.

1. The ^{152m}Eu isomer was obtained by irradiating samples containing 25 mg of separated ^{151}Eu for 20 hours in the VVR-M LIYaF reactor. The thermal neutron flux at the location of irradiation, which was measured by using iron foils, varied from one experiment to another within the limits $(1-2)\times 10^{14}$ $n/\text{cm}^2\cdot$sec. After irradiation the target, which contained several tenths mg of the isomer, was placed in the neutron beam (Fig. 1). Because the predicted effect is small, we modulated the thermal neutron beam by a shutter in order to isolate it. The measurement cycle was 22 sec. The accelerated neutrons were slowed down in plastic and detected by proportional

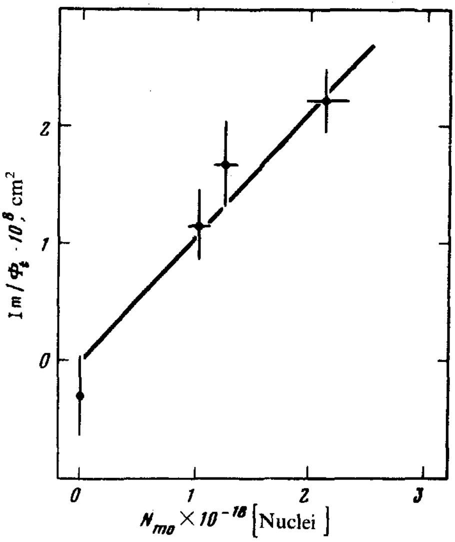

FIG. 2. The ratio of the number of recorded accelerated neutrons I_m to the incident flux of thermal neutrons Φ_{th} as a function of the number of isomeric nuclei N_{m0} (the straight lines has a slope $\bar{s}$).

counters. The counters were protected from the decay γ-ray quanta whose intensity approached almost 10^3 Ci and exceeded the predicted intensity of the accelerated neutrons by a factor of 10^{12}. For this purpose, the target was surrounded by a lead shield.

The detector's recording efficiency of fast neutrons, which was measured by a calibrated Sb-Be source, was $\epsilon = 6.6 \pm 0.7\%$. The signal from the detector, which corresponds to an open and closed shutter [$I(t)$ and $I_b(t)$, respectively], was recorded separately. In the difference of these counts, which contains the effect to be measured, we separated the component that decreases exponentially with the constant τ_m the least-squares method: $I(t) - I_b(t) = I_m \exp(-t/\tau_m) + I_0$. The measurement accuracy in these experiments was limited by the background count (I_b = 13–28 pulses-/sec) and one error in each individual experiment reached 0.3–0.5% of the background.

Control experiments were performed to verify the absence of the influence of extraneous factors.[8] The experimental setup proved to be stable within the limits of statistical error. It was shown that the false effects, which were produced as a result of cutting off the thermal neutrons or removal of the excited isomeric nuclei, were missing. Additional experiments (replacement of a removable lead shield by an iron shield) established that the fast photoneutrons, which were produced by capture γ rays from the isomer and from the lead shield of the neutron counters, had no effect.

2. The cross section of inelastic acceleration was determined by

$$s = \frac{I_m}{N_{m0}\Phi_t} = \delta_r \delta_t \epsilon \sigma_{in} . \quad (1)$$

Here Φ_t is the thermal neutron flux with a velocity $V = 2200$ m/sec, which is incident on the target's surface, δ_t relates the average target flux $\langle \Phi_t \rangle$ to Φ_t, the product $N_{m0}\delta_r = N_m$ gives the total number of isomeric nuclei after irradiation in the reactor, N_{m0} denotes the number of stored nuclei, disregarding the blocking effects due to irradiation in the reactor channel, and the coefficient δ_r takes these effects into account, and finally, ϵ denotes the recording efficiency of the accelerated neutrons.

The weighted mean of the value s from the nine experiments turned out to be $\bar{s} = (1.08–0.12) \times 10^{-26}$ cm^2, for which $\chi^2 = 1.19$. This means that the accelerating effect of thermal neutrons is observed at the level of eight standard deviations. The data are shown in Fig. 2, in which the results of some experiments are represented by a single point.

The average neutron flux in the target was measured as the half-sum of its value at the edges: $\delta_t = 0.83–0.03$. The self-shielding and blocking coefficient in the reactor δ_t, which was obtained by measuring the absolute activation of the ground state of ^{152g}Eu, turned out to be $\delta_r = 0.7 \pm 0.1$. In calculating the value of σ_{in}, we disregarded the possible burnup of the isomer, since the individual measurements of the x-ray lines using a silicon spectrometer indicated that there was no burnup up to fluxes of 1.2×10^{14} n/cm^2 sec within a 13% accuracy. From the last equality in Eq. (1) for the cross section of neutron acceleration at the velocity $V = 2200$ m/sec we obtain the value

$$\sigma_{in} = 0.28 \pm 0.06 \text{ b} \tag{2}$$

3. We can obtain an approximate theoretical estimate of σ_{in}^* by treating the cross section as a sum of the resonances and substituting their average values for all the widths and distances between the levels (D), and also by assuming that the distance to the nearest resonance is equal to $D/2$ [9]:

$$\sigma_{in}^*(E) = \frac{\pi^3}{k_0^2} S_0^2 \frac{T_{2,5/2}(E_m)}{T_0(E_0)} \sqrt{\frac{E_0}{E}} , \tag{3}$$

where k_0 is the wave vector of the neutron at the energy $E_c = 1$ eV, S_0 is the strength function for the s neutrons, and T_0 and $T_{2,5/2}$ are the penetrabilities for the s and d neutrons, respectively. For ^{152g}Eu the experimental value is $S_0 = (3.6 \pm 1.2)\times 10^{-4}$ [10] and the evaluating, optical-model calculation for the spherical nucleus gives $T_{2,5/2}(E_m)/T_0\,(E_0) \approx 0.4$, so that $\sigma_{in}^* \approx 2$ b at $E = 0.025$ eV. Taking into account the fluctuations of the parameters, the most probable value is $\sigma_{in}^T \approx 0.15\ \sigma_{in}^*$,[9] and the theoretical estimate gives $\sigma_{in}^T \approx 0.3$ b. Although this value is valid only with accuracy to an order to magnitude, its agreement with the measured cross section (2) shows that the (n,n'') reaction offers no appreciable hindrance to the nuclear transition ^{152m}Eu $\rightarrow ^{152g}$Eu, whereas the γ-ray transition is hindered by a factor of more than 10^6–10^8.[11]

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