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RATIO OF THE CROSS SECTIONS FOR THE PRODUCTION OF THE ISOMER AND GROUND STATES OF NUCLEI IN THE (p, n) REACTION AT ENERGIES FROM THE THRESHOLD TO 20 MeV

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Cross sections for the reactions $Y^{89}(p, n)Zr^{89m}$, $Y^{89}(p, n)Zr^{89g}$, $Pr^{141}(p, n)Nd^{141m}$, $Pr^{141}(p, n)Nd^{141g}$, $Au^{197}(p, n)Hg^{197m}$, and $Au^{197}(p, n)Hg^{197g}$ were measured with the purpose of studying the mechanism of nuclear reactions for incident-particle energies ranging from the threshold of the (p, n) reaction up to 20 MeV. The ratios of the cross sections for the production of isomer and ground states in (p, n) reactions are discussed under the assumption that the compound-nucleus mechanism is involved.

INTRODUCTION

In recent years numerous experiments have shown that for incoming-nucleon energies of 10—30 MeV the effect of direct interactions becomes appreciable along with reactions occurring via the formation of a compound nucleus. To elucidate the role of direct interactions for incoming particles with energy up to 20 MeV, we have investigated the ratios of the cross section for the production of a nucleus in the isomer state, σ_m, to the cross section for the production of a nucleus in the ground state, σ_g, for (p, n) reactions on various nuclei.

The direct-interaction mechanism and the reaction with the production of a compound nucleus result in one and the same intermediate nucleus with approximately the same excitation energy, but with a different angular-momentum distribution. This in turn leads to different yields of the nuclear-reaction products, differing considerably in their spins, such as the ground and isomer states of the nucleus. If the (p, n) reaction occurs via the formation of a compound nucleus, then an incoming proton of low energy carries a small angular momentum into the intermediate nucleus, since the proton must overcome the centrifugal barrier. Consequently, the compound nucleus will have a spin close to the spin of the target nucleus. The emitted neutron, its energy being small, carries away a small angular momentum. The gamma cascade emitted by the nucleus after the emission of the neutron is likewise not capable of changing the spin of the final nucleus considerably. Thus, the product nucleus has a spin close to that of the target nucleus. Experiments carried out with 6.7-MeV protons[1] do not contradict such an assumption. With increasing energy the incoming proton introduces a large angular momentum into the compound nucleus, and the final nucleus will be produced with a broad range of spin states, and its decay to a given final state will depend on the statistical weight of these states.[2] Thus, from the standpoint of the statistical model, the ratio σ_m/σ_g will for high energies of the incoming particle be determined by the ratio of the statistical weights of these states.

If the (p, n) reaction occurs via the direct-interaction mechanism, then the reaction results in a final nucleus with a spin which does not differ considerably from the spin of the target nucleus.

EXPERIMENTAL METHOD

The cross sections were measured by determining the induced activity. The excitation functions of the (p, n) reactions were measured by the well-known method employing a stack of foils. The stack of foils with aluminum absorbers between the targets was irradiated with 20.2 ± 0.2 MeV protons in the linear accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences. The collimated proton beam, 1.1 cm in diameter, was incident on a stack of targets which was placed in vacuum and served as the bottom of a Faraday cylinder. The charge on the Faraday cylinder was measured by means of a current integrator whose linearity was checked within the range from 10^{-6} to 10^{-11} A.[3] The average accelerator current was on the order of 10^{-9} A. In studying short-lived activities, when it was impossible to employ the method of a stack of foils, the excitation function was obtained by irradiating the same target at various energies. The energy was varied with the aid of aluminum foils. The proton energy for each target of the stack was determined from the stopping-power curves for the corresponding substances, calculated from Bethe's formula,[4] for which the mean excitation energy of the atom was taken from the paper of Do In Seb.[5]

The Y^{89} and Pr^{141} targets were in the form of oxides $Y_2O_3 \cdot H_2O$ and PrO_4, while the gold was in the form of a free foil. The 3—8 mg/cm^2 thick oxide targets were prepared by depositing the oxide from a suspension of finely divided powder in acetone onto degreased aluminum backing. The gold foils obtained by electrodeposition were 5—30 mg/cm^2 thick. The target thickness was determined by weighing and by the x-ray absorption method, the difference between the two amounting to less than 5 percent.

The gamma radiation of the activity induced in the target was registered by a 3.0 × 1.5 cm NaI(Tl) crystal with an FÉU-11 photomultiplier. The pulses from the photomultiplier were amplified and entered a 100-channel pulse-height analyzer. The efficiency of the photon registration of the NaI(Tl) crystal was calculated by the Monte-Carlo method for a source-to-crystal distance of 3.6 cm.[6] To obtain the absolute activity of the gamma radiation, we measured the area under the photon peak of the gamma line and introduced a coefficient to account for the registration efficiency of the measured radiation and the solid angle. For all measured activities we plotted decay curves for precise subtraction of the background and the contribution of other activities. From the decay curves we obtained the activity of the sample at the end of the irradiation.

MEASUREMENT RESULTS AND DISCUSSION

The absolute cross sections were determined for a number of points; the excitation function was then normalized to these points. The accuracy in the determination of the absolute values of the cross sections was no worse than 30 percent. The ratios of the cross sections for the production of the isomer and ground states were measured with an accuracy of no worse than 20 percent.

$\underline{Y^{89}(p, n)Zr^{89}}$. The decay schemes for Zr^{89m} and Zr^{89g} were taken from the work of Dzhelepov and Peker.[7]

The cross section for the production of the isomer state with $T_{1/2} = 4.3$ min was measured by means of the line with $E_\gamma = 590$ keV. The oxygen contained in the $Y_2O_3 \cdot H_2O$ target gives rise to a rather intense ten-minute β^+ activity of the N^{13} nuclei produced in the $O^{16}(p, \alpha)N^{13}$ reaction, and at proton energies larger than 16 MeV there appears the two-minute β^+ activity of O^{15} produced in the $O^{16}(p, pn)O^{15}$ reaction. The measured 590-keV line was distinguished from the 510-keV annihilation gamma line by its half-life. The number of decays obtained from the gamma-ray intensity was corrected for the total internal-conversion coefficient α (the theoretical value $\alpha = 0.07$ was used[8]). The cross section for the production of the ground state was measured by means of the line with $E_\gamma = 910$ keV, introducing a correction for the internal conversion of gamma rays ($1 + \alpha = 1.04$). The results of the measurements of the cross sections as well as their ratios as a function of the incoming-proton energy are shown in Fig. 1.

The spin of the isomer state Zr^{89m} is $I_m = 1/2$, and the spins of the ground state and of the target nucleus are $I_g = 9/2$ and $1/2$ respectively. At proton energies somewhat above threshold the reaction occurs predominantly with the formation of the isomer state, since its spin is closer to the spin of the target nucleus. With increasing energy there is an increase in the role of states with higher spin, and the yield of the ground state with spin $I_g = 9/2$ increases. The ratio σ_m/σ_g, as can be seen from Fig. 1, decreases with increasing energy, a fact which corresponds to the conclusions of the theory of the compound nucleus. However, this ratio does not reach the ratio of the statistical weights. With increasing energy the role of direct interactions which lead to the formation of the state with spin $I_m = 1/2$ probably increases. The

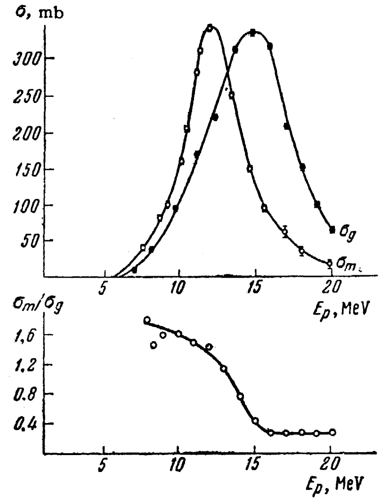

FIG. 1. Production cross sections of the isomer σ_m and ground σ_g states, and the ratio of these cross sections for the $Y^{86}(p, n)Zr^{89}$ reaction as a function of the proton energy (here and hereafter only statistical errors are indicated).

ratio of the statistical weights is 0.2. The experimentally measured value of σ_m/σ_g for 20-MeV protons is 0.3.

$Pr^{141}(p, n)Nd^{141}$. The decay scheme of the ground ground and isomer states of Nd^{141}, and also the characteristics of these states are taken from the work of James and Bingham.[9] The production cross section of the isomer state with $T_{1/2} = 1.04$ min was measured by means of the line with $E_\gamma = 760$ keV, introducing a correction for the internal conversion of the gamma transition $(1 + \alpha = 1.11)$. The cross section for the production of the ground state was measured from the x-ray emission of the Pr^{141} nuclei which are produced as a result of ϵ capture in Nd^{141} and decay with a half-life of 2.42 hours. The correction for the absorption of the x radiation in the wrapping of the NaI(Tl) crystal was determined for Cs^{137} with an x-ray quantum energy of 30.3 keV, and was interpolated for the 35.2-keV x-radiation of Pr. The cross section for the production of the ground state of Nd^{141} up to a proton energy of 11 MeV was measured by Olkowsky et al.[10] The values of the cross sections obtained from our results are somewhat higher than those published in that work. The measured cross sections and the ratio of the cross sections for the $Pr^{141}(p, n)Nd^{141}$ reaction are presented in Fig. 2.

The spin I_m of the isomer state of Nd^{141m} is 11/2, the spin I_g of the ground state is 3/2, and the spin of the target nucleus is 5/2. Applying the same arguments as for the preceding reaction, we see that the dependence of the cross sections on the proton energy corresponds in general to that predicted on the basis of the compound-nucleus mechanism. However, the measured ratio σ_m/σ_g at a proton energy of 20 MeV is considerably lower than the ratio of the statistical weights: the latter is 3, while the measured σ_m/σ_g is 1. We are inclined to ascribe this deviation to a contribution of direct interactions which lead to the formation of the ground state, consequently decreasing the ratio σ_m/σ_g.

$Au^{197}(p, n)Hg^{197}$. The decay scheme of the ground and isomer states of Hg^{197} and the characteristics of these states are known from the work of Dzhelepov and Peker.[7] The cross section for the production of the isomer state with $T_{1/2} = 24$ hours was measured from the line with $E_\gamma = 133$ keV, introducing a correction for the internal conversion $(1 + \alpha = 3.1)$. The production cross section of the ground state was measured from the compound line consisting of the x-ratiation of Pt^{197}, Au^{197}, and the 77-keV gamma line. The calculation of the cross sections was carried out by the method described in the work of Hansen et al.[11] At proton energies above 16 MeV a considerable contribution to the x-ray peak is due to the 6.2-day activity from the $Au^{197}(p, pn)Au^{196}$ reaction. This activity can be well separated from the 65-hour activity by means of its half-life. The measured cross sections for the production of the ground and isomer states of the nucleus in the $Au^{197}(p, n)Hg^{197}$ reaction as a function of the proton energy are shown in Fig. 3. Our results are in good agreement with the data of[11] for a proton energy of 13 MeV.

The Hg^{197} nucleus has an isomer level with spin

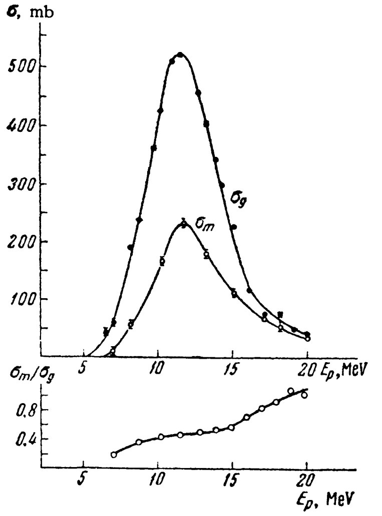

FIG. 2. The cross sections for the production of the isomer and ground states of Nd^{141} and the ratio of these cross sections for the $Pr^{141}(p, n)Nd^{141}$ reaction as a function of the proton energy.

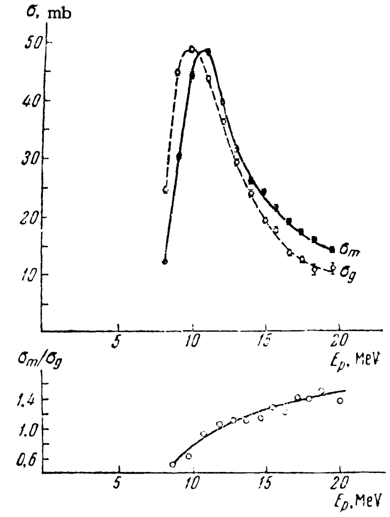

FIG. 3. The cross sections for the production of the isomer and ground states of Hg^{197} and the ratio of these cross sections for the $Au^{197}(p, n)Hg^{197}$ reaction as a function of the proton energy.

$I_m = 13/2$ which decays to the ground state with spin $I_g = 1/2$ through an intermediate level with spin $I_f = 5/2$. The spin of the target nucleus is 3/2. According to the statistical theory the cross section for the production of the ground state will be proportional to $2I_f + 1 + 2I_g + 1$, and that of the isomer state will be proportional to $- 2I_m + 1$. Within the precision of the experiment at a proton energy of 20 MeV the measured ratio σ_m/σ_g is equal to the ratio of the statistical weights. This reaction probably occurs predominantly via the production of a compound nucleus up to an incoming-proton energy of 20 MeV.

Our results of the measurements of the ratios of the cross sections for the production of the isomer and ground states of the nucleus for (p, n) reactions, and the results of[2] show that the dependence of the ratios on the proton energy up to 20 MeV follows in general the laws predicted by the statistical theory of compound-nucleus production. However, the experimentally obtained numerical values of σ_m/σ_g differ in some instances considerably from the values predicted by this theory.

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