SPINS AND PARITIES OF SOME STATES OF MOLYBDENUM ISOTOPES

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The angular distributions of protons from the (d, p) reactions on the $Mo^{92,94,95,96}$ isotopes are measured for 13.6-MeV deuterons. By comparing with the Butler theory, values of the angular momenta l_n for neutron capture in the ground and first excited states of the $Mo^{93,95,96,97}$ nuclei are obtained and possible values of the spins and parities of these states are determined.

INTRODUCTION

THE possibility of determining the angular momentum transferred to the target nucleus in (d, p) reactions from the shape of the angular distribution of the protons [1,2] makes the study of these reactions extremely valuable for nuclear spectroscopy, since it allows to ascribe parities and possible spin values to the states of the final nuclei. Recently, ever increasing attention is given to the investigation of the structure of intermediate nuclei with the aid of stripping reactions. In the region of nuclei with A ~ 100 the Coulomb barrier reaches values of 9 MeV, and at deuteron energies of 10—15 MeV the angular distribution of the nucleons is distorted by the Coulomb interaction of the deuteron and proton with the nucleus. However, the distortion is not so strong as to make the determination of the values of the transferred angular momentum ambiguous. This allows in most cases a reliable determination of the quantum characteristics of intermediate nuclei from stripping reactions.

This paper is devoted to an investigation of angular distributions of protons from (d, p) reactions on four molybdenum isotopes: $Mo^{92,94,95,96}$. The measurements were carried out on targets made of enriched isotopes in the form of polystyrene films containing metallic molybdenum powder. An ionization chamber, [3] with an absorber at the entrance window that excluded deuterons, served as the spectrometer. The 13.6-MeV deuteron beam was extracted from the cyclotron of the Physics Institute of the Ukrainian Academy of Sciences.

RESULTS AND DISCUSSION

The experimental angular distributions of some proton groups, corresponding to the ground and lower excited states of the final molybdenum isotopes are shown in Figs. 1—4. The same figures show the curves calculated in the simple stripping theory for the best values of the radius r_0 and various values of l_n.

The reaction $Mo^{92}(d, p)Mo^{93}$. From the proton angular distributions for transitions to the ground and first excited (0.91-MeV) state of Mo^{93} it is seen (Fig. 1) that the value of the angular momentum of the captured neutron is equal to 2 and 0 respectively, and consequently the possible spins and parities of the ground state are $3/2^+$ or $5/2^+$ and those of the excited state are $1/2^+$, since the spin and parity of the initial even-even Mo^{92} nucleus are 0^+.

With regard to the spin of the ground state of Mo^{93}, data obtained in the investigation of decay schemes of radioactive nuclei are available. Thus, Goldhaber and Hill [4] cite as possible values $5/2^+$ and $7/2^+$. In the book of Dzhelepov and Peker [5] in which spectroscopic data from work up to 1958 are

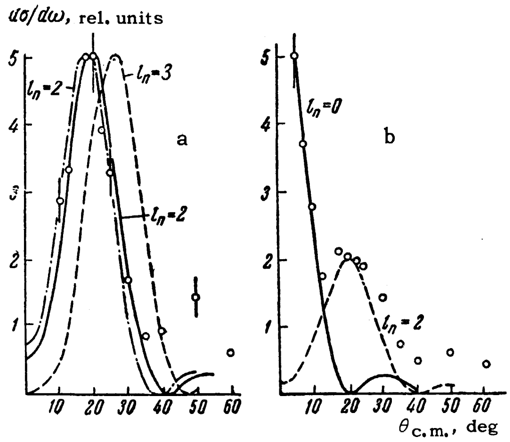

FIG. 1. Angular distributions of protons for the $Mo^{92}(d,p)Mo^{93}$ reaction: a — for the transition to the ground state of Mo^{93}, b — for the transition to the first excited (0.91-MeV) state. The curves were calculated by the simple stripping theory; the values of l_n are indicated on the curves, r_0 = 6.0 F.

collected, the spin of the ground state is given as $7/2^+$; however, Levi and Papineau[6] indicate that the most probable value is $5/2^+$. The value of $7/2^+$ disagrees with the shell model,[7] according to which, after the filling of the shell containing 50 neutrons, the $d_{5/2}$ state is filled, and the Mo^{93} nucleus has one neutron outside the filled shell.

It should be noted that the spins of the ground states of even-odd nuclei with the 51st neutron (Sr^{89}, Zr^{91}) are $5/2^+$; this value was also confirmed in the study of stripping reactions[7,8] (the angular distributions of protons, corresponding to the ground states of Sr^{89} and Zr^{91}, as in the case of Mo^{93}, indicate a transfer of angular momentum $l_n = 2$ to the nucleus).

Figure 1a shows the theoretical curve for $l_n = 4$ which would describe the proton angular distribution if the spin of the ground state of Mo^{93} were $7/2^+$. However, this curve is wide off the experimental data. Thus, the value of the spin is undoubtedly $5/2^+$.

As regards the first excited state of Mo^{93}, no information on its quantum characteristics is given in the book by Dzhelepov and Peker.[5] The obtained value of $1/2^+$ confirms once more that in the spectrum of the excited levels the $s_{1/2}$ state lies below the $g_{7/2}$ state (see [8,9]).

The reaction $Mo^{94}(d, p)Mo^{95}$. The angular distributions (Fig. 2) shown are not for protons corresponding to discrete levels of Mo^{95}, but those corresponding to several levels which could not be separated with our resolution. Thus the ground-state protons were registered together with the protons emitted in the transition to the 0.2-MeV level.[5] Since the angular momentum of the captured neutron is in this case 2 (Fig. 2a), the possible values of the spins are $3/2^+$ or $5/2^+$. Generally speaking, this agrees with the values of these states, $5/2^+$ and $3/2^+$ respectively, given in [5].

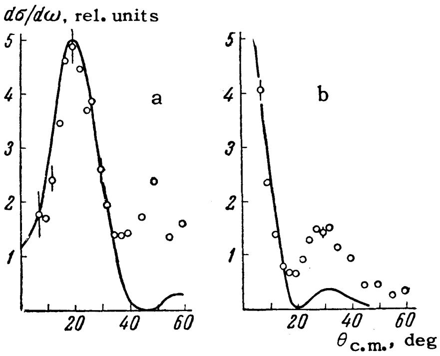

FIG. 2. Angular distributions of protons from the $Mo^{94}(d, p)Mo^{95}$ reaction: a – for transitions to the ground and excited (0.2-MeV) state of Mo^{95} ($l_n = 2$), b – for transitions to a number of states with energies 0.77-1.0 MeV ($l_n = 0$). In both cases $r_0 = 6.2$ F.

We note, however, that the main contribution to the angular distribution is evidently due to the protons corresponding to the transition to the ground state, which is probably a single-particle state, while the 0.2-MeV level can hardly be a single-particle level on account of the rather small splitting of the $d_{5/2}$ and $d_{3/2}$ states.

The group of protons, corresponding to excited states in the 0.77–1 MeV region includes, apparently, a whole series of levels.[10] From the fact that in the angular distribution there appears only the component corresponding to a value of $l_n = 0$, one can conclude that here the most intensively excited state is the single-particle $s_{1/2}$ state; this conclusion is also favored by the fact that the ratio of the cross sections of the ground and excited states is here of the same order of magnitude as for the $Mo^{92}(d, p)Mo^{93}$ reaction.

The reaction $Mo^{95}(d, p)Mo^{96}$. In contrast to the preceding reactions, the final nucleus of this reaction is even-even. The angular distribution of the protons corresponding to a transition to the ground state of Mo^{96} (Fig. 3a) is described by the theoretical curve with $l_n = 2$. The possible values of the spin are within the range $0^+–5^+$.

In studying the proton angular distribution from the (d, p) reaction on Zr^{91} for the transition to the first excited state of Zr^{92} (0.93 MeV, $J^\pi = 2^+$) it was found[8] that the angular momentum of the captured neutron $l_n = 2$, whereas according to the selection rules a transfer of angular momentum $l_n = 0$ is possible, since the spin and the parity of the ground state of Zr^{91} are $5/2^+$. The same situation occurs also in the case of the transition to the

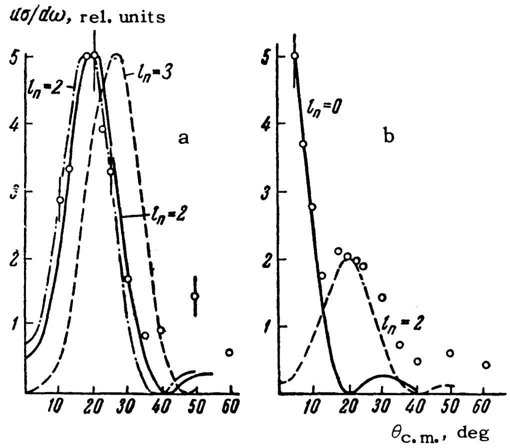

FIG. 3. Angular distribution of protons from the $Mo^{95}(d, p)Mo^{96}$ reaction: a – for transitions to the ground state of Mo^{96}, b – for transitions to the first excited (0.77-MeV) state; $r_0 = 6.6$ F. The dash and dot-dash curves are for a value of $r_0 = 7.3$ F determined from the formula $r_0 = (1.7 + 1.22\,A^{1/3})$ F.

first excited state of Mo^{96} (0.77 MeV, $J^{\pi} = 2^{+}$ [5]; however, as can be seen from the angular distribution (Fig. 3b), in this case the component corresponding to $l_n = 0$ appears strongly, which is obviously connected with the larger number of neutrons outside the closed shell: in Mo^{96} there are four, whereas in Zr^{92} there are two neutrons. Analogous cases of mixing of components with $l_n = 0$ and $l_n = 2$ were observed in transitions to the first excited 2^{+} states of even-even nuclei when the initial nucleus has a $5/2^{+}$ characteristic in the $O^{17}(d, p)O^{18}$ [11] and $Mg^{25}(d, p)Mg^{26}$ [12] reactions.

The reaction $Mo^{96}(d, p)Mo^{97}$. From Fig. 4 it is seen that the angular momenta l_n transferred to the nucleus are 2 and 0 for the case of the ground and excited (0.66-MeV) state respectively. The first of these values admits possible spins and parities $3/2^{+}$ and $5/2^{+}$; the value of $5/2^{+}$ agrees with that required by the shell model for the neutron configuration ($d_{5/2}$) and with the value given in [5].

The spin $1/2^{+}$ contradicts the value $7/2^{+}$ for the 0.665-MeV level given in [5], where it is shown that 99 percent of the beta transitions from Nb^{97} ($J^{\pi} = 9/2^{+}$) go to this level. We are probably dealing here with a case of two unresolved levels: $1/2^{+}$ and $7/2^{+}$. The state with the spin and parity $1/2^{+}$ was not observed in the investigation of the beta decay of Nb^{97} because the transition to this state is forbidden, and the absence of the component with $l_n = 4$ in the measured angular distribution is apparently explained by the small intensity of the transition to the $7/2^{+}$ state, in agreement with the theory of stripping reactions.

In conclusion let us dwell briefly on the problem of the radius in comparing the experimental data with the theory. In choosing the radius, experimenters commonly employ the empiral formula $r_0 = (1.7 + 1.22\,A^{1/3})F$. The radii obtained from this expression give in the majority of cases, excluding the very light nuclei, satisfactory agreement of the theory with experiment. However, with increasing atomic number (up to $A \sim 60$ at $E_d \sim 9$ MeV, or up to $A \sim 100$ at $E_d \sim 14$ MeV) it turns out that to obtain better agreement one must choose radii smaller than those given by the formula, i.e., we are confronted with the necessity of shifting the theoretical curves towards larger angles. This shifting of the experimental angular distributions is explained by the more complete theories of stripping reactions (see, for example, [13]), and is due to Coulomb effects. How a decrease of the radius can lead to ambiguity in the determination of the value of l_n can be partly seen from Fig. 3a, which shows the theoretical curves with r_0 calculated from the formula, and $l_n = 2$ and $l_n = 3$, and with a better fit for $l_n = 2$. It is seen that there is in this case no ambiguity in the determination of l_n. However, in other cases [for instance, for $Mo^{96}(d, p)Mo^{97}_{\text{ground}}$] the experimental angular distribution may occur midway between the theoretical curves for $l_n = 2$ and $l_n = 3$ with a radius calculated from the formula. This is chiefly explained, except for the aforementioned Coulomb effect, by the experimental independence of the position of the main maximum of the Q value of the reaction, naturally on condition that the transitions are to states with equal angular momenta. Thus, it can be seen from the present, and also from preceeding[7,8] work that the main maxima of the experimental angular distributions for $l_n = 2$ occur at angles of 20–22°, independently of the value of Q, whereas the theoretical curves are shifted with decreasing Q towards smaller angles. Similar experimental results have also been observed at an energy of 10 MeV[14] and 15 MeV.[15]

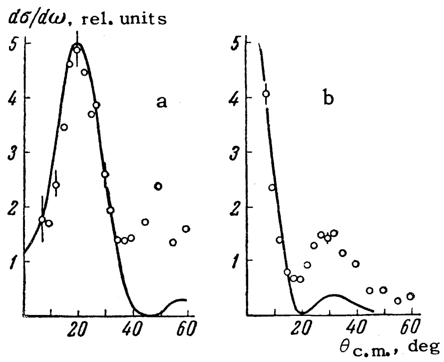

FIG. 4. Angular distribution of protons from the $Mo^{96}(d, p)Mo^{97}$ reaction: a – for transitions to the ground state ($l_n = 2$), b – for transitions to the excited (0.66-MeV) state ($l_n = 0$); in both cases $r_0 = 5.8$ F.

Considering the above, one can make reliable use in nuclear spectroscopy of (d, p) reactions in the range of atomic weights ~ 100 at energies of 13–15 MeV.

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