Structure of the $^{90,94}$Zr Nuclei: Global Analysis of Data on the Elastic and Inelastic Scattering of Alpha Particles and on the Total Cross Sections for the Reactions Induced by Their Interaction with These Nuclei

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Abstract—A global analysis of experimental data on the elastic and inelastic scattering of alpha particles by $^{90,94}$Zr nuclei and on the total cross sections for their interaction with these nuclei is performed. The deformation lengths and the neutron-to-proton multipole-matrix-element ratios for the $2^+_1$ and $3^-_1$ states of the $^{90,92,94,96}$Zr nuclei are obtained for various projectile species, and a comparative analysis of these quantities is performed. With the aim of revealing the origin of the phase shifts found in the present study, experimental data on the inelastic scattering of 35.4-, 40.0-, 50.1-, and 65.0-MeV alpha particles on $^{90,94}$Zr nuclei are analyzed on the basis of a unified approach.

1. INTRODUCTION

The scattering of high-energy electrons on nuclei furnishes detailed information about the distribution of the protonic component in nuclei [1], while the scattering of alpha particles, which strongly interact with nuclei, makes it possible to study the distribution of nuclear matter in nuclei. A comparison of data from such experiments permits exploring distinctions between the neutron and the proton distributions in nuclei and their structure.

Experimental data on the quasielastic scattering of composite particles are the main source of information about the distribution of matter in nuclides and about the properties of nucleus–nucleus interaction.

The parameters of the optical potential that is employed to simulate alpha-particle interaction with medium-mass nuclei at low and intermediate energies are usually determined from an analysis of the angular distributions of elastic-scattering differential cross sections that is performed within the optical model, but the results obtained in this way suffer from ambiguities, so that reliable estimates are required in these realms. A global analysis of the angular distributions of differential cross sections for elastic scattering and total reaction cross sections makes it possible to impose constraints on the ambiguities in the optical-potential parameters, since data on differential and total cross sections are basic nuclear quantities derived within the optical model. There presently exist only a few studies where the angular distributions of differential cross sections for scattering and total reaction cross sections are simultaneously analyzed within the same model. The choice of optimum optical-potential parameters would make it possible to extract, at the next stage, reliable information about the structure of excited states of the nucleus being studied.

In the present article, we report the results obtained by measuring the angular distributions of 40.0- and 50.1-MeV alpha particles that undergo elastic or inelastic scattering on $^{90,94}$Zr nuclei. The measurements were performed at the U-150M Kazakh isochronous cyclotron. We also quote new data from the U-240 Kiev isochronous cyclotron on the total cross sections for the reactions on the $^{90}$Zr isotope that are induced by alpha particles of energy 96(1) MeV and by $^3$He ions of energy 95(1) MeV. Within a unified approach, we analyze experimental data on the quasielastic scattering of 35.4-, 40.0-, 50.1-, and 65.0-MeV alpha particles (see [2, 3], [4], [5], and [6], respectively) on the even

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isotopes of Zr, as well as data on the total cross sections for the reactions between alpha particles of these energies and the isotopes in question. The data are analyzed on the basis of the deformed-optical-potential model by using the coupled-channel and distorted-wave methods and on the basis of the semimicroscopic folding model. A comparative analysis is performed for the deformation-length parameters $\delta_2^N$ and $\delta_3^N$ characterizing low-lying states of the nuclei being investigated and for the neutron-to-proton multipole-matrix-element ratios $M_n/M_p$ as obtained in this and other studies, the analysis being based on different methods for different projectile particles. In the angular distributions of 40.0- and 50.1-MeV alpha particles undergoing inelastic scattering, the phase shifts are investigated for the $2^+_1$ and $3^+_1$ states of the $^{90,94}$Zr nuclei.

2. EXPERIMENTAL METHODS

AND EXPERIMENTAL CROSS SECTION

At the isochronous cyclotron installed at the Institute of Nuclear Physics of the National Nuclear Center of the Republic of Kazakhstan (Almaty), the angular distributions of the differential cross sections for the elastic and inelastic scattering of 40.0- and 50.1-MeV alpha particles on $^{90,94}$Zr nuclei were measured in the angular range $12^\circ$–$75^\circ$ (in the laboratory frame) with a step varying between 0.3° and 1°. The total energy resolution of the measuring apparatus was 0.8% of the projectile energy. Reaction products were recorded and identified by means of a system that relied on the $\Delta E$–$E$ procedure and which employed CAMAC and PC/AT equipment [7].

The total angular resolution of the $\alpha$ spectrometer was measured by the method proposed in [8], the result being 0.3°. It was shown that the systematic angular uncertainty $\delta \theta$ caused by the noncollinearity of the chamber axis and the projectile-beam axis was 0.5°, on average, and that it is necessary to measure it in each series of experiments.

For targets, we employed zirconium foils enriched in the $^{90}$Zr (to 95%) or in the $^{94}$Zr (to 91.2%) isotope, their thickness being 2.13(8) or 2.60(8) mg/cm$^2$, respectively.

The errors in the absolute cross-section values were between 3 and 8% for the elastic channel and between 7 and 10% for the inelastic channel.

For the elastic scattering of 40.0- and 50.1-MeV alpha particles on $^{90,94}$Zr nuclei and for the inelastic scattering of such projectiles on the target nuclei in question that is accompanied by the excitation of the $2^+_1$ and $3^+_1$ collective states of $^{90}$Zr at 2186 and 2748 keV and the excitation of the $2^+_1$ and $3^+_1$ collective states of $^{94}$Zr at 920 and 2120 keV, the resulting angular distributions of the differential cross sections are displayed in Figs. 1 and 2 for, respectively, the first and the second energy value.

The experiment devoted to determining the total reaction cross sections was performed at the U-240 Kiev isochronous cyclotron at an alpha-particle energy of 96(1) MeV and at a $^3$He energy of 95(1) MeV. The total cross sections for the reactions induced by alpha particles and $^3$He ions were determined by the charge-integration method [9]. The layout of our experimental facility and the procedure used to obtain total reaction cross sections were described elsewhere [10].

The $^{90}$Zr target that was used in the experiments aimed at measuring the total reaction cross sections and which was manufactured by the method of pressing was $75 \pm 3.60$ mg/cm$^2$ thick and was enriched to 96.8%. The target was characterized by a high mechanical strength, but it was not free from drawback. The porosity of the target was 26.5%, while its inhomogeneity at the place hit by the beam ranged between 5 to 7%.

Originally, experiments devoted to determining the total cross sections for the reactions occurring on a $^{90}$Zr nucleus were performed at an alpha-particle energy of about 100 MeV [11]. Later on, the experiment was repeated at an energy of 96.0 MeV. The discrepancy between the results obtained in [11] and those that are presented here is due not only to the energy dependence but also to introducing improvements in the experimental procedure and to more correctly taking into account corrections.

The experimentally determined attenuation of the beam in the target, $q/Q$, is related to the total reaction cross section ($\sigma_R$) by the equation

$$\sigma_R = \frac{1}{n_x} \left( \frac{q_m \theta_{\text{bg}}}{Q} \right) - 2\pi \int_{\theta_1}^{\pi-\theta_1} \sigma_{\text{el}}(\theta) \sin \theta d\theta + 2\pi \left( \int_{0}^{\theta_1} + \int_{\pi-\theta_1}^{\pi} \right) K \sigma_{\text{d}}(\theta) \sin \theta d\theta \tag{1}$$

Table 1. Total cross sections (in millibarn units) for the interaction of alpha particles and $^3$He ions with a $^{90}$Zr nucleus

<table>
<thead>
<tr>
<th>Projectile type</th>
<th>$E_\alpha$, MeV</th>
<th>$\sigma_R$</th>
<th>$\sigma_{\text{el}}$</th>
<th>$\sigma_{\text{d}}$</th>
<th>$\sigma_{\text{a}}$</th>
</tr>
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<tr>
<td>$\alpha$</td>
<td>96</td>
<td>1833 $\pm$ 90</td>
<td>40 $\pm$ 20</td>
<td>130 $\pm$ 70</td>
<td>1923 $\pm$ 120</td>
</tr>
<tr>
<td>$^3$He</td>
<td>95</td>
<td>1895 $\pm$ 85</td>
<td>45 $\pm$ 10</td>
<td>280 $\pm$ 70</td>
<td>2130 $\pm$ 110</td>
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