STUDYING MATTER DISTRIBUTION IN INTERMEDIATE NUCLEI USING NUCLEAR REACTIONS WITH COMPLEX PARTICLES

K.A. Kuterbekov
Institute of Nuclear Physics of NNC RK, 480082, Almaty, Kazakhstan

The main experimental and theoretical methods for studying differences in matter allocations (protons and neutrons, electromagnetic and nuclear components) in intermediate nuclei are discussed. As a special application of these methods, one can investigate the elastic and inelastic interaction of particles with nuclei. We also present factors that explain the difficulties in getting reliable information about protons and neutrons, electromagnetic and nuclear components involved in the deformation lengths of low-lying nuclear states.

Experimental investigations of elastic and inelastic interactions at low and intermediate energies play an important role in the study of nuclear structure. The “straight” mechanism dominates at energies of 7-20 MeV/nucleon in complicated particles (α and ^{3}He-ions*)*, such as those that might be accelerated on the INP isochronous accelerator of NNC RK. In more complex reactions where several mechanisms interplay, a considerable amount of kinetic energy is transferred to the nucleus during scattering, causing extensive reorganization of its constituent particles. For direct processes, it is comparatively simple to decode the experimental data on angular distributions and cross-section values of the interacting particles to get information about the structure of excited nuclear states. On the other hand, experimental data on differential and full cross-sections (their joint analysis) allows one to limit the ambiguity of parameters describing the optical potentials (OP) of an interaction [1]. It is necessary to note that there are very few works where angular distributions (ADDS) of scattering and the full cross-section of reactions were simultaneously examined within one model. The parameters of OP are usually selected in such way to give a decisive meaning, compared to different theoretical approaches, and allow one to learn well-founded information about nuclear, structural characteristics.

At near-barrier energies, intensive excitation of rotational and low frequency oscillatory nuclear states (Coulomb excitation) is induced. (The ^{3}He and ^{4}He particles used in this study were produced by the U-150M isochronous accelerator for moderate-weight nuclei.) When energy approaches the Coulomb barrier, transmission of particles from one nucleus to another becomes possible. At the same time, the effects of Coulomb-nuclear interference determine the angular distributions of elastic scattering and quasi-elastic processes. Its observation allows one to specify our knowledge of nuclear potential at large distances and also to investigate differences in the correlation of electromagnetic and nuclear components in deformation lengths (i.e., parameters of deformation) of nuclei.

Competition among different scattering mechanism is one of the peculiarities of optical potential study at low energies. As one may know, the optical model allows one to calculate cross-sections of absorption and potential elastic scattering, whereas the measured reaction cross-section represent the scattering mechanisms through the compound nucleus and the interference between resonance and potential scattering. We considered the conditions where it is possible to disregard the non-potential contributions to the elastic scattering cross-sections. This allows one to choose appropriate nuclei and energy values for the investigations. We show that there is little relative difference between the calculated differential cross-sections for elastic and inelastic scattering of ^3He and ^4He particles at low energy, when the potential of a uniformly charged sphere (as is commonly used in the Coulomb term of optical potentials) is replaced by the potential of a realistic charge distribution.

Nuclei used in the investigation were selected taking into account the above requirements and available data on the reaction cross-sections in the energy range used. According to calculations, the compound elastic scattering is negligible for the selected nuclei in the considered energy range.

Taking into account the situation stated above, we carry out a complex analysis of experimental data on elastic and inelastic interaction of α-particles on moderate-weight nuclei within the framework of the optical model (OM), the methods of distorted waves (MDW) and connected canals (MCC), and the semi-microscopical (folding) approach.

Experimental information about differences in distribution of protons and neutrons, electromagnetic and nuclear parameters of dynamic quadrupole (octupole) deformation, along with their mass and sizes, determine the most important characteristics of moderate-weight nuclides [2].

Detailed information about proton (charge) distribution component in nuclei is obtained with the study of high-energy electron scattering on nuclei, Coulomb excitation, electromagnetic transitions and x-ray spectra of μ-mesoatoms [2]. The mass distribution in nuclei is studied with scattering of α and ^3He-particles, which interact strongly with the nucleus.

A comparison of the present theoretical analysis and accompanying experimental data is presented within the framework phenomenological and semi-microscopical optical-potential models; a comparison that allows one to investigate differences in nuclear matter distribution and nuclear structure.

The main methods for analysis of experimental ADDS at inelastic scattering of α and other complex particles are MDW and MCC. At the same time, a collective model for the description of interaction of these particles with the target nucleus is applied.

We now discuss a macroscopic model of inelastic scattering of low and moderate energy complex particles on nuclei and the deformation length parameters. The half recession radius of the potential in this model for a deformed nucleus can be described as follows:

$$R(\theta,\varphi) = R\,[1 + \Sigma\beta_\lambda^{\nu} Y_\lambda(\theta,\varphi)\,], \qquad (1)$$

where β_λ^{ν} are parameters of the potential form. There is a common expansion for axial-symmetric distributions and is expressed in the form

$$U(R)=\Sigma\, U_\lambda(R)\; Y_\lambda(\theta,\varphi), \qquad (2)$$

where, the constituent $U_o(R)$ coincides with the central part of the OP within a factor of $\sqrt{4\pi}$, and the components $U_\lambda(R)$, $\lambda \neq 0$ define the radial form-factors of inelastic transitions with moment transfer λ. In [3], expanding $U(R)$ in a Taylor series and using small-scale parameters β_λ,one obtains

$$U_\lambda(R) = \beta_\lambda^{v} R \frac{dU_t(R)}{dR}. \quad (3)$$

Expression (3) is used in MDW and MCC to describe elastic and inelastic transitions and determine the parameters of nuclear deformation. Here, the parameters of deformation lengths $\delta_I = \beta_\lambda^{v} R$ are a normalizing factor between calculated and experimental sections. Due to this dependence on R, it is preferable to use δ_I itself, instead of the individual components β_λ, in comparisons of inelastic scattering data of different types of particles.

In the formalism of MDW and MCC, there is only the description of the direct mechanism of scattering; yet indirect, resonance or statistical scattering processes play important roles at low energies (E<7 MeV/nucleon). Consideration of the indirect mechanisms results in a distortion of $\beta_\lambda R$ values, which are derived from an analysis of experimental data. From data analysis of ADDS, some effective parameters, i.e. $\beta_\lambda R$, are extracted, depending on energy and characterizing both the nuclear potential and scattering mechanism, as well as the nuclear structure and matter distribution in the nucleus. As an illustration, Table 1 shows values of $\beta_\lambda R$ for different types of particles and different energy intervals using, as an example, the 2_1^+ low-lying nuclear state of ^{94}Zr.

Table 1: Parameters of deformation lengths δ_I for the 2^+_1 nuclear state of ^{94}Zr

I^π	Level energy, MeV	δ_I, фм	Particle, energy (MeV)	calculation method
2^+_1	0.918	0.636	(α, 35.4)	CC, SMA
		0.754	(α, 40)	CC, SMA
		0.575	(α, 50)	CC, SMA
		0.575	(α, 65)	CC, SMA
		0.632	(α, 35.4)	CC, FM
		0.633	(α, 35.4)	DWBA, CC
		0.451	(t, 20)	DWBA
		0.860	(p, 18.8)	DWBA
		0.557	(^{3}He, 43.7)	DWBA
		0.65	(n, 8-24)	CC

Notes to Table 1. *Data on δ_I (from our measurements and literature sources) are taken from the works of K. A. Kuterbekov., A. D. Duisebaev., B. M. Sadykov., I. N. Kuhtina, L. I. Slyusarenko, S. A. Fayans, proceedings of MON RK, NAS RK, phys.-math. series, 2001, #2, p.53; R.B Firesrone, Table of Isotopes, Eighth Edition (A. Wiley-Interscience Publication JOHN WILEY & SONS, New York, 1999, Update)] and set to a uniform form. The following notations for the methods are accepted in fourth column of the Table: CC, SMA – method of connected channels, semi-microscopic analysis; CC, DOMP – macroscopic method of connected channels, deformed optical model potential; CC, FM-method of connected channels, folding-model; DWBA – method of distortion waves; CC – method of connected channels.*

The effectiveness of CC and DW, as well as the reliability of information about deformation length parameters derived from the scattering of moderate energy particles, depends on the extent the direct excitation mechanism plays a dominant role, especially at forward angles (< 90 deg); its description is available in the theoretic methods we employ. It is necessary to note that absolute values of the multipole deformation parameters possess less precision than the relative parameters. That is why the changes in surface form from nucleus to nucleus and comparison of deformation lengths should be developed in the framework of the same method (CC or DW) and data analysis on the scattering of particles.

An important shortcoming of the standard collective approach is that information of potential form, but not of the nucleus form, is extracted from analysis of experimental data. The connection between nuclear potential form and form of matter distribution in the nucleus is set reliably and identically in the framework of the semi-microscopic approach using the method of double folding [4].

In the approach of the Semi-microscopic optical model, the optical potential U(R) is built in the framework of a folding-model on the basis of the full M3Y-effective interaction and nuclear densities, calculated in the method of a density matrix functional [5]. In the first order of effective forces, the interaction potential of two colliding nuclei can be represented as a sum:

$$U(R) = U^E(R) + U^D(R), \qquad (4)$$

where $U^D(R)$ denotes the "direct" model potential of double contraction [1],

$$U^D(R) = \iint \rho^{(1)}(r_1) V^D(s)\ \rho^{(2)}(r_2) dr_1\, dr_2\,. \qquad (5)$$

In Expression (5), $V^D(s)$ is a straight component of effective interaction ($s = r_1 - r_2 + R$), and $\rho^{(i)}(r_i)$ are densities of colliding nuclei (i =1, 2). The detailed scheme for calculating the "exchange" potential $U^E(R)$ is shown in [6]. The effects of single-nucleon exchange, which are described in the formalities of the density matrix, are the main contributions to the matrix [7]:

$$U^{EX}(R) = \iint \rho^{(1)}(r_1, r_1 + s) V_{EX}(s)\ \rho^{(2)}(r_2, r_2 - s) \exp(ik(R)\, s/\eta)\, dr_1\, dr_2\,, \qquad (6)$$

where $V_{EX}(s)$ is the exchange part of the effective nucleon-nucleon forces, $\rho^{(i)}(r, r')$ ($i=1,2$) are density matrix elements of collided nuclei with mass numbers A_1 and A_2, and $k(R)$ is local impulse of relative motion of nuclei, defined by the relation

$$k^2(R) = (2m\eta/h^2)[E - U(R) - V_c(R)]. \qquad (7)$$

Here,

$\eta = A_1 A_2 /(A_1 + A_2)$, $s = r_2 - r_1 + R$, E is energy in the system's center-of-mass and $V_c(R)$ is the Coulomb potential. Thus, the total potential, even taking into account the effects of single-nucleon exchange, depends upon the energy. Effective nucleon-nucleon forces, as well as proton and neutron densities of collided nuclei, are the input data for potential calculations.

The full optical potential must include an imaginary part to describe the absorption of incident particles into the inelastic channels. In the model we use, the absorption potential depends on the calculated real part [8] as follows:

$$W(R) = i\,[N_w U(R) - \alpha_w\, R\, dU(R)/dR], \tag{8}$$

where $U(R)$ is the double folding potential of Eqn. (4), and N_w and α_w are parameters that characterize volumetric and surface parts of the absorption potential, respectively. The surface term is added into the real part of the potential, imitating the contribution of the dynamic polarized potential [9]. The full optical potential has the form

$$U_t(R) = U(R) - \alpha_v * dU(R)/dR + i\,[N_w U(R) - \alpha_w * dU(R)/dR], \tag{9}$$

where α_v, N_w and α_w are variable parameters.

For cross-section calculations of inelastic scattering, the form-factor of inelastic charge was taken as $\alpha_L \dfrac{dU_t(R)}{dR}$. [10]

For α-particles, the nucleon densities were calculated as a Gaussian distribution with root-mean-square radius of 1.57 fm [11], and for nucleus targets the densities were calculated by the method of density matrix functional [10]. The density distributions for neutrons, protons and matter in them are shown for the example of nuclei $^{90,\,94}$Zr [12] in Figure 1. It is shown that, for the marked nuclei (in the field of r < 4 fm) of neutron density, the components exceed the corresponding values of proton component, on average, by 0.002 fm^{-3} for ^{90}Zr and in 0.004 fm^{-3} for the ^{94}Zr nucleus.

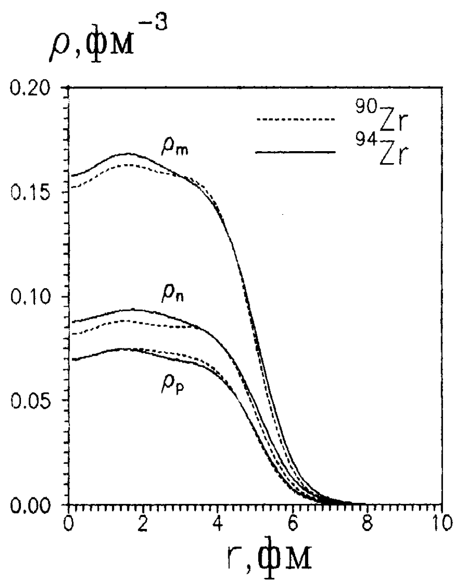

Figure.1. Density distribution of neutrons, protons and matter in $^{90,\,94}$Zr nuclei

A study has been designed to investigate the scattering of complex particles at energies near the Coulomb barrier on medium-weight nuclei (in particular, ^{116}Cd and ^{206}Pb nuclei) and the parameters characterizing the optical potential (which would correspond to a description of the direct processes) both in the elastic and inelastic channels. The angle distribution structure of α-particles, as observed in the inelastic distribution in the forward hemisphere, is a consequence of the interference between Coulomb and nuclear interactions, providing a definite self-descriptiveness of the data with respect to parameters corresponding to the two processes. The calculations (from our data analysis, and experimental information from literature sources) have been carried out in the framework of the optical model, methods of distorted waves and connected channels, supposing the collective vibration excitation of the 2_1^+ level. A preliminary analysis suggests that the data on inelastic scattering at overbarrier and underbarrier energies cannot be satisfactorily described with the same parameter of deformation length δ_2 (and, respectively, quadrupole deformation β_2). Thus, following theoretical predictions [13] of the difference between electromagnetic and nuclear deformation parameters typical for magnetic nuclei, the parameters β_2^{em} and β_2^{nuc} have been used in calculations, instead of the β_2 parameter, corresponding to oscillations of equipotential charge and nuclear surfaces. To connect the calculations to the experimental data over the full range of scattering angles, also included is the radius and diffuseness of the supposed potential in the number of free parameters, as well as depths of real and supposed potential parts and β_2^{em}, β_2^{nuc} parameters. The relationship observed between the calculation and the experiment confirms the supposition that the scattering mechanism of alpha and ^{3}He particles is due to Coulomb and direct nuclear interaction. The values obtained for β_2^{em} and β_2^{nuc} are close to the corresponding values of β_2, measured from ^{206}Pb nuclei in experiments on Coulomb excitation of nuclei and inelastic scattering of α-particles of high enough energies. As was supposed, the calculation results for methods of distorted waves and connected channels are found to be close due to small values of deformation length for the 2_1^+- nuclear state of ^{206}Pb.

The present investigation has shown that a joint study of elastic and inelastic scattering of complex particles of near-barrier energies may be carried out within a uniform approach in the framework of the optical model, DW and CC. Self-descriptiveness of such an investigation allows one to fine-tune optical potential parameters in the near-barrier field of energy. The distinction discovered in one experiment in electromagnetic and nuclear excitation of a nucleus introduces the interest for further investigation of peculiarities of collective nucleus properties.

It is necessary to point out that, for complex cross-section analysis of elastic and inelastic interactions in the near-barrier field of energies, the necessity of including a phenomenological analysis of the full collection of data and calculation of a-priori-known tendency towards an increase of the optical model parameters.

REFERENCES

1. Satchler G.R, Direct Nuclear Reactions (Oxford University Press, New York, 1983).
2. Barret R., Jakson D., Sizes and structure of nucleuses. Kiev, science, 1981.
3. Prenston M. Physics of nucleus, Moskow, Piece, 1964
4. Knyazkov O.M. , ЭЧАЯ. 1986, vol.17, p.318
5. Knyazkov O.M., Kuchtina I.N., Fayans S.A., Physics of Particles and Nuclei. 1999. V.30. P. 870.
6. Knyazkov O.M., Kuchtina I.N., Fayans S.A., Physics of Particles and Nuclei. 1997. V.28. P. 1061.
7. Ghaudhuri A.K., Basu D.N., Sinha B., Nucl. Phys. 1985. V.A439. P.415.
8. Fayans S.A., Knyazkov O.M., Kuchtina I.N. et al., Phys. Lett. 1995. V.B357. P.509.
9. Bolotov D.B., Knyazkov O.M., Kukhtina I.N., Fayans S.A., NP. 2000. V.63. p.1631.
10. Tanihata I. et al., Phys. Lett. 1988. V.B206. P.592.
11. Nolte M., Machner H., Bojowald J., Phys. Rev. 1987. V.C36. P.1312.
12. Kukhtina I.N., Fayans S.A., Kuterbekov K.A., Sadykov B.M., Burtebaev N., international conference "Klasters in nuclear physics", July, 14-17, 2000. Saint Petersburg., Rusia. 2000 C. 270
13. Madsen V. A., Brown V.R., Anderson J.D., Phys. Rev. 1975. V.C12. P.1205