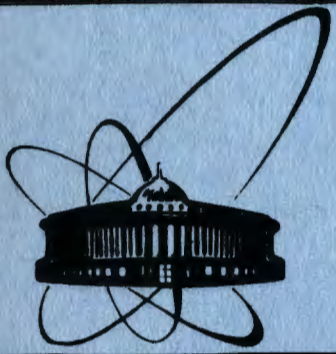

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A MICROSCOPIC APPROACH TO THE DESCRIPTION OF HEAVY-ION ELASTIC SCATTERING

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1. INTRODUCTION

A unified microscopic approach is developed for the description of elastic and inelastic heavy ion scattering. The nuclear potential between two nuclei of heavy ions is derived from appropriate effective nucleon-nucleon (N-N) interaction and the nuclear densities calculated in microscopic models with the optimum fit to the basic experimental data. Within this approach it is possible to calculate not only diagonal but also nondiagonal matrix elements of heavy-ion interaction, so, one can consider either elastic or inelastic processes. Calculations of the scattering cross-sections have been performed with one adjustable parameter, namely, only the strength of the imaginary, absorptive part of the optical potential is varying.This approach has been applied first to investigate elastic and inelastic scattering for ions with $A \leq 16$ in [1,2], where the problem of possible excitation of the monopole resonance in the heavy-ion collisions has been considered. Theoretical description of elastic scattering at different energies [3] has shown that a good fit to the experimental data can be reached by varying only amplitude of the imaginary part of the optical potential. In ref.[4] an analytical form for double-folding potential with effective N-N interaction of Satchler and Love's forces, i.e., nonzero range forces in the Gaussian form, has been used for systems with $A = 4,6,12,16$. Recently, the elastic $^{16}O+^{16}O$ scattering at different projectile energies has been investigated[5], the nuclear densities used for nuclear potential calculation are calculated by the method of hyperspherical functions. The stability of the results to the choice of models for potential calculation (the double-folding model and energy-density formalism) has been analysed. However, all these investigations have been performed so far only for light systems ($A \leq 16$). In this work the proposed approach is applied to heavier systems. The elastic scattering processes, such as $^{6}Li + ^{58}Ni$, $^{6}Li + ^{90}Zr$, $^{6}Li + ^{124}Sn$, $^{6}Li + ^{208}Pb$, $^{12}C + ^{142}Nd$, $^{12}C + ^{144}Nd$, $^{12}C + ^{90}Zr$, $^{12}C + ^{208}Pb$ and $^{16}O + ^{60}Ni$ are considered. The nuclear densities of light ions (^{6}Li, ^{12}C, ^{16}O) are calculated by the method of hyperspherical functions (MHF)[6] the densities for heavy ions (^{124}Sn, $^{58,60}Ni$, ^{90}Zr, $^{142,144}Nd$, ^{208}Pb) are calculated within the quasiparticle-phonon model (QPM)[7]. The interacting heavy-ion potential has been calculated in the folding model[9] with effective N-N interaction of Yukawa forces M3Y[8].

2. DETAILS OF CALCULATION

At first we give a short description of the density calculation in the MHF. In the K-harmonics method, the wave function of nucleus A is sought in the form of an expansion in the K-harmonics polynomials $Y_{K\gamma}(\theta_i)$

$$\Psi(1,2,\ldots,A) = \xi^{-\frac{1}{2}(3A-4)} \sum_{K\gamma} \chi_{K\gamma}(\xi) Y_{K\gamma}(\theta_i), \qquad (1)$$

where $\gamma = [f] \in LST$ /6/.

The hyperspherical harmonics are eigenfunctions of the angular part of the Laplacian

$$\Delta_{\Omega_n} Y_{K\gamma}(\theta_i) = -K(K+n-2) Y_{K\gamma}(\theta_i) \qquad (2)$$

K is an analogue of the angular momentum for $n = 3$ and is called the global moment. The nuclear Hamiltonian is of the form

$$H = -\frac{\hbar^2}{2m} \frac{1}{\xi^{3A-4}} \frac{\partial}{\partial\xi} \left(\xi^{3A-4} \frac{\partial}{\partial\xi}\right) - \frac{\hbar^2}{2m} \frac{\Delta_\theta}{\xi^2} + V. \qquad (3)$$

The Schrödinger equation for the radial functions can be written as

$$\left\{\frac{d^2}{d\xi^2} - \frac{\mathfrak{L}_K(\mathfrak{L}_K+1)}{\xi^2} - \frac{2m}{\hbar^2}(E + W^{K\gamma}_{K\gamma}(\xi))\right\}\chi_{K\gamma}(\xi) = \frac{2m}{\hbar^2} \sum_{K'\gamma' \neq K\gamma} W^{K'\gamma'}_{K\gamma}(\xi)\chi_{K'\gamma'}(\xi), \qquad (4)$$

where $\mathfrak{L}_K = K + \frac{1}{2}(3A-6)$, $W^{K'\gamma'}_{K\gamma}(\xi)$ are the matrix elements of the potential energy of the N-N interaction.

With the wave functions calculated in the K-harmonics method, one can obtain the ground-state density for light nuclei in the form:

$$\rho_0^A(r) = \frac{16}{\sqrt{\pi}} \frac{\Gamma(\frac{5A-11}{2})}{\Gamma(\frac{5A-14}{2})} \int_r^\infty \frac{(\xi^2 - r^2)^{(5A-16)/2}}{\xi^{5A-13}} \chi_0^2(\xi)\,d\xi + \frac{8(A-4)}{3\sqrt{\pi}} \frac{\Gamma(\frac{5A-11}{2})}{\Gamma(\frac{5A-16}{2})} \int_r^\infty \frac{r^2(\xi^2 - r^2)^{(5A-15)/2}}{\xi^{5A-13}} \chi_0^2(\xi)\,d\xi. \qquad (5)$$

The densities for heavy nuclei are calculated within the QPM. The QPM Hamiltonian is of the form:

$$H = H_{av} + H_{pair} + H_M + H_{SM}, \qquad (6)$$

where H_{av} is the average field describing independent single-particle motions. H_{pair} describes the monopole pairing interaction between the neutrons or protons. H_M and H_{SM} are separable multipole and spin-multipole interaction terms generating the nuclear excitations. The explicit form of the QPM Hamiltonian is given in /12/ for example. In the calculation of transition nuclear density one must take into account all terms in (6). H_M and H_{SM} give no contributions to the ground-state density and in this case one has

$$H_0 = H_{av} + H_{pair} = \sum_{jm\tau} E_j a^+_{jm} a_{jm} - \frac{1}{4} \sum_{\tau jj'mm'} G_\tau (-)^{j-m+j'-m'} a^+_{jm} a^+_{j-m} a_{j'-m'} a_{j'm'}, \qquad (7)$$

where a^+_{jm} and a_{jm} are the nucleon creation and annihilation operators; $j \equiv (n, \ell, j)$ is the set of quantum numbers for a single-particle state with energy E_j; $\tau = n, p$ is the isotopic index; G_N and G_Z are the monopole pairing constants. In the calculation the average field is taken as Saxon-Woods potential. The potential parameter set used in the QPM is given in detail in /13/.

After Bogolubov's transformation $a_{jm} = u_j \alpha_{jm} + (-)^{j-m} v_j \alpha^+_{j-m}$, where α^+_{jm} and α_{jm} are the quasiparticle creation and annihilation operators, one can obtain the ground state density for heavy (spherical) nuclei in the form:

$$\rho_0(r) = \frac{1}{4\pi} \sum_j (2j+1) |R_j(r)/r|^2 v_j^2, \qquad (8)$$

where $R_j(r)/r$ is the radial part of the wave function for single-particle state $j \equiv (n, \ell, j)$. In further calculations the nuclear densities are normalized as

$$4\pi \int \rho_0(r) r^2 dr = A, \qquad (9)$$

where A is the mass number of the nucleus.

Now, we discuss the method used here for nucleus-nucleus potential calculations. The most popular approximation for heavy-ion potential is the double-folding method, where the potential is derived from realistic N-N interaction averaged over the density distributions of two colliding nuclei. Since the elastic heavy-ion scattering cross-section is sensitive only to the tail of the potential, in the vicinity of the strong absorption radius

$$R_{cr} \simeq 1.5(A_1^{1/3} + A_2^{1/3}), \qquad (10)$$

where the densities of two colliding nuclei almost do not over-

lap, one can assume that the densities are not deformed. The folding potential can be written as

$$U_F(\vec{R}) = \int d\vec{r}_1 d\vec{r}_2 \rho_1(\vec{r}_1)\rho_2(\vec{r}_2)\, v(\vec{r}_{12} = \vec{R} + \vec{r}_2 - \vec{r}_1)\,, \qquad (11)$$

where ρ_i is the ground-state density of the i-th nucleus. Expression (11) involves six-dimensional integral. The central part of effective N-N interaction can be written as

$$v(\vec{r}_{12}) = v_{00}(\vec{r}_{12}) + v_{01}(\vec{r}_{12})\vec{\tau}_1\cdot\vec{\tau}_2 + v_{10}(\vec{r}_{12})\vec{\sigma}_1\cdot\vec{\sigma}_2 + v_{11}(\vec{r}_{12})\vec{\sigma}_1\cdot\vec{\sigma}_2\,\vec{\tau}_1\cdot\vec{\tau}_2. \qquad (12)$$

When both colliding ions have no spin, the terms v_{ST} in (12) with $S=1$ give no contribution to $v(\vec{r}_{12})$. In general U_F is nonspherical and contains terms depending on spins and isospins of interacting ions. The spin-orbit and tensor terms may also be included. However, for scattering processes considered here the influence of these terms is negligible /9/ and in the folding calculations only term $v_{00}(r)$ in (12) is taken into account. There are some typical radial dependences for effective interaction $v_{00}(r)$: zero-range Skyrme forces /14/, nonzero-range Satchler and Love's forces in the Gaussian form /9/, Yukawa forces (M3Y) /8/. In earlier applications of the MHF /1-5/ only Skyrme δ-forces and nonzero-range forces in the Gaussian form have been used. In this work all calculations are performed with realistic M3Y interaction. From the comparison of the results calculated with δ-forces with the results calculated with Yukawa forces one may conclude that the most appropriate interaction for folding calculation is the M3Y interaction.The main difficulty in the calculation with M3Y interaction comes from six-dimensional integral (11). It is very complex in coordinate space, but if we work in momentum space, this integral is reduced to a product of three one-dimensional integrals /9/ and in some cases one of these integrals can be calculated analytically. A short description of this procedure is the following: If we denote Fourier transform of the function $f(\vec{r})$ as $\tilde{f}(\vec{k}) = \int d\vec{r}\exp(i\vec{k}\vec{r})\, f(\vec{r})$, so for $v(\vec{r}_{12})$ in (11) we have

$$v(\vec{r}_{12}) = \frac{1}{(2\pi)^3}\int d\vec{k}\,\tilde{v}(\vec{k})\exp[-i\vec{k}(\vec{R} + \vec{r}_2 - \vec{r}_1)] \qquad (13)$$

and

$$U_F(\vec{R}) = \frac{1}{(2\pi)^3}\int d\vec{k}\exp(-i\vec{k}\vec{R})\,\tilde{v}(\vec{k})\,\tilde{\rho}_1(\vec{k})\,\tilde{\rho}_2(-\vec{k})\,, \qquad (14)$$

$$\tilde{U}_F(\vec{k}) = \int d\vec{R}\exp(i\vec{k}\vec{R})\,U_F(\vec{R}) = \tilde{v}(\vec{k})\,\tilde{\rho}_1(\vec{k})\,\tilde{\rho}_2(-\vec{k}). \qquad (14')$$

In the folding calculation for elastic scattering one just needs to calculate the following integrals:

$$\tilde{\rho}(k) = 4\pi\int_0^\infty r^2 dr\, j_0(kr)\,\rho(r)\,, \qquad (15)$$

$\tilde{v}(\vec{k})$ can be calculated analytically if one has M3Y interaction /9/ in the form

$$v(\vec{r}_{12}) = 6315\frac{\exp(-4r)}{4r} - 1961\frac{\exp(-2.5r)}{2.5r} - 81\delta(\vec{r}_{12})\,, \qquad (16)$$

where $r = |\vec{r}_{12}| = |\vec{r}_1 - \vec{r}_2|$.

The double-folding potential calculated in such a way has been used to calculate cross-sections of elastic heavy ion scattering. It was assumed that the imaginary part of the optical potential has the same shape as the real part, so the calculations have been performed with one adjustable parameter, namely, only the strength of the imaginary part was varying.

$$U = U_F(1 + i\beta). \qquad (17)$$

Parameter β was found by minimizing the quantity

$$\chi^2 = \sum_i \left[\frac{\sigma_{exp}(\theta_i) - \sigma_{cal}(\theta_i)}{\Delta\sigma_{exp}(\theta_i)}\right]^2, \qquad (18)$$

where $\sigma_{cal}(\theta_i)$ are the calculated cross-sections; $\sigma_{exp}(\theta_i)$ are the measured cross-sections; $\Delta\sigma_{exp}(\theta_i)$ correspond to the experimental uncertainty.

3. RESULTS OF CALCULATION AND DISCUSSION

The densities for nuclei ^{6}Li, , ^{12}C and ^{16}O shown in fig.1 are calculated in the MHF /8/ with N-N potentials V7 (for ^{6}Li and ^{12}C) and B4 (for ^{16}O). The fitting to the basic experimental data, such as binding energy, monopole resonance excitation energy, RMS nuclear radius, form-factor minimum... is shown in Table 1.

It should be noted that the densities for light nuclei calculated in the MHF have certain advantages in comparison with the shell model densities used in /9/, namely, within the MHF the densities describe nuclear asymptotics more correctly /6/. The densities for heavy-ion targets are very close to the shell model densities used in /9/. But in contrast with /9/, we have included into our calculations effect of monopole pairing interaction (7). The single-particle potential parameters and the pairing constants $G_{N,Z}$ for considered nuclei /13/ are shown in Table 2. Figure 2 shows the results of calculations for elastic scattering cross-sections depending on the choice of effective N-N interaction. The double-folding potentials

Table 1

	exp.	Li^6 (V7)	exp.	C^{12} (V7)	exp.	O^{16} (B4)
E_B (MeV)	31.99	19.8	92.2	83.1	127.2	122.2
$E_{ex}^{0^+}$ (MeV)		14.7	20.3	21.5		29.1
RMS (fm)	2.353	2.325	2.294	2.325	2.541	2.460
q (fm^{-1})	5	5	4.1	4.1	4	4.4

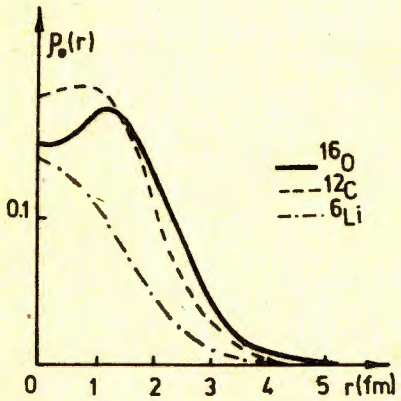

Fig.1. The nuclear ground-state densities calculated in the method of hyperspherical functions for ^6Li, ^{12}C, ^{16}O.

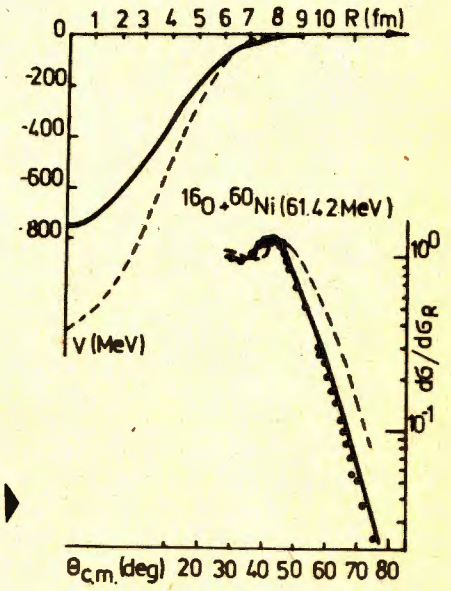

Fig.2. Folded potential and elastic cross-sections, calculated with M3Y (Skyrme) interaction, for system $^{16}O + ^{60}Ni$ at energy 61.42 MeV - solid (dashed) lines.

Table 2

Woods-Saxon potential parameters and pairing constants

A	N,Z	r_0, fm	V_0, MeV	$\varkappa$, fm^2	α, fm^{-1}	$G_{N,Z}$, MeV
59	N=31	1.31	46.2	0.413	1.613	0,280
	Z=27	1.24	53.7	0.308	1.587	0.302
91	N=53	1.29	44.7	0.413	1.613	0,168
	Z=39	1.24	56.9	0.338	1.587	0.194
121	N=71	1.28	43.2	0.413	1.613	0,122
	Z=51	1.24	59.9	0.346	1.587	0,136
141	N=83	1.27	46.0	0.413	1.613	0,116
	Z=59	1.24	57.7	0.349	1.587	0,122
209	N=127	1.26	44.8	0.376	1.587	0.074
	Z= 83	1.24	60.3	0.371	1.587	0.080

and corresponding elastic cross-sections for system $^{16}O + ^{60}Ni$ at projectile energy 61.42 MeV are shown in the top and bottom parts of fig.2, respectively. The dashed lines show the results calculated with effective N-N of zero-range Skyrme forces and the solid lines - the results calculated with M3Y interaction /9/. Points are experimental data taken from /15/. As one can see, the double folding potential calculated with M3Y effective forces is shallower at small distances between interacting ions and deeper in the vicinity of the strong absorption radius in comparison with the potential calculated with Skyrme zero-range forces. And one may conclude that the calculations with M3Y effective forces fit the experimental data better than the calculations with zero-range forces. All results for other scattering processes considered here are calculated with M3Y effective interaction (16). The results of cross-section calculations for elastic ^6Li scattering from different heavy targets (^{58}Ni, ^{90}Zr,, ^{124}Sn and ^{208}Pb) are shown in fig.3. Experimental data for $^6Li + ^{58}Ni$ at energies 22.8 MeV and 50.6 MeV, $^6Li + ^{90}Zr$ at energy 34 MeV, $^6Li + ^{124}Sn$ and $^6Li + ^{208}Pb$ at energies 50.6 MeV are taken from /16-18/. As one can see, on the whole our calculations with one parameter fit the experimental data well. Comparison of our results with those from /9/ shows undoubtedly the

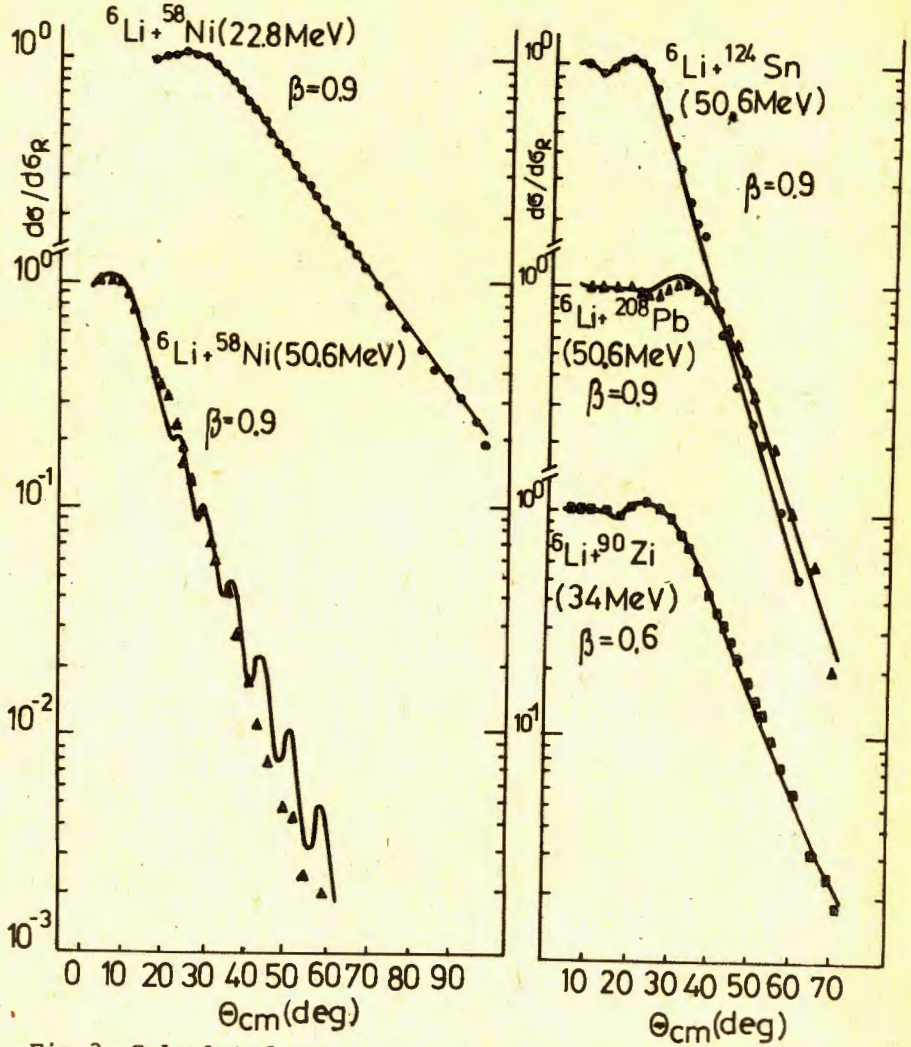

Fig.3. Calculated cross-sections for elastic ^{6}Li scattering from ^{58,60}Ni, ^{90}Zr, ^{124}Sn, ^{208}Pb.

advantage of the nuclear densities used here. In /9/ ^{6}Li scattering is considered as anomalous process and the description of elastic cross-sections has been performed with four parameters. The renormalization factor for amplitude of the real potential is about 0.5, this factor for the imaginary potential in most cases considered in /9/ is 2÷3. Our calculations describe the experimental data with the same accuracy as in /9/ via adjusting only one parameter - the strength of the imaginary

potential, which is about 0.6÷0.9 times the strength of the real part. One can see from this picture evidently the advantage of ^{6}Li -nuclear density calculated in the MHF. However, in some cases the imaginary potential amplitude is rather great, so one needs to calculate more correctly the density for ^{6}Li in the MHF by taking into account the harmonics of higher order which contribute to the asymptotics of the wave function and at the same time lead to the cluster structure of the wave function for ^{6}Li. Calculations for ^{6}Li + ^{58}Ni at different projectile energies are fitting the experimental data with the same value of the imaginary potential amplitude, namely, with β= 0.9. This is in contrast with the conclusion made in /3/ from calculations for ^{6}Li + ^{12}C. In this case the imaginary potential amplitude for elastic scattering at energy 30.6 MeV is 4 times as small as the corresponding value at energy 90 MeV. The results of cross-section calculations for elastic ^{12}C scattering from nuclei ^{142}Nd, ^{144}Nd at energy 70.4 MeV, ^{90}Zr at energies 98 MeV and 60 MeV, ^{208}Pb at energy 96 MeV and the corresponding experimental data taken from /19-22/ are shown in Fig.4. For all nuclei considered here, the calculations reproduce the observed elastic ^{12}C scattering, except for the scattering from ^{208}Pb target. And the imaginary potential amplitudes are substantially smaller than those in the ^{6}Li case (β= 0.1÷0.3). It seems evident that the density of ^{12}C calculated in the MHF describes the real situation in this nucleus rather well. It has been shown that the exception is the scattering of ^{12}C from ^{208}Pb target. In this case it is impossible to fit the data for angles greater than 40° even with rather large imaginary potential amplitude (β = 0.7). It seems likely that such a discrepancy is due to an unwise choice of density distribution used here for ^{208}Pb. As is seen from the results of calculations for ^{12}C scattering from Nd isotopes at energy 70.4 MeV, one is able, within this formalism, to fit the experimental data with the same parameter β = 0.3. It should be noted that the density used for ^{142}Nd differs slightly from the density of ^{144}Nd by the fact that in magic ^{142}Nd nucleus the pairing interaction between neutrons is absent. Our calculations show that the experimental data for elastic ^{12}C scattering from ^{146}Nd /19/ can also be fitted with the same β= 0.3. Fig.5 shows the results of calculations for elastic ^{16}O scattering from ^{60}Ni target at two energies: 61.42 MeV /15/ and 141.7 MeV /23/. As one can see, a good fit to the experimental data can be reached for projectile energy of 61.42 MeV. It is impossible to fit the data for ^{16}O + ^{60}Ni at energy of 141.7 MeV by varying only one parameter β. This discrepancy seems to be due to the small number of partial waves taken into cross-section calculation (the maximum number of partial waves available in the computer code CHUCK is 50).

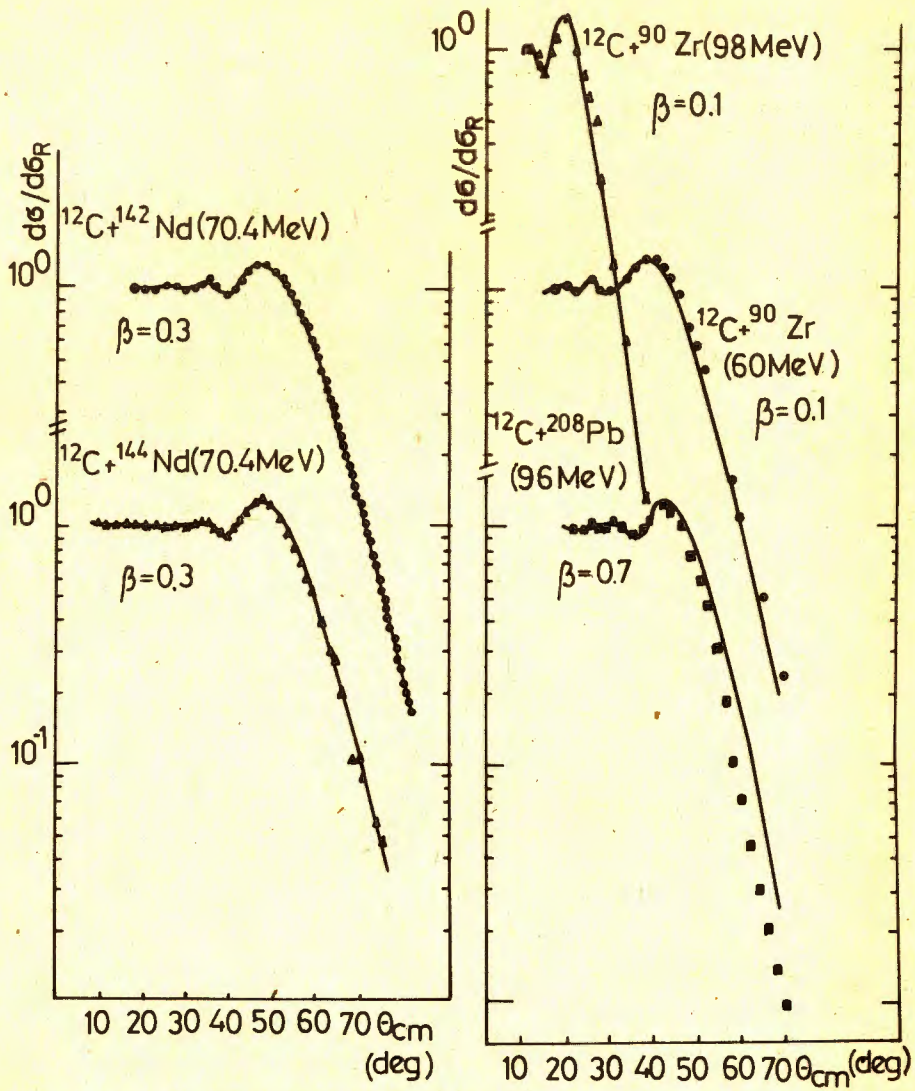

Fig.4. Calculated cross-sections for elastic ^{12}C scattering from $^{142,144}Nd$, ^{90}Zr, ^{208}Pb.

CONCLUSION

A unified microscopic approach is proposed and developed for the description of elastic heavy-ion scattering. Theoretical investigations have been performed for elastic ^{6}Li, ^{12}C, ^{16}O scattering from $^{58,60}Ni$, ^{90}Zr, ^{124}Sn, $^{142,144}Nd$, ^{208}Pb

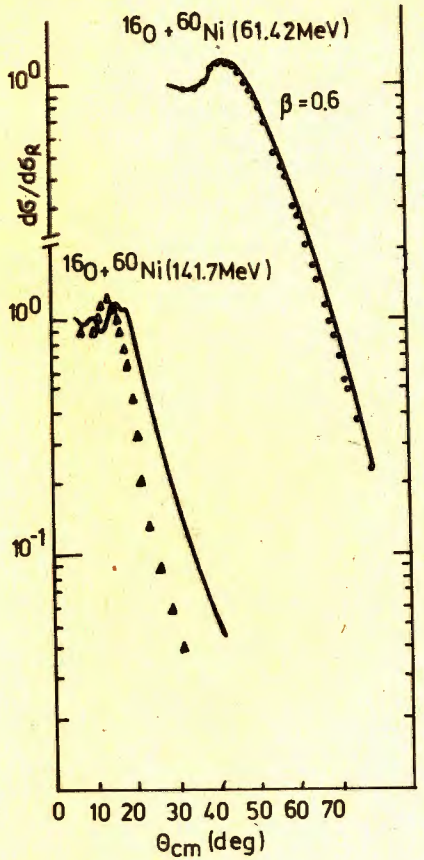

Fig.5. Calculated elastic cross-sections for system $^{16}O+^{60}Ni$.

heavy targets. The results of calculations show that the experimental data can be reproduced in most cases with only the adjustable parameter. The influence of the microscopic structure of the wave functions for considered nuclei on the cross-section calculations is discussed. The influence of the imaginary potential amplitude on the heavy targets is not as strong as in the case of light targets.

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Микроскопический подход к описанию
упругого рассеяния тяжелых ионов

Развивается единый микроскопический подход к описанию упругих сечений реакций с тяжелыми ионами. Цель этих исследований - изучение структуры ядра в реакциях с тяжелыми ионами. Потенциал взаимодействия тяжелых ядерных частиц строится в фолдинг-модели. Исследовались реакции упругого рассеяния ионов ^{6}Li, ^{12}C, ^{16}O на мишенях ^{58,60}Ni, ^{90}Zr, ^{124}Sn, ^{142,144}Nd, ^{208}Pb. Плотности для легких ядер получены в методе гиперсферических функций. Ядерные плотности для тяжелых ионов были получены в рамках квазичастично-фононной модели.

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Dao Tien Khoa, Shitikova K.V. E4-84-305

A Microscopic Approach to the Description
of Heavy-Ion Elastic Scattering

A microscopic approach is developed for the description of elastic heavy-ion scattering to study the nuclear-structure effects in heavy-ion collisions. Nucleus-nucleus interaction potential is calculated within the folding model. The elastic ^{6}Li, ^{12}C, ^{16}O scattering from ^{58,60}Ni, ^{90}Zr, ^{124}Sn, ^{142,144}Nd, and ^{208}Pb has been investigated. The nuclear densities for light nuclei-projectiles are calculated in the method of hyperspherical functions, the densities for heavy ions-targets are calculated within the quasiparticle-phonon nuclear model.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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