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STUDY OF LIGHT EXOTIC AND STABLE NUCLEI WITH HEAVY ION REACTIONS*

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The indirect method of the light exotic nuclei study in the experiments with the stable ion beams produced in many-nucleon-transfer reactions is presented. The data of elastic and inelastic scattering as well as of transfer reactions were analysed with the optical model (OM) and coupled-reaction-channels method (CRC). The potential parameters for the entrance reaction channel must be deduced from the analysis of the elastic and inelastic scattering data before the CRC-calculation of reaction cross-section. The results for the ^{12}C(^{11}B, ^{15}N)^{8}Be reaction are presented as an example. The energy dependence of optical potential parameters for this reaction are also presented.

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1. Introduction

The structure and interactions of nuclei out of stability region *(exotic nuclei)* are studied insufficiently yet. There are two experimental methods to realize such investigations: first one are the experiments with radioac-

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tive (secondary) beams *(direct method)* and second one are the experiments with the stable ion beams producing many-nucleon-transfer reactions. Both methods are used at present and successfully complement one another.

The development of nuclear reaction theory and the computational methods gave the possibilities of more widely using of the second method — stable ion beams experiments with the nucleon- and cluster-transfer reactions. It should be noticed, that investigation of exotic nuclei interactions, presented in this seminar, needs of simultaneous investigation of stable nuclei, taking part in these same reactions.

The theoretical analysis of the data, concerning study of exotic nuclei with heavy-ion reactions is more complex than the investigations using direct method. Whereas the data of elastic and inelastic scattering of radioactive ions are analysed with the optical model (OM) and coupled-reaction-channels method (CRC) using in entrance and exit channels the nucleus–nucleus potentials of the same systems, the incoming and outgoing reaction systems are different for the transfer reactions. Before the CRC-calculation of reaction cross-section, the potential parameters for the entrance reaction channel must be deduced from the analysis of the elastic and inelastic scattering data. Moreover, because the parameters of nucleus–nucleus potentials are energy-dependent, the studies of energy dependence of these parameters play important role in investigation of nuclear reaction of the exotic nuclei.

The next problem for the transfer reaction studies is the calculations of the nucleon and cluster spectroscopic amplitudes (SA). At present, these amplitudes can be calculated for the 1p-shell nuclei within the translationary-invariant-shell-model (TISM) [1]. The large base of TISM-cluster SA were calculated and successfully applied in the present reaction studies.

2. Theoretical calculations

The scattering and transfer reaction data were analyzed within Optical Model (OM) and Coupled-Reaction-Channels method (CRC) [2–5]. The nucleus–nucleus optical potential of Woods–Saxon type $U(r, V, r_V, a_V, W_S, r_W, a_W)$ with volume absorption and the Coulomb potential of uniform charged sphere $V_{\rm C}(r, r_{\rm C})$.

In the CRC method, for calculation of distorted waves $\chi_\alpha(r_k)$ for k channels, the following system of coupled equations [4] are solved

$$
\begin{aligned}
&[E_k - \hat{T}_{kL}(r_k) - V_{{\rm C}k}(r_k) - U_k(r_k)]\chi_\alpha(r_k) = \qquad (1)\\
&\sum_{\alpha',\lambda>0} i^{L'-L} V^\lambda_{\alpha;\alpha'}(r_k)\chi_{\alpha'}(r_k) + \sum_{\alpha',k'\neq k} i^{L'-L}\int\limits_0^{R_m} V_{\alpha;\alpha'}(r_k, r_{k'})\chi_{\alpha'}(r_k)dr_{k'}\,,
\end{aligned}
$$

where the indexes α and α' denote the sets of quantum numbers for channels k and k', respectively;

$\hat{T}_{kL}(r_k)$ — kinetic energy operator for k-channel;

$U_k(r_k)$ and $V_{\mathrm{C}k}(r_k)$ — nuclear and Coulomb potentials for k-channel;

E_k — kinetic energy of k-channel;

$V^{\lambda}_{\alpha;\alpha'}(r_k)\chi_{\alpha'}(r_k)$ — matrix element (operator) for transitions to discrete states of nuclei with λ- multipolarity (λ is transfer orbital momentum);

$V_{\alpha;\alpha'}(r_k, r_{k'})$ — matrix element (operator) for transfer reactions;

L and L' — orbital momentum for k and k' channels.

Two kinds of rotational transitions were included into coupled-channels scheme in the CRC-calculations: first, the rotational transitions

$$\langle E^*_{\mathrm{ex}}, J^{\pi}_{\mathrm{ex}} \mid V_\lambda(r_k) \mid E, J^\pi\rangle \tag{2}$$

with changes of energy of internal state of nuclei and, second, the quadrupole rotational transitions without energy changes

$$V^{\lambda=2}_{J^\pi;J^\pi}(r_k) = \langle E, J^\pi \mid V_2(r_k) \mid E, J^\pi\rangle \tag{3}$$

called as *reorientations* of nuclei [5]. The CRC-analysis of elastic scattering data showed that the *reorientations* processes are important for the scattering of deformed nuclei at large angles.

3. The experimental results

We have measured and published the angular distributions of reaction products at different energies using ion beams and targets presented in the Table I below. Only one example, the ^{12}C(^{11}B, ^{15}N)^{8}Be reaction, is discussed in this proceedings. Most of these experiments were performed in Heavy Ion Laboratory, Warsaw, Poland. Some previously measured data on Kyiv cyclotron U-240 and Moscow cyclotron U-150 were also included in the analysis.

TABLE I

Beam	Energy (MeV)	Target	Reaction products
Warsaw cyclotron C-200P			
^{10}B	51	^{7}Li	$^{6-8}$Li, $^{7-10}$Be, ^{10,11}B
^{11}B	44	^{7}Li	$^{6-8}$Li, $^{7-10}$Be, ^{10,11}B, ^{12}C
^{11}B	45	^{9}Be	^{9,10}Be, $^{10-12}$B, ^{12}C
^{11}B	45	^{13,14}C	^{9,10}Be, ^{10,11}B, $^{12-14}$C, $^{14-16}$N
^{11}B	49	^{12}C	^{10,11}B, ^{12,13}C
^{18}O	114	^{7}Li	$^{6-8}$Li, $^{7-11}$Be, $^{10-12}$B, $^{12-14}$C, $^{14-17}$N, $^{16-19}$O
^{18}O	117	^{9}Be	$^{6-8}$Li, $^{7-11}$Be, $^{10-12}$B, $^{12-14}$C, $^{14-17}$N, $^{16-19}$O
^{18}O	117	^{12,13,14}C	$^{6-8}$Li, $^{7-11}$Be, $^{10-12}$B, $^{12-14}$C, $^{14-17}$N, $^{16-19}$O
Kyiv cyclotron U-240			
^{12}C	65	^{9}Be	$^{7-10}$Be, $^{10-11}$B, ^{12,13}C
^{14}N	110	^{7}Li	$^{6-8}$Li, ^{14,15}N
^{14}N	116	^{12}C	^{12,13}C, ^{14,15}N
Kurchatov Institute cyclotron U-150, Moscow			
^{7}Li	82	^{12}C	^{7}Be
^{6}Li	93	^{14}C	^{6}He

4. Example of reaction

4.1. Reaction $^{12}C(^{11}B,\ ^{15}N)^{8}Be$

As an example of using reactions for study interaction of unstable nuclei can be results of study of ^{12}C(^{11}B, ^{15}N)^{8}Be reaction. Angular distributions of this reaction were measured at the energy $E_{\rm lab}(^{11}B) = 49$ MeV for the transitions to the ground and excited state of ^{8}Be and ^{15}N using the ^{11}B ion beam of the Warsaw cyclotron U-200P (Fig. 1) [7]. The data were analyzed within the CRC method. The elastic, inelastic scattering and one- and two-step transfers were included in the coupling scheme. It was found that only the α- and t-cluster transfers dominate in this reaction. The α-transfer (see curve $\langle\alpha\rangle$) is important at forward angles and t-transfer (curve $\langle t\rangle$) dominates at backward angles. The data of the ^{12}C(^{11}B, ^{8}Be)^{15}N reaction at $E_{\rm c.m.} = 9.4$–17.8 MeV [8] were also included in the analysis. As a result, the energy dependence of the OM parameters for the ^{15}N+^{8}Be interaction was obtained (Fig. 2). The energy dependence of the ^{13}C+^{8}Be potential parameters [9] is also presented in Fig. 2 for comparison. One can see a significant difference between these energy dependences which can be explained by the difference of the Coulomb barriers of these systems.

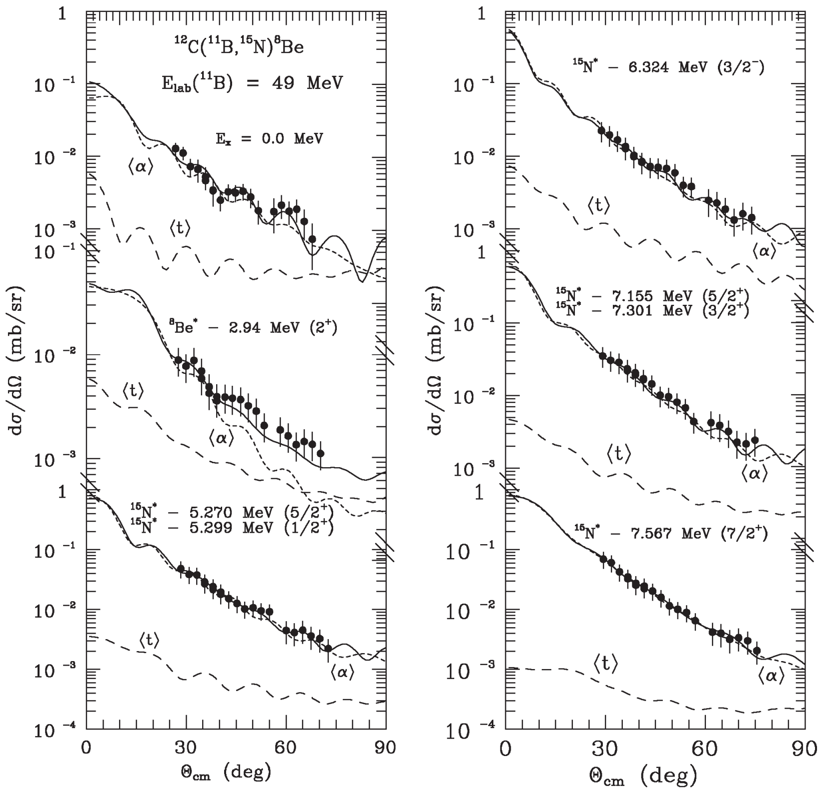

Fig. 1. Angular distributions of the $^{12}C(^{11}B,\ ^{15}N)^{8}Be$ reaction at the energy $E_{\rm lab}(^{11}B) = 49$ MeV [7]. Dashed curves $\langle\alpha\rangle$ and $\langle t\rangle$ show the CRC calculations for the α- and t-cluster transfers, respectively. Solid curves represent the coherent sums of both transfers.

5. Conclusions

The presented method of indirect determination of the optical potential parameters of the interaction of nuclei (also exotic, radioactive and short-living) in the exit channels of nuclear reactions can be used in conventional experiments with heavy ions without using radioactive beams.

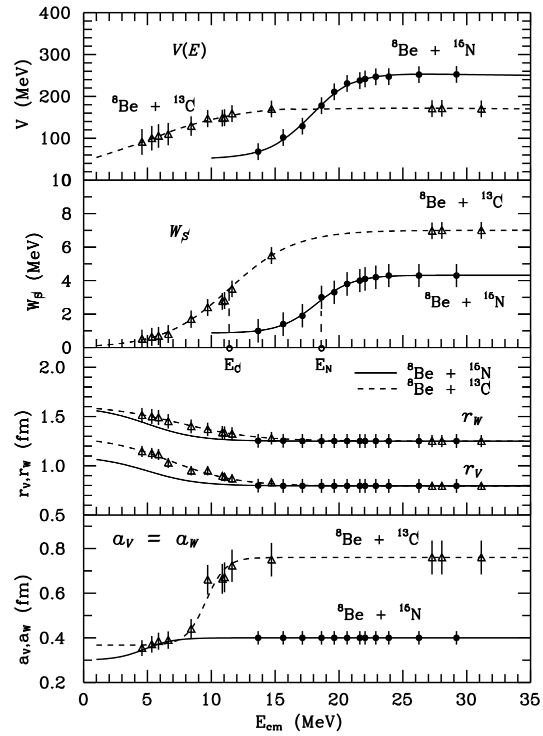

Fig. 2. Energy dependence of the ^{8}Be+^{15}N [7] and ^{8}Be+^{13}C [9] optical potential parameters.

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