High-performance analysis of the nucleus-nucleus elastic scattering data within the microscopic model of optical potential: scattering of $^{12,14}Be+^{12}C$ at 56 MeV/nucleon

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The aim

- The presentation aims a demonstration of possibilities to investigate, numerically, a multi-parameter model of physical process using parallel computing techniques and facilities of the HybtiLIT platform of the Multifunctional information and computing complex (MICC) of the Meshcheryakov Laboratory of Information Technologies of JINR.
- As example, we consider a calculation of the differential cross sections of the $^{12,14}Be+^{12}C$ scattering at energy about 56 MeV/nucleon within the 4-parameter model.
- To this end, the combined parallel C++/Fortran/MPI/OpenMP computer code has been carried out where the ”brute force” minimization approach has been implemented for the fitting of parameters of model to the experimental data from [*Phys Rev C49 (1994) 1540*] .

Model: Basic Formulae

The observables of the nucleus-nucleus scattering are expressed via the wave functions of the three-dimensional Schrödinger equation:

$$\frac{\hbar^2}{2m}\Delta\Psi + (E - U)\Psi = 0,\ U = U_C + U_N,\ m = m_0\frac{A_p A_t}{A_p + A_t}$$

The hybrid model of OP: $U_N = N_R V_{DF} + iN_I W_H,$

- ✓ The real part V_{DF} is constructed within the microscopic double folding model (DFM);
- ✓ The imaginary part W_H is calculated in the high-energy approximation (HEA).
- ✓ Factors N_R and N_I are the normalization coefficients which are determined from the experimental data.
- ✓ Both real and imaginary potentials depend on the density distribution of nuclear matter in interacting nuclei

Model: nuclear density and formulation of the problem

To construct the OP, we used the phenomenological density of exotic nuclei ^{12}Be and ^{14}Be in the form of symmetrized Fermi function (SF), which depends on two parameters: diffusion a and radius R:

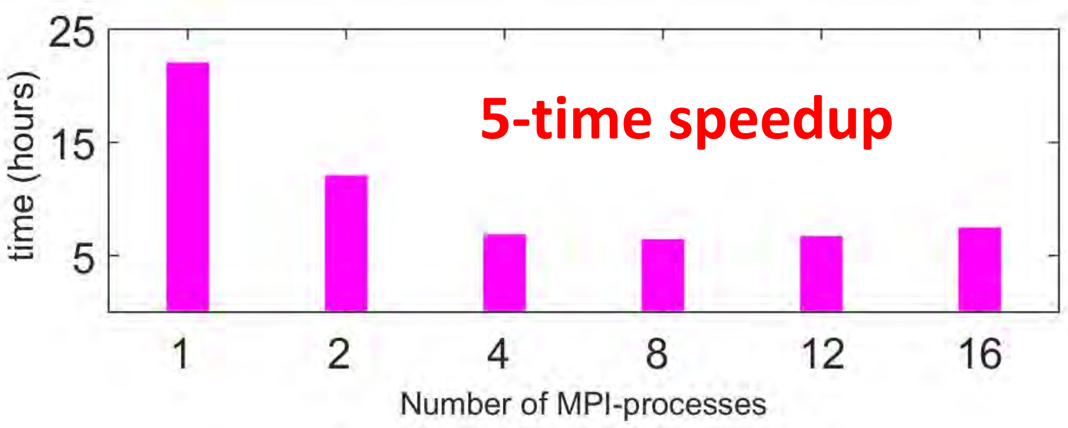
$$\rho_{SF}(r) = \rho_0 \frac{sinh(R/a)}{cosh(R/a) + cosh(r/a)} \qquad \rho_0 = \frac{A}{(4\pi R^3/3)}\left[1 + \left(\frac{\pi a}{R}\right)^2\right]^{-1}$$

- *Ref. Nucl Phys A875 (2012) 8*: The SF-density parameters were determined within the Glauber theory from the experiments the scattering of $^{12;14}$Be by protons at relativistic energy about 700 MeV.
  - for ^{12}Be: a=0.67 fm, R=1.37 fm;
  - for ^{14}Be: a=0.84 fm, R=0.99 fm.
- *Ref. Phys Rev C100 (2019) 034602*: 2-parameter fit. The calculations have been done with fixed a and R while parameters N_R and N_I are fitted to experimental data. –A noticeable discrepancy of theoretical differential cross sections with the experimental data at the region of small angles.
- *It is still unclear*: are the density parameters used appropriate in the $^{12;\,14}$Be+^{12}C scattering case at significantly lower energies?
- *The question*: can the 4-parameter model to improve an agreement with the ^{12,14}Be+^{12}C experimental data?

So, in our study, we fit the following parameters: diffuseness a and radius R of the $^{12;14}$Be SF-density and the parameters N_R, N_I, "responsible" for the depth of the real and imaginary OPs, respectively.

Software details and effect of parallel implementation

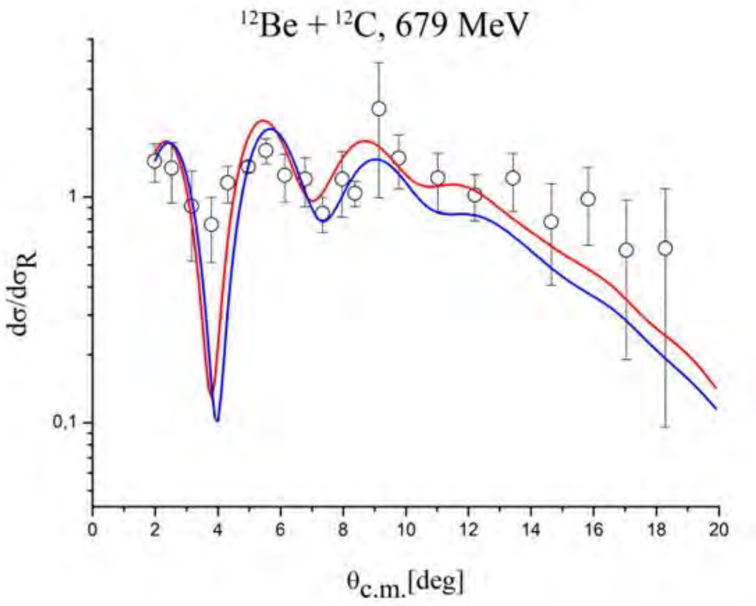
- The real DFM OP: a modification of the C++/OpenMP computer program available in the JINRLIB library (http://wwwinfo.jinr.ru/programs/jinrlib/dfm-potm/indexe.html).
- The imaginary HEA OP: a modification of the HEA-POT Fortran code from the HEA package available in the JINRLIB program library (http://wwwinfo.jinr.ru/programs/jinrlib/hea/indexe.html).
- The input parameters for the both procedures: atomic mass and energy of colliding nuclei, the interval and the step of numerical integration. In addition, for each nucleus, a nuclear density distribution function has to be specified.
- The differential cross sections calculation: the DWUCK4 package was used, adapted to combine it with the other modules in the complex.
- The main program: the parallel C++\MPI code joins all above procedures, provides the input of data, calculation of the discrepancy between the numerical and experimental cross sections, saves the results

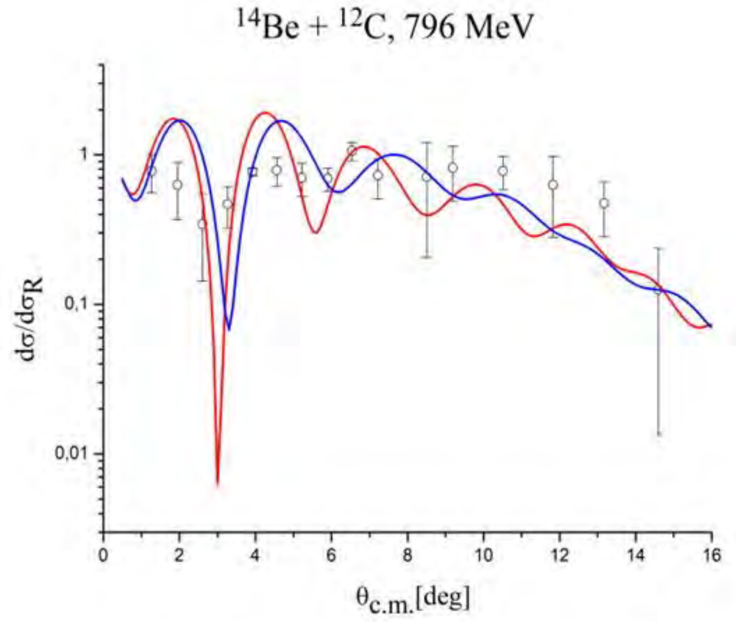


The 4-parameter fit execution time depending on the MPI-processes number.

- The determination of the best-fit values of the 4 adjustable parameters was implemented by means of 4 nested loops, where each of the parameters a, R, N_R, N_I runs over the values in a given interval with some step.
- Parallel implementation of such “brute force” approach is performed using the MPI technology. The iterations of the outer loop in terms of diffusion parameter a are distributed in blocks between parallel MPI-processes.

Results of numerical investigation





Elastic scattering of ^{12}Be+^{12}C at 679 MeV: the ratio of the differential cross section to the Rutherford cross section in comparison with experimental data [*Phys Rev C49 (1994) 1540*]

Red curve: 2-parameter fit from [*Phys Rev C100 (2019) 034602*] with the parameters N_R=0.767, N_I = 0.593, R = 1.37 fm, a = 0.67 fm, χ^2=4.54.

Blue curve: the result of 4-parameter fit: N_R=0.7, N_I=0.6, R=1.1 fm and a = 0.63 fm, χ^2=2.01.

Elastic scattering of ^{14}Be+^{12}C at 796 MeV: the ratio of the differential cross section to the Rutherford cross section in comparison with experimental data [*Phys Rev C49 (1994) 1540*]

Red curve: 2-parameter fit from [*Phys Rev C100 (2019) 034602*] with the parameters N_R=0.913, N_I=1.3, R=0.99 fm, a=0.84 fm, χ^2=11.77.

Blue curve: the result of 4-parameter fit: N_R=0.61, N_I=0.6, R=0.81 fm, a=0.85 fm, χ^2=5.44.

Summary

- The purpose of the numerical study was to reveal the influence of the varied parameters of the nucleus-nucleus OP on the agreement between the experimental and theoretical differential cross sections of the $^{12;14}Be+^{12}C$ scattering at 56 MeV/nucleon.
- Shown that:
  - by varying the ^{12}Be and ^{14}Be density parameters, it is possible to improve an agreement between numerical results and the experimental data.
  - there still remains a discrepancy between the calculated and experimental differential cross sections in the region of the first minimum. Thus, the necessity to take into account the processes occurring in inelastic channels, as it was done in [*Phys Rev C100 (2019) 034602*], is confirmed.
- The use of parallel "brute force" method in this numerical study has justified itself, since it is not technically difficult, expects an effective parallel implementation, does not require to create the Jacobian or Hessian matrices for the objective function
- Such approach can preferred for the high-performance computer analysis of a wide range of multi-parameter physical processes requiring a complex multistep computation of a minimization function.

Publications

1. Bashashin M.V. et al. Analysis of differential cross sections of $^{12;14}Be+^{12}C$ with energy of 56 MeV/nucleon on the basis of parallel implementation of a four–parameter microscopic nucleus–nucleus scattering model. System Analysis in Science and Education, 2020 (4) 10–19 (In Russ)
2. Bashashin M.V. et al., Analysis of the $^{12;14}Be+^{12}C$ Scattering Data within a Parallel Implementation of 4-Parameter Model, AIP Conference Proceedings, 2021, in press