

## Synergy of Nuclear Data and Nuclear Theory Online

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**Abstract.** The paper describes the NRV web knowledge base on low-energy nuclear physics developed in the Joint Institute for Nuclear Research. The NRV knowledge base working through the Internet integrates a large amount of digitized experimental data on the properties of nuclei and nuclear reaction cross sections with a wide range of computational programs for modeling of nuclear properties and nuclear dynamics. Today, the NRV becomes a powerful instrument for nuclear physics research as well as for educational applications. Advantages of the functioning scheme of the knowledge base provide the synergy of coexistence of the experimental data and computational codes within one platform.

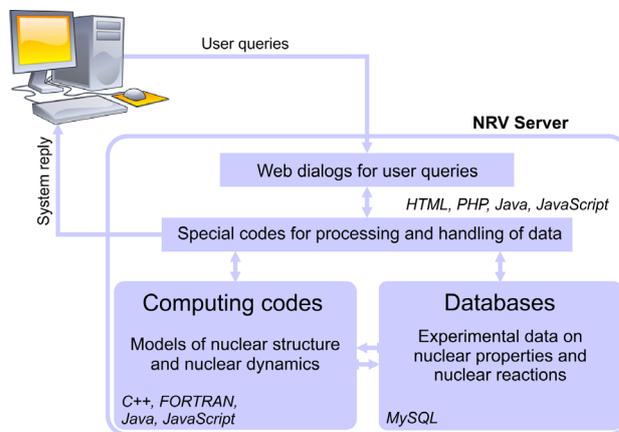
### 1 Introduction

Over the last hundred years, progress in nuclear physics has generated a vast amount of the experimental data both on nuclear properties and on reactions induced by nuclear particles. In recent years, advances in the Internet technologies have led to the development of web-based nuclear resources. As a rule, such nuclear databases supply users with text files including tabular information on a specific subject only. Certainly, cumulative data and its free accessibility assist in the day-to-day work of a modern nuclear physicist. However, the variety of data requirements, for example, in the case of planning new experiments, results in the work consisting of the following steps. First, search for and following processing of available experimental data. In some cases, an analysis of these data within appropriate theoretical models is required. Next, a simulation of the experiment and a choice of optimal parameters of experimental setups. Finally, when the experiment is completed, the obtained data must be processed and analyzed using modern theoretical approaches. All these steps require considerable amount of time, resources, and experience.

In order to simplify this work, we propose a unique web-based system which we call the web knowledge base on low-energy nuclear physics “Nuclear Reaction Video” (NRV) [1, 2]. It has been created in the Joint Institute for Nuclear Research. This knowledge base, working through the Internet directly in the browser of a remote user, integrates a large amount of digitized experimental data on the properties of nuclei and nuclear reaction cross sections with a wide range of computational programs for modeling of nuclear properties and nuclear dynamics. Today, the NRV knowledge base is both a powerful tool for nuclear

physics research and an educational resource demonstrating the synergy of this approach.

The detailed description of the developed knowledge base was given in Ref. [2]. Fig. 1 shows the functioning scheme of the NRV.

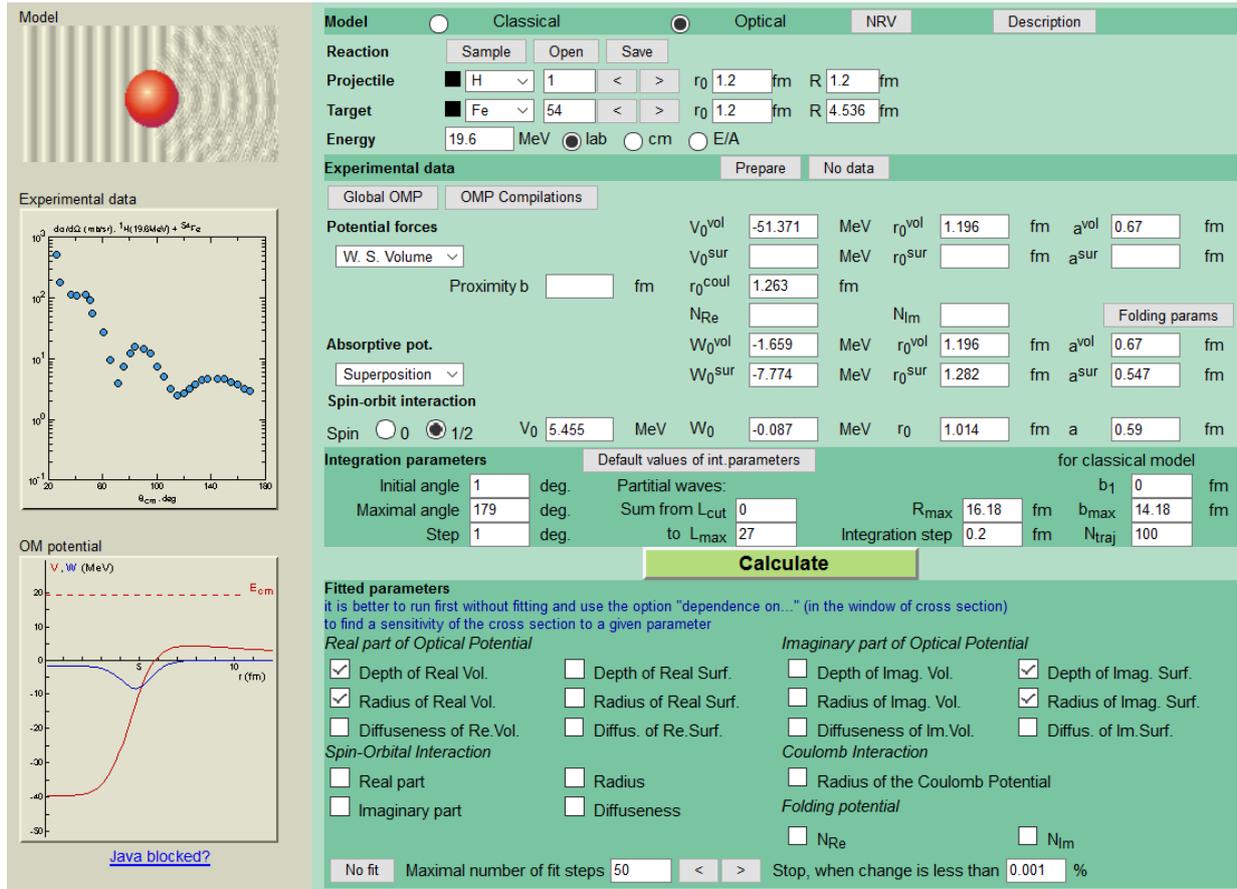


**Figure 1.** The functioning scheme of the NRV knowledge base

The system implements the following principles: (1) constantly updated experimental databases on the properties of nuclei (masses, electromagnetic properties, half-lives, decay modes, level schemes, *etc.*) adopted from open sources [3–8]; (2) constantly updated experimental databases on the cross sections of various nuclear processes; (3) a large number of quite complex models and algorithms that describe the properties of nuclei and the processes of nuclear dynamics at low and intermediate energies, *e.g.* [9–11]; (4) a unified, user-friendly, interface.

Within this project, access to complex computer programs having a visual graphical interface for setting initial parameters as well as for graphical representation and pro-

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**Figure 2.** Screenshot of the NRV web page providing means for preparation of the Optical Model input parameters

cessing of the results is made via the Internet browser window. A special feature is that the computer programs are both located and executed on the server side and the client receives the results of their work via the web browser supporting Java, JavaScript, and HTML languages. All results obtained by the user are available for further processing, saving, and analysis.

In this paper, we present an example of application of the NRV in order to demonstrate the advantages of the functioning scheme providing synergistic effect of the interplay between nuclear databases and computational codes.

## 2 Analysis of Elastic Scattering within NRV Knowledge Base

Elastic scattering of nuclear particles is the most vivid example of efficiency of the NRV. The NRV provides two theoretical models for elastic scattering analysis – the quantum optical model (OM) and the semiclassical approach. The OM is the most reputable theoretical method among the mentioned above.

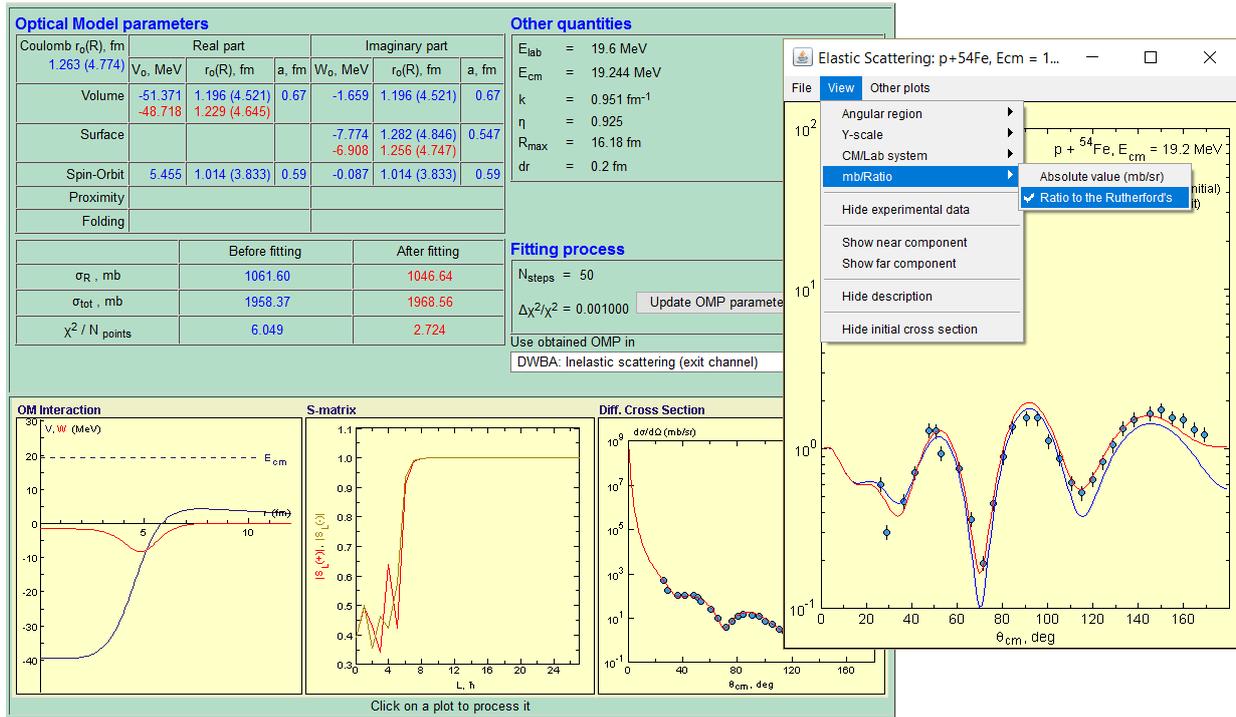
Let us imagine that one needs to perform an analysis of the experimental data on proton elastic scattering by  $^{54}\text{Fe}$  target nuclei at energy  $E_{lab} = 19.6$  MeV. These data might be obtained as a result of experimental research or extracted from the database including the database on elas-

tic scattering reaction cross sections available in the NRV. For our example, we adopt the experimental data for the  $^{54}\text{Fe}(p, p)$  reaction from Ref. [12].

The OM section of the NRV is shown in Fig. 2. It is implemented in the form of a web dialog allowing one to define all necessary parameters for the optical model calculations. Here, a user may set the projectile and target nuclei, collision energy, the optical model potential parameters, and even indicate the parameters that must be varied in order to fit the theoretical cross section to the experimental data if they are available. All notations of input parameters are familiar to the users experienced in OM application. Visualization of the data and optical potential in the figures on the left side additionally simplifies model perception.

A special web form for preparing experimental data may be activated by the *Prepare* button. In this form, users can enter either their own data set or data from the NRV database on elastic scattering cross sections. Availability of the reaction data within the same system and simplicity of its treatment is one of the manifestations of the synergistic effect mentioned above. The uploaded data is visualized in the main dialog in the figure on the left side. The user may also choose the *No Data* regime when nothing is fitted.

OM calculations are based on the solution of the partial Schrödinger equations. The numerical procedure re-



**Figure 3.** Screenshot of the NRV web page with the results of the Optical Model calculation

quires setting the so-called integration parameters in addition to the model parameters. Sometimes, even advanced users are not able to define the maximum orbital momentum  $L_{max}$  to be taken into account or integration mesh size  $R_{max}$  and its step  $dR$ . The NRV provides the possibility of setting default values of these and other integration parameters.

The main ingredient of the phenomenological OM is the optical potential. There are a few frequently used parameterizations for this potential, *e.g.*, the Woods–Saxon volume or/and surface parameterizations that are well adapted for the wide range of the nuclear masses and collision energies, proximity potential, double folding potential, Thomas form of the spin-orbit interaction. All these form factors are available for use in the NRV optical model.

The main challenge, even for an experienced OM user, is definition of the values of the optical potential parameters due to the well-known ambiguity of the optical potential. There is a vast amount of publications devoted to the optical model analysis of elastic scattering cross sections. The most significant studies provide the so-called global parameterizations with analytic expressions for the OM parameters as functions of the target mass and collision energy. The NRV Optical model has a convenient instrument activated by the *Global OMP* button that allows one to choose the appropriate global OMP parameterization from the list included in the corresponding database. Particularly, in the case of the  $^{54}\text{Fe}(p, p)$  reaction considered here, we chose the parameterization recommended for the proton-induced reactions in Ref. [13]. The optical potential parameters in the web form shown in Fig. 2 are set automatically in this case.

After defining the OM potential, we are ready to start calculation by pressing the *Calculate* button (see Fig. 2). Note that the user does not need to download the corresponding software, install it, and study how to run it. All calculations are performed on the side of the NRV server and then transferred to the user in the form of a web page shown in Fig. 3. The resulting information is presented here both in text and in graphical forms. It includes the optical potential parameters, total  $\sigma_{tot}$  and reaction  $\sigma_R$  cross sections, *S*-matrix elements, and the plots of differential cross sections. These plots are not static objects, but Java applets incorporated into the web page. This technology provides the user an additional possibility of processing the obtained results within a separate window shown in Fig. 3. This particular window depicts the angular distribution of the elastically scattered projectile nuclei calculated within the OM in comparison with the experimental data. The window has its own menu for data manipulation, *e.g.*, conversion them the center-of-mass system to the laboratory system, plotting in millibarn units or as a ratio to the Rutherford cross section, *etc.* Finally, the menu *File/Save as ...* includes items for saving the obtained results to the user’s disk in graphical (eps, gif, png) or text formats.

As one can see from Fig. 2, the optical model web dialog has the section *Fitted parameters* where the user may specify the OM parameters by running the code in the fitting regime. This option is very useful in the case when there is no appropriate optical potential or available global parameterizations do not cover a particular target or energy domain.

In Fig. 3, the blue line corresponds to the OM calculation with the optical potential recommended in Ref. [13]. One may see that the structure of the angular distribution

is reproduced very well, however, the absolute value of the cross section is underestimated at large scattering angles. By fitting the depths and radii of the real and imaginary parts of the optical potential, one obtains the cross section shown by the red line. The obtained new values of these parameters are also presented in the resulting web page in the tabular form together with the initial values. The quality of fitting procedure may be estimated by comparing the standard deviation  $\chi^2$  before and after fitting. In the particular case shown in Fig. 3, the value of  $\chi^2$  decreases by a factor of 2 after fitting and the red curve provides better agreement with the experimental data than the initial one. If the user is satisfied with the fitted optical potential, the button *Update OMP parameters* may be used to save the results and update the corresponding parameters in the Optical model web dialog (see Fig. 2).

The optical model potential is an essential ingredient for many other theoretical models, for example, the distorted wave Born approximation for inelastic scattering or nucleon transfer reaction modeling. These models are also implemented in the NRV knowledge base in a similar way. In order to simplify transfer of the optical potential parameters between different models, the web page with the optical model results (see Fig. 3) provides the user with such an instrument.

### 3 Conclusions

In this paper, we demonstrated the application of the NRV knowledge base to the analysis of elastic scattering reactions. In addition, the NRV system provides many other theoretical instruments in combination with a wide range of data on nuclear properties and reaction cross sections (see, for example, Ref. [2]). Among them, in particular, there are  $\alpha$  and  $\beta$  decay models, characteristics of induced and spontaneous nuclear fission. The NRV project also provides the possibility of calculating nuclear level densities, decay widths, and survival probabilities of excited nuclei within the statistical model. Calculation of single-particle levels (energies and wave functions) for spherical and deformed nuclei is possible in the framework of the shell model with the Woods–Saxon mean field as well as the two-center shell model.

Beside the optical model and DWBA for elastic, inelastic, and transfer reaction treatment mentioned above, the NRV includes other theoretical approaches to studying nuclear processes. For instance, characteristics of complete fusion of heavy ions can be calculated in the NRV system within the quantum and empirical coupled-channel approaches. The combination of the codes for calculation of fusion cross sections with the code of the statistical model of decay of excited rotating nucleus allows one to simulate the processes of fusion with subsequent fission or survival with respect to neutron, proton, alpha particle, and gamma quantum emission. The *Kinematics* section

provides the possibility of kinematic analysis of nuclear reactions with two and three particles in the exit channel as well as  $Q$ -value calculations for different processes. The NRV also provides the possibility of calculation and visualization of the multidimensional adiabatic (within the two-center shell model) and diabatic (within the double-folding and the proximity models) driving potentials.

In addition to research applications, the NRV manifests itself as an efficient educational resource. Many universities in different countries use it as a practical training tool for the students specializing in nuclear physics.

New web technologies that appeared during the last few years stimulate us to perform a deep update of the NRV system. The new version of the knowledge base is coming soon under the support of the RSA-JINR (Dubna) Cooperation program.

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