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NRV web knowledge base on low-energy nuclear physics

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ABSTRACT

The paper describes the principles of organization and operation of the NRV web knowledge base on low-energy nuclear physics (http://nrv.jinr.ru/) which 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 various processes of nuclear dynamics which work directly in the browser of a remote user. The paper also gives an overview of the current situation in the field of application of network information technologies in nuclear physics. The features of the NRV knowledge base are illustrated in detail on the example of the analysis of nucleon transfer reactions within the distorted wave Born approximation.

1. Introduction

The NRV web knowledge base on low-energy nuclear physics [1–5] has been created in the Joint Institute for Nuclear Research. This 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 various processes of nuclear dynamics which run directly in the browser of a remote user. Today, the NRV knowledge base is both a powerful tool for nuclear physics research and an educational resource.

The system is widely used, as evidenced by the large number of user queries to its resources and the number of references to the knowledge base in the articles published in scientific journals. In particular, over the past few years the average number of queries to the nuclear data and the average number of calculation requests exceeded 100,000 and 35,000 per year, respectively, which is a good indicator taking into account the focus of the project.

The following gives an overview of the current situation in the field of application of network information technologies in nuclear physics, the basic principles of the NRV knowledge base are covered, and a brief description of its structure is given. The practical usage of the NRV knowledge base is demonstrated in detail on the example of the analysis of nucleon transfer reactions within the distorted wave Born approximation (DWBA). A short technical guide on how to start working with NRV is provided in the Appendix.

2. Application of network information technologies in nuclear physics

2.1. Nuclear data

For more than 100 years of nuclear physics research a large amount of experimental data on the properties of nuclei and the cross sections of nuclear reactions has been accumulated. These data are contained in the articles published in numerous nuclear physics journals. The modern way of accumulating and organizing this information is to create databases. In recent years, online versions of the databases available on the Internet in a digital form via a web browser are the most intensively developed. Among the major resources of nuclear data one should mention NNDC [6], IAEA-NDS [7], CDFE [8], TUNL [9], NEA [10], NACRE [11], and NACRE-II [12].

The existing nuclear physics resources contain, as a rule, exhaustively detailed information about a subject (properties of atomic nuclei or reactions with them). Many of these resources are created by either major research institutions (e.g., Brookhaven National Laboratory maintains NNDC [6], Moscow State University maintains CDFE [8]) or within international collaborations (e.g. IAEA-NDS [7] and NEA [10]). However, for the theoretical analysis of the data the user has to look for and apply separate computational codes.

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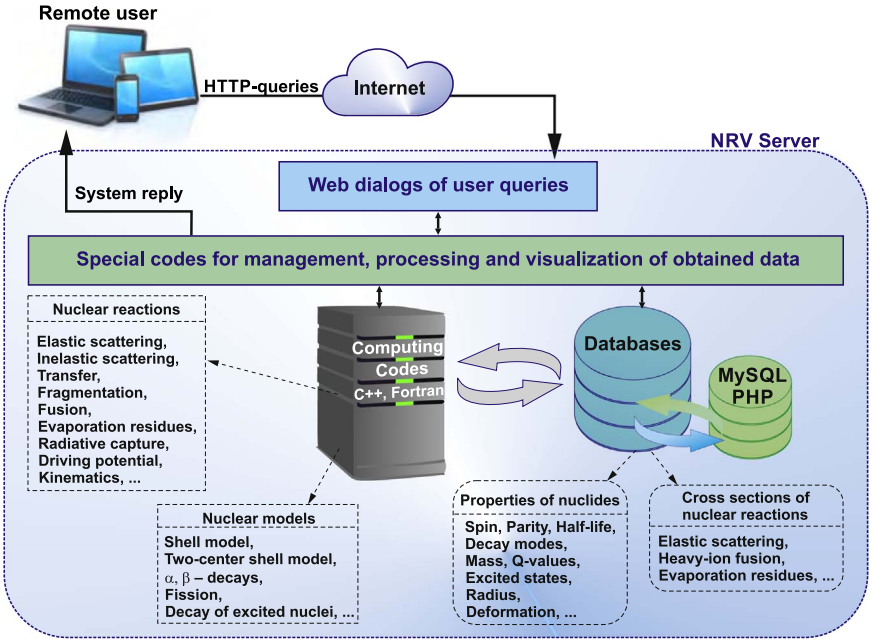

Fig. 1. The functioning scheme of the NRV knowledge base.

2.2. Modeling of nuclear dynamics

Over the years of the development of nuclear physics and, in particular, study of the dynamics of nucleus-nucleus collisions a number of theoretical approaches which became generally accepted in the scientific community has been developed. These include, for example, the optical model of elastic scattering or the coupled channel method for the calculation of fusion cross sections of atomic nuclei. For many years, software codes (e.g., FRESCO [13], GRAZING [14], DWUCK [15], etc.) are being developed which provide the possibility of simultaneous modeling of several competing processes occurring in the collisions of nuclei. Many of these software packages are freely distributed. The main drawback of many of these codes is an awkward interface. Here, the interface means the way the users interact with the software code, for running of which it is necessary to prepare an input file correctly. Typically, the input file is a text file with a lot of input parameters, for the proper preparation of which it is necessary to study quite complex and not always complete instructions. As a result of running the program, the user usually obtains another text file, for processing of which some third-party graphical applications should be used. Therefore, the work with these programs for a beginner is problematic. There are two main ways of solving the problem indicated.

The first method is to create a software package for simulation of the nuclear dynamics in the form of the programs that are loaded on a specific local computer and run on it under a particular operating system. Such packages include, for example, TALYS [16], EMPIRE [17], LISE++ [18], and NRV for Windows [2]. All of these software products have (or may have) a graphical user interface for preparing input data, tools for analysis of simulation results, as well as the system of prompts and descriptions. All this greatly facilitates the work of the user.

The second method is to organize the work of the computational code on a single server (or a system of interconnected servers) available to the users via the Internet. This is the way the NRV web knowledge base is organized.

Each of the methods offer some challenges. For example, the first method is dependent on the operating system. In addition, the developers have to implement the software updates properly, in particular, to inform the user about the new features of the system and bug fixes, etc. Such challenges are absent when choosing the second method. However, the second method has the challenges associated with the organization of a much more complex functioning of the system via the Internet and the management of computing tasks with a large number of user requests overlapping in time.

3. Structure and basic components of NRV

The developed system — the NRV web knowledge base on low energy nuclear physics — is designed to combine nuclear databases with generally accepted theoretical approaches to modeling of the dynamics of nuclear reactions into a single system with a uniform graphical user interface and easy access. The NRV is based on the following foundations: (1) constantly updated experimental databases on the properties of nuclei (masses, electromagnetic properties, half-lives, decay modes, level schemes, etc.); (2) constantly updated experimental databases on the cross sections of various nuclear processes; (3) implementation of a large number of quite complex (yet easy to use) models and algorithms that describe the properties of nuclei and the processes of nuclear dynamics at low and intermediate energies; (4) implementation of a unified, user-friendly, interface.

Within this project, complex computer programs having a visual graphical interface for setting initial parameters as well as for graphical representation and processing of the results are made available via the Internet. This is achieved through the development of the web applications based on the client-server architecture. A special feature of them is that the computer programs are both located and executed on the server and the client receives the results of their work via the Internet. This approach makes the work with the knowledge base independent of the operating system.

The functioning scheme of the NRV knowledge base is shown in Fig. 1.

3.1. Structure of NRV

The system is accessible using a web browser supporting the Java plugin (e.g., Microsoft Internet Explorer, Mozilla Firefox, etc.) via the Internet (see Appendix for details). This allows any user to access the NRV knowledge base from anywhere where there is an Internet connection. The interaction between the client and the server is organized using HTML forms. The appropriate forms are implemented

using Java, JavaScript, PHP, and HTML languages. Creating and testing the work of many HTML forms is the most time-consuming task that must be solved independently for each problem in order to provide an interactive and convenient interface as well as perform all the necessary checks at the stage of preparing the data to prevent execution of nonphysical requests.

The communication between the server and the client as well as creation of dynamic content is organized and implemented by means of the PHP language and the AJAX technology. Substantial computer resources required for modeling of complex processes of nuclear dynamics (the duration of the calculation, for example, may range from a few minutes to a few days), require special organization of the interaction of the remote user with the computing server. For this purpose, the server has a resident service that starts the execution of computational programs, monitors the calculation progress, and sends intermediate information to the client. After calculation, all the results are sent to the user as an HTML document for further processing and analysis. This approach allows one to run complex calculation programs and obtain final results in a web browser, even in the case of a very long calculation.

Most of NRV sections were developed with the use of Java applets to make an interactive graphical user interface. The Java applets provide rich possibilities for this purpose. However, the current trends in the evolution of web technologies cause difficulties with the further use of the Java applets (see Section 4 and Appendix for details).

The databases are a valuable component of the NRV knowledge base. For storing experimental data we use the open-source relational database management system MySQL.

All the NRV sections have detailed descriptions and/or references (including hyperlinks) to relevant publications.

3.2. Databases on nuclear properties and nuclear reactions

Our databases on the experimental properties of nuclei are filled mainly using some of the most reputable existing databases: NNDC [6] and AMDC [19]. Some of the information (e.g., nuclear radii) is found and entered into our databases independently, using the original publications in journals.

We also independently create and fill databases of digitized experimental cross sections of nuclear reactions (angular distributions of elastic scattering, fusion excitation functions, evaporation residue cross sections, etc.) based on original publications.

For brevity, in the following we will refer to all of these databases as NRV databases. The list of the presently available NRV databases on experimental properties of nuclei and experimental cross sections of nuclear reactions along with their sources and dates of revision is given in Table 1.

In addition to the experimental data on the properties of nuclei, we have a database on theoretical properties of ground-states (deformations, shell corrections, and mass excesses) based on Ref. [26].

As can be seen, the NRV databases are constantly updated. Because of the possible difficulties connected with the use of Java applets (see Section 4) some of the NRV sections for work with the experimental data are already available in both versions: Java- and JavaScript-based. At present, the following possibilities of work with the experimental data are implemented:

1. Access to the data on nuclear properties via the *Nuclear Map* section. The data can be retrieved both for a single nucleus and for a group of nuclei (the *Systematics* option).
2. Access to the data on the reaction cross sections. The example of presentation of information on the experimental fusion cross section for the reaction $^{16}O + ^{144}Sm$ is shown in Fig. 2. The data is displayed both in the text and in the graphical format. In addition, information about the data source (reference and hyperlink to the publication) and a brief description of the experiment are given. The selected data may be saved in the text (tabular) or in the graphical formats on the user's computer (the option *Download data*). There is also the possibility of comparing the fusion cross sections for the current reaction to the data for other (similar) reactions available in the NRV database (the option *Compare and process data*). The option *Theoretical analysis of the data* redirects the user to the section of the theoretical analysis of fusion cross sections for the selected reaction.
3. Use of the experimental data on nuclear properties to determine the model parameters. This option significantly simplifies the use of many theoretical models.

Table 1
The list of the presently available NRV databases on experimental properties of nuclei and experimental cross sections of nuclear reactions along with their sources and dates of revision.

NUCLEAR PROPERTIES	
Data	***Source***
Ground states: *spins, parities, half-lives;* Excited states: *energies, spins, parities, half-lives (widths);* Decays: *modes, intensities;* Abundances	NNDC, ENSDF: Evaluated Nuclear Structure Data File, (2016) [6]
Charge radii	I. Angeli, K. P. Marinova, (compilation, 2013–2016) [20]
Charge densities	H. de Vries et al. (compilation, 1987) [21]
Masses	M. Wang et al., Atomic Mass Evaluation (2012) [19]
Electric quadrupole moments	N. J. Stone, (compilation, 2016) [22]
Magnetic dipole moments	N. J. Stone, (compilation, 2014) [23]
B(E2) transitions: *energies of the first excited 2+ states, reduced electric quadrupole transition rates, quadrupole deformation parameters*	B. Pritychenko et al., adopted (recommended) values, (2016) [24]
B(E3) transitions: *energies of the first excited 3- states, reduced electric octupole transition rates, octupole deformation parameters*	T. Kibedi, R. H. Spear, (compilation, 2002) [25]

NUCLEAR REACTIONS	
Data	***Source***
Elastic scattering cross sections (angular distributions), Fusion cross sections, Evaporation residue cross sections	NRV (compilation based on original publications, 2016) [1]

3.3. Models of nuclear properties and nuclear reactions

The sophisticated computer programs implementing physical models of nuclear properties and nuclear reactions are located and executed on the side of the computing server (these programs are usually created in C++ and Fortran). The users can keep track of starting the programs and the progress of their execution using HTML forms in the browser. Almost all dialogs for preparing model parameters have the option of setting these parameters to default values chosen based on the

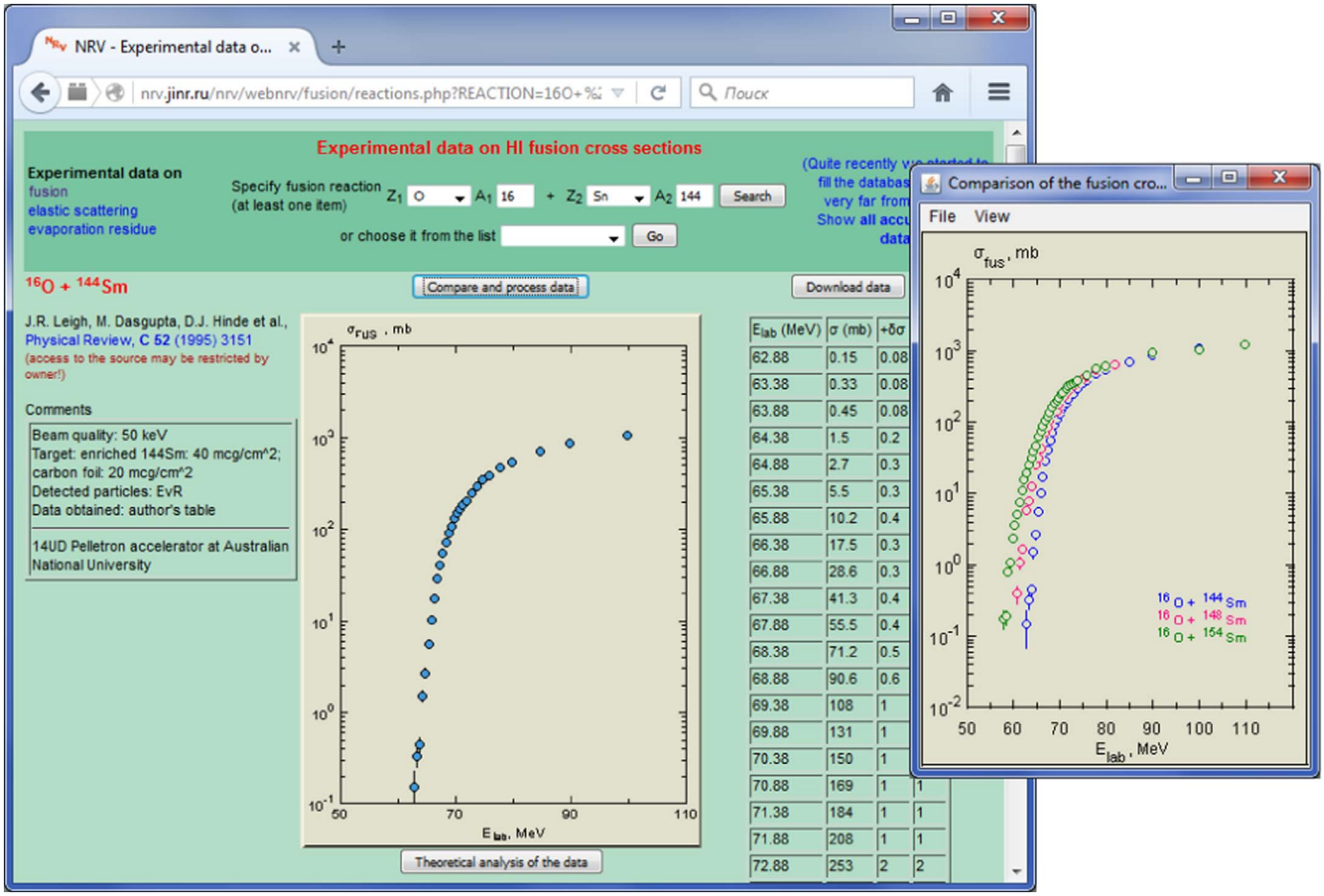

Fig. 2. Example of presentation of information about the experimental fusion cross section for the reaction $^{16}O + ^{144}Sm$.

experimental properties of nuclei, available systematics, or our own experience in using the corresponding codes.

3.3.1. Models of nuclear properties

Shell model and two-center shell model. The knowledge base includes the programs for calculating single-particle levels (energies and wave functions) for spherical and deformed nuclei in the framework of the shell model with the mean field in the form of the Woods-Saxon potential (with default parameters of the potential from Ref. [27]) as well as the two-center shell model [28,29] which provides the possibility of the calculation of single-particle levels from the configuration of two separate nuclei to the compact shapes of the compound nucleus. The example of the calculation of single-particle levels using the Woods-Saxon potential for the ^{208}Pb spherical nucleus is shown in Fig. 3.

Alpha decay. This part of the project allows one to study the properties of the alpha decay process: half-life, experimental decay chain, decay scheme as well as the alpha-particle wave function calculated for a particular potential, the parameters of which can be varied using the web interface. The code is based on Refs. [19,30–34]. For calculation of the decay energy the experimental masses of the ground states are used if they are available in the NRV database, otherwise a theoretical estimation [26] is used. The spins and the parities of the ground states are also taken from our database, if available, otherwise the minimum possible spins and positive parities are assumed. For estimation of the half-life we use the WKB approximation, the empirical Viola-Seaborg relation [30] with the parameters [31], the Viola-Seaborg relation [30] with the parameters [32], as well as the relation of Sobiczewski et al. [33].

Beta decay. This part of the project allows one to study the properties of the beta decay process: allowed decay types, half-life, and decay scheme. The code is based on Refs. [35–37]. The total half-life is calculated taking into account all energetically allowed transitions. Energies, spins, and parities of the states are taken from the NRV database, but the possibility of varying them manually is also provided. In the case of absence of reliable spectroscopic data, only transitions to the ground state of the daughter nuclei may be chosen (this is done by setting the appropriate checkboxes).

Fission. This part of the project allows one to study the processes of induced fission and spontaneous fission. For the induced fission $Z - N$ or $Z - A$ distribution of fragments, mass distribution, and charge distribution are displayed. The calculation of these distributions is performed using the GEF code [38] specially adapted for operating within the NRV knowledge base. The multiplicity of pre- and post-fission neutrons are calculated according to Ref. [39]. The total kinetic energy of the fragments is calculated according to Refs. [39,40]. The web interface allows one to vary the excitation energy and the angular momentum of the nucleus as well as the range of Z, N, A taken into account. For the spontaneous fission the experimental half-life taken from the NRV database (if any) as well as theoretical estimates calculated according to Refs. [37,41,42] are displayed.

Decay of excited nuclei. This part of the project allows one to calculate level densities, decay widths, and survival probabilities of excited nuclei. The code is based on the statistical model of decay of excited rotating nucleus by fission and evaporation of neutrons, protons, alpha particles, and dipole gamma quanta [43–45]. The properties of the nuclei are taken from the NRV database (if any), but the possibility of varying them manually is also provided. In

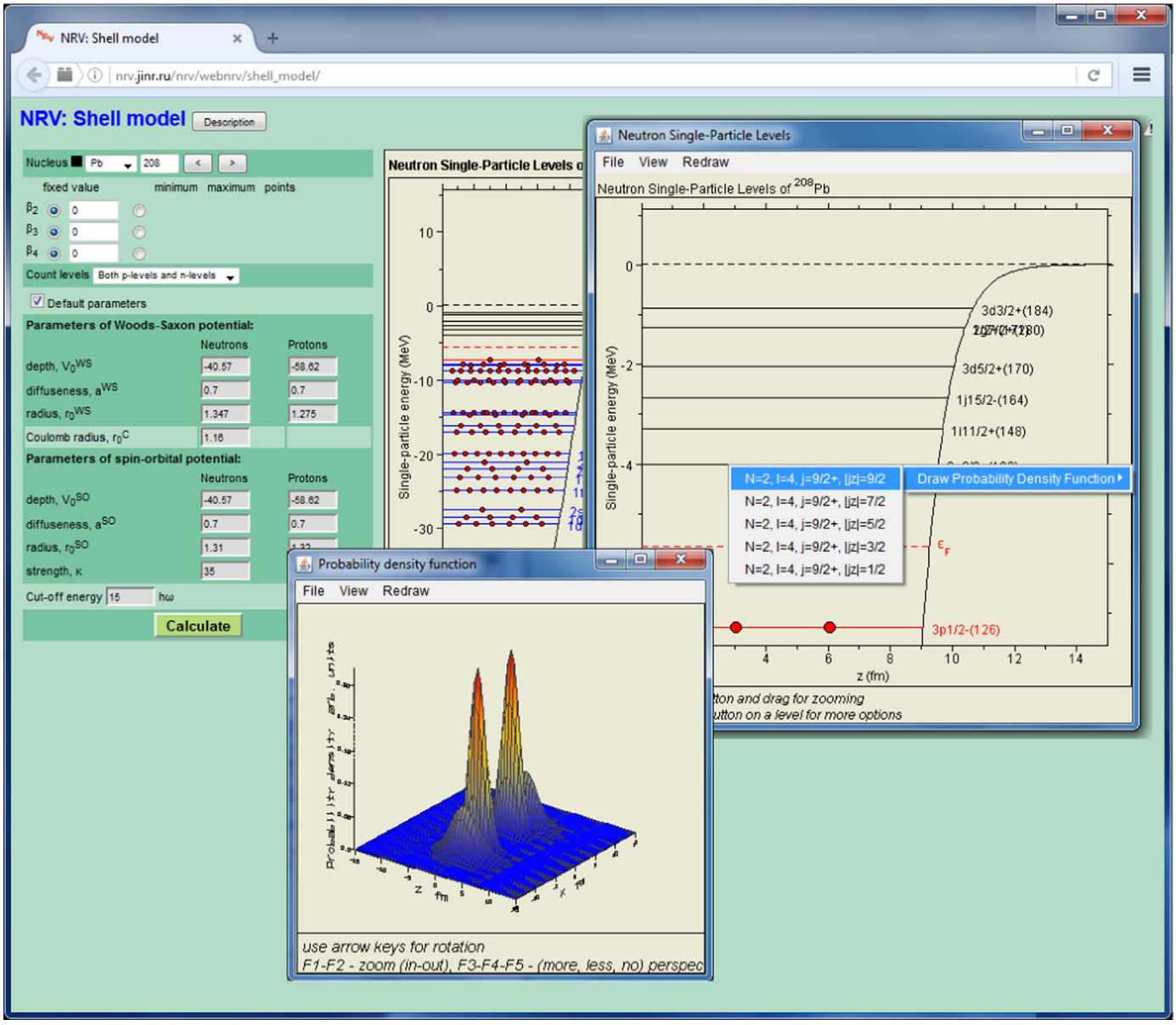

Fig. 3. Example of calculation of single-particle levels and probability density function for one of the neutron states of the ^{208}Pb nucleus.

addition, the interface allows one to vary the range of excitation energies, the level density parameters, moments of inertia, the type and the parameters of the collective enhancement of the level density.

3.3.2. Models of nuclear reactions

Elastic scattering. The system includes the optical and the classical model of elastic scattering of nuclei. These models allow the user to calculate the differential cross section of elastic scattering, *S*-matrix, field of trajectories, the deflection function, partial wave functions, phase shifts, etc. The possibility of choosing the optical model parameters according to the global parametrizations as well as the possibility of their automatic fitting to the experimental data (available in the NRV database or entered by the user manually) significantly simplifies the analysis.

Inelastic scattering. The cross sections of the processes of inelastic excitation of collective states can be analyzed within the DWBA approach (DWUCK4 code [15]) and the coupled channel approach (FRESCO code [13]).

Transfer reactions. The system provides the possibility of studying few-nucleon transfer cross sections in the framework of the DWBA approach (see Section 6 for details) and the semiclassical GRAZING code [14]. The GRAZING code [14] of the NRV allows one to calculate mass, charge, total kinetic energy, and angular distributions of the transfer reaction products.

Fusion. The fusion cross sections and the fusion barrier distribution functions can be calculated in the NRV system within the quantum [46] and the empirical [47] coupled channel approaches. Both approaches allow one to take into account the coupling of relative motion of colliding nuclei with their collective degrees of freedom (surface vibrations and/or rotations). In addition, within the empirical model there is the possibility of taking into account the influence of neutron transfer channels on the fusion cross section [48,49].

Evaporation residues. 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 system has the additional possibility of taking into account the probability of formation of the compound nucleus from the configuration of two touching nuclei, which is extremely important for the reactions leading to the

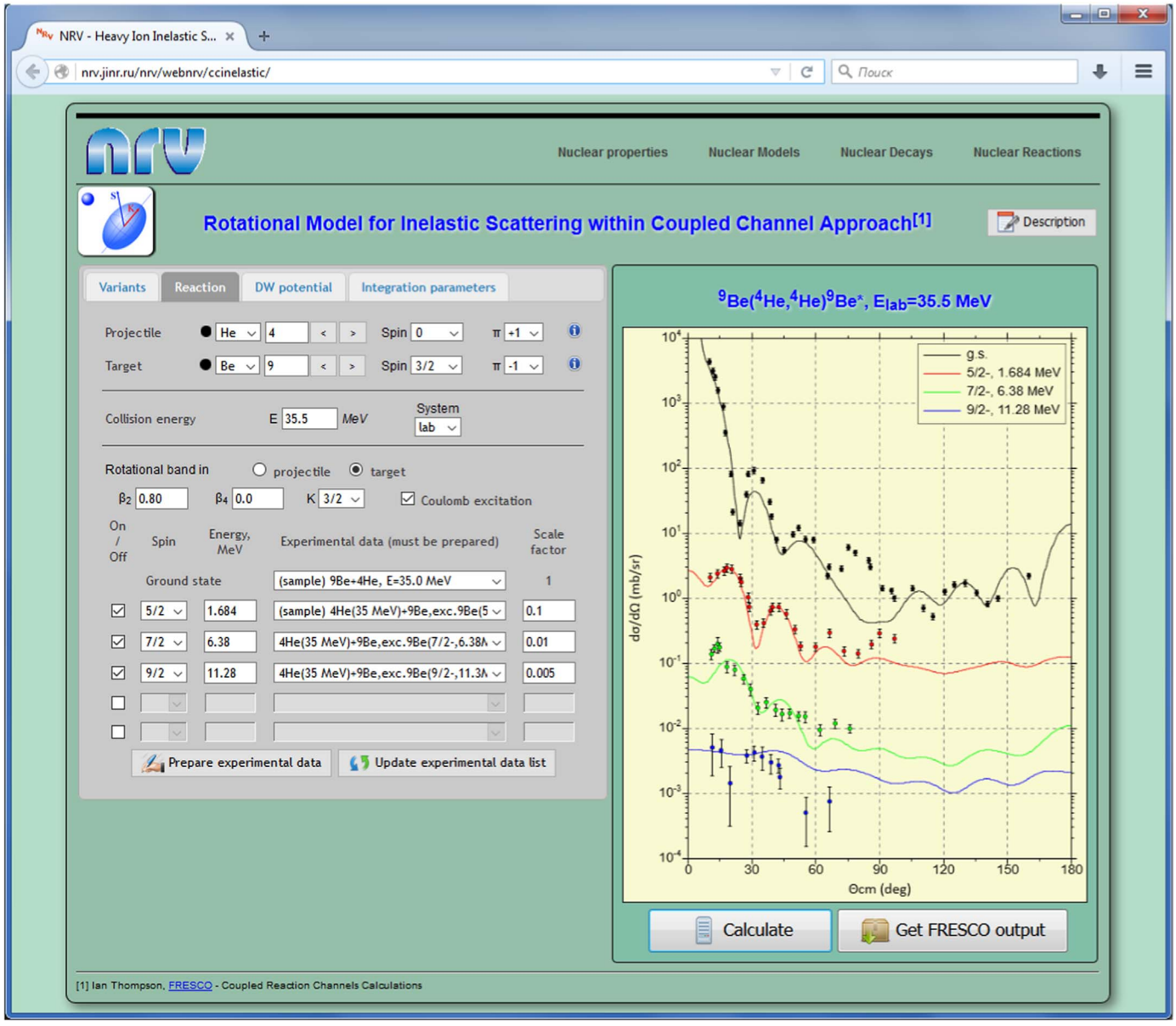

Fig. 4. Interface of the adiabatic rotational model (FRESCO [13]) of the section *Inelastic scattering*.

formation of superheavy nuclei. The option *Calculate Z-N yield* allows one to analyze the mass and the charge distributions of fission fragments based on the GEF code [38]. The partially implemented option *Decay of fragments* presently provides the possibility of calculation of pre-scission, post-scission, and total neutron, proton, alpha-particle, and gamma-quantum multiplicities.

Radiative capture. This part of the project allows one to study the radiative capture reactions of the type $a(b,\gamma)c$ within the potential model [50]. It is assumed that the nuclei a and b are structureless. The state of the nucleus c is obtained by the solution of the Schrödinger equation for the relative motion of the clusters a and b in their effective interaction potential. The spectroscopic factor of this state can be included into the calculations. The code allows one to calculate the radiative capture cross sections and the astrophysical S-factors taking into account $E1$, $E2$, and $M1$ electromagnetic transitions.

At the moment we do not have our own database of experimental radiative capture cross sections and S-factors. However, this data may be found in the databases NACRE [11] and NACRE-II [12]. The hyperlinks to these databases are provided on the NRV web site.

Fragmentation. This part of the project allows one to study the fragmentation reactions. The yields of different products are calculated using the phenomenological code EPAX3 [51].

Kinematics. This section provides the possibility of kinematic analysis of nuclear reactions with two and three particles in the exit channels as well as Q-value calculations for different processes.

Driving potentials. The potential energy of a heavy nuclear system is a key quantity determining its evolution in the processes of nucleus-nucleus collisions. The NRV 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 [29].

4. System development strategy

The development of the NRV knowledge base is planned in the three main directions: (1) filling and updating of the existing nuclear databases as well as adding new ones; (2) implementation of new physical models as well as extending the possibilities of the existing ones; (3) modernization of the user interface. The last point requires an additional discussion.

Until now, for displaying and processing of the results of user queries we have used Java applets because they provide rich possibilities for the development of the interactive graphical user interface. However, there are trends of gradual drop of support of the Java plugins (and, hence, Java applets) by the new versions of browsers. Some browsers (e.g., Google Chrome) do not support the Java plugin any more, explaining this by its insecurity. In addition, the browsers of the widespread tablet computers and other mobile devices do not support the Java plugins.

In our opinion, the most promising solution to this problem may be the gradual transition from the Java applets technology to the JavaScript language which is currently supported by all browsers without installing additional plugins. At present, the JavaScript technology (in particular, AJAX) in conjunction with PHP and HTML5 Canvas provide all the necessary tools for the correct work of the knowledge base: the creation of controls, the work with graphical primitives, the communication between the client device and the server. Therefore, we consider the possibility of transition from the Java applets to the code written in JavaScript.

At the moment, the code in JavaScript, intended for making plots on the Canvas element defined in the HTML5 standard has already been implemented in the knowledge base. This code is used, for example, in the interface of the adiabatic rotational model (FRESCO [13]) of the section *Inelastic scattering* (Fig. 4) as well as for visualization of experimental data on nuclear properties and nuclear reactions.

It should also be mentioned that in recent years several interesting development tools based on free software have been created. Among them, the Google Web Toolkit (GWT), which allows web developers to create AJAX applications based on the Java language. When including in the knowledge base new codes for the analysis of phase shifts in the elastic scattering of nuclei, we used the GWT package. In general, our experience with GWT may be considered successful. Another possible solution may be the use of the ASP.NET platform.

Finding the most effective solution is a difficult task, because it requires detailed consideration of the possibilities and the limitations of each technology, as well as evaluation of its long-term development and support by IT community.

5. Using NRV for educational purposes

The NRV knowledge base may be used for both scientific and educational purposes. Based on its resources, the students specializing in the field of nuclear physics may study the dynamics of nuclear reactions, analyze experimental data using the generally recognized models (e.g., the optical model of elastic scattering, the DWBA approach applied to the reactions of inelastic excitation and transfer, the coupled channel method for description of fusion reactions, etc.). In all these models the dynamics of nuclear collisions is determined, above all, by the interaction potential. Conducting this study implies the correct choice of properties of nuclei (e.g., their radius, deformation, mass, spin, etc.), their interaction potential and its parameters. For example, based on the analysis of data on elastic scattering, conclusions can be made about the radii of the nuclei. In the course of work on the study of fusion reactions, the data at energies both above and below the Coulomb barrier may be analyzed. The comparison of calculations in the one-dimensional model with the experimental data allows one to make conclusions about the influence of collective degrees of freedom on the process of fusion of atomic nuclei. Based on the structure of the excited states of the colliding nuclei, the most important degrees of freedom, which contribute to the fusion cross section, can be chosen. The influence of these degrees of freedom on the process of nuclear fusion may be taken into account and analyzed in both the quantum and the empirical coupled channel approaches.

Thus, the NRV is an efficient tool for acquisition and development of skills of work with modern theoretical approaches to the description of properties of individual nuclides, modeling of the dynamics of nuclear collisions, as well as the skills of work with experimental data and their systematization. The development of manuals and guidelines for the implementation of practical work may effectively introduce the NRV knowledge base in the educational process of any university preparing students in the field of nuclear physics.

6. Analysis of nucleon transfer process within NRV knowledge base

The most important goal of creating the NRV knowledge base is to provide the user with the opportunity of modeling of many channels of nuclear reactions at low and intermediate energies: elastic and inelastic scattering, transfer reactions, fusion, etc. This section demonstrates the capabilities of the NRV knowledge base in the analysis of nucleon transfer reactions on the example of the ^{208}Pb(d,p)^{209}Pb($\frac{9}{2}^{+}$, g.s.) reaction studied experimentally in [55].

The transfer reaction part of the NRV is based on the computer code DWUCK5 [15]. It calculates the scattering observables for binary nuclear reactions using the finite range DWBA approach. In the following section a brief description of the DWBA is given (for details see, e.g., books [52,53]).

6.1. DWBA transfer amplitude and cross section

We consider the reaction $A(a, b)B$ where the projectile a is treated as the composite system $a = b + x$ (Fig. 5). The particle x could be either a nucleon or a few-nucleon cluster, for example, an α-particle. The transfer of the particle x to the target leads to the formation of the composite target-like fragment in the exit channel $B = A + x$. It is also assumed that all the particles may have non-zero spins.

The computer code DWUCK5 [15] calculates the transition amplitude for the reaction $A(a, b)B$ within the post (β) or the prior (α) form

$$T_{fi}^{\alpha(\beta)} = \mathcal{J} \iint d^3r_b d^3r_a \, \chi_{\mathbf{k}_f}^{(-)*}(\mathbf{r}_b) \langle bB|\Delta V_{\alpha(\beta)}|aA\rangle \chi_{\mathbf{k}_i}^{(+)}(\mathbf{r}_a), \tag{1}$$

where $\chi^{(\pm)}$ are the distorted waves, $\mathbf{r}_a$ and $\mathbf{r}_b$ are the relative coordinates (Fig. 5) for the systems (a,A) and (b,B), respectively, and $\mathcal{J}$ is the Jacobian of the transformation to these coordinates. The angle brackets imply integration over all variables independent of $\mathbf{r}_a$ and $\mathbf{r}_b$. The quantity $\langle bB|\Delta V|aA\rangle$ discussed below is the form factor for the transfer reaction that couples the bound states in the entrance and the exit channels.

The asymptotics of the distorted waves $\chi_{\mathbf{k}}^{(\pm)}(\mathbf{r})$ is the combination of the plane wave with the momentum $\mathbf{k}$ and the outgoing (or incoming) spherical scattered wave. Without the Coulomb potential it has the form

$$\chi_{\mathbf{k}}^{(\pm)}(\mathbf{r} \to \infty) \to e^{i\mathbf{k}\cdot\mathbf{r}} + f(\theta)\frac{e^{\pm ikr}}{r}. \tag{2}$$

It is convenient to decompose the distorted wave functions into the partial waves. As shown in detail in Refs. [52,53], the radial partial

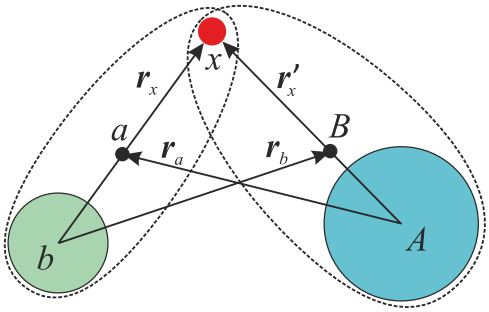

Fig. 5. Definition of the coordinates for the nucleon transfer reaction $A(a, b)B$.

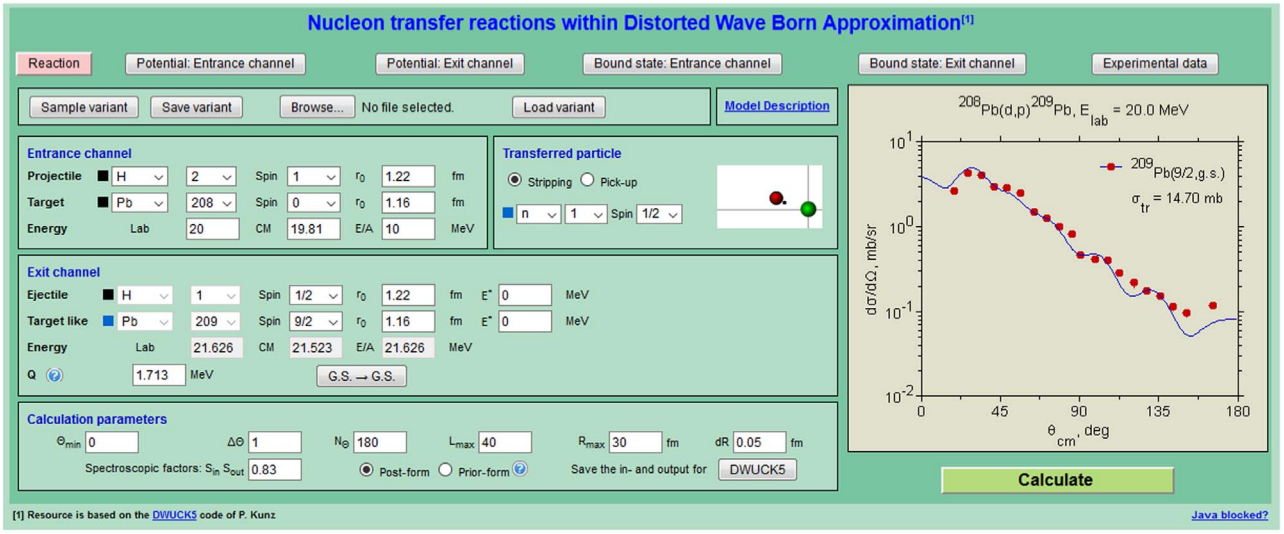

Fig. 6. NRV web dialog for setting input parameters in calculation of neutron transfer cross sections within the DWBA approach on the example of the ^{208}Pb(d,p)^{209}Pb($\frac{9^+}{2}$, *g. s.*) reaction.

wave functions satisfy the equation

$$\left(\frac{d^2}{dr^2} + k^2 - \frac{l(l+1)}{r^2} - \frac{2\mu}{\hbar^2}U_{\alpha(\beta)}(r)\right)\chi^{(+)}_{Jls}(r) = 0. \tag{3}$$

Here $U_{\alpha(\beta)}(r) = U_N(r) + U_C(r) + (\mathbf{l}\cdot\mathbf{s})U_{SO}(r)$ is the optical potential describing the relative motion of the projectile and the target in the entrance (α) or the exit (β) channels. U_N is the central nuclear potential with real and imaginary parts, U_C is the Coulomb potential for the uniform charge distribution with the radius R_C and U_{SO} is the spin-orbit potential. We take into account the projectile spin s coupled with the orbital momentum l into the total angular momentum J. The radial functions $\chi^{(+)}_{Jls}(k, r)$ satisfy the boundary conditions $\chi^{(+)}_{Jls}(k, 0) = 0$ at the origin and

$$\chi^{(+)}_{Jls}(k, r) \to \frac{i}{2}e^{i\sigma_l}[H^-_l(kr) - S_{Jls}H^+_l(kr)] \tag{4}$$

for $r \to \infty$, where the nuclear part of the potential may be neglected. The functions $H^{\pm}_l(kr) = G_l(kr) \pm iF_l(kr)$ are the outgoing (+) and the incoming (−) Coulomb waves, S_{Jls} is the elastic scattering S-matrix element and σ_l is the Coulomb phase shift.

The form factor $\langle bB|\Delta V_{\alpha(\beta)}|aA\rangle$ contains information about the nuclear structure and depends on the potential $\Delta V_{\alpha(\beta)}$ defined in the following way

$$\Delta V_\nu = \sum_i V_{i,\nu}(r_i) - U_\nu(r_\nu), \tag{5}$$

where $r_{\alpha(\beta)} = r_{a(b)}$. In the case of the prior form ($\nu = \alpha$), $V_{i,\alpha}$ are the interaction potentials between the target (A) and the projectile constituents (i=b or x). The potential $V_{i,\beta}$ in the post form ($\nu = \beta$) is defined as the interaction potentials between the projectile-like fragment (b) and the components of the target-like fragment (i=A or x). Similarity between the potentials U_α and V_{bA}, allows one to apply the approximation $\Delta V_\alpha \approx V_{xA}$ in the prior-form calculations, whereas $\Delta V_\beta \approx V_{xb}$ is justified in the post form, since the U_β potential is supposed to be close to the V_{bA} potential.

Thus in the prior and the post forms the coupling potentials ΔV are the binding potentials in the entrance and the exit channels, respectively. These potentials are also used in order to calculate the bound state wave functions $\varphi_a(\mathbf{r}_x)$ for the composite projectile ($a = b + x$) in the entrance channel and $\varphi_B(\mathbf{r}'_x)$ for the target-like fragment ($B = A + x$) in the exit channel (definition of the coordinates $\mathbf{r}_x$ and $\mathbf{r}'_x$ see in Fig. 5). The wave functions $\varphi_i(\mathbf{r})$ are used in calculation of the transfer form factor $\langle bB|\Delta V|aA\rangle$.

The cross section for the reaction $A(a, b)B$ may now be expressed in terms of the transition amplitude

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{\mu_\alpha\mu_\beta}{(2\pi\hbar^2)^2}\frac{k_\beta}{k_\alpha}\frac{S_aS_B}{(2J_A+1)(2j_a+1)}\sum_{M_AM_Bm_am_b}|T_{M_AM_B,m_am_b}|^2, \tag{6}$$

where $\mu_{\alpha(\beta)}$ and $k_{\alpha(\beta)}$ are respectively the reduced mass and the wave number in the corresponding channel, and $\mathcal{S}_i$ are the spectroscopic coefficients carrying information about the structure of the composite systems. The cross section in Eq. (6) is averaged over the initial spin orientations and summed up over the final spin orientations. Here J_A and j_a are the spins of the target and projectile, M_A and m_a are their projections, and M_B and m_b are the projections of the spins of the reaction products.

Thus in order to calculate the transfer cross section within DWBA one needs to specified (1) the entrance and exit channels of the reaction, (2) the optical potentials describing corresponding distorted waves, and (3) the parameters of the initial and final bound states for the transferred particle.

6.2. Input parameters

The NRV knowledge base provides the web dialog for setting the input parameters for calculation of the nucleon transfer cross sections within the DWBA approach. The screenshot of the web dialog is shown in Fig. 6.

In the upper row of buttons the user may choose the specific sections (*Reaction*, *Potentials*, *Bound states* or *Experimental data*) in order to modify the corresponding parameters (Fig. 7).

6.2.1. Reaction

In the *Reaction* section the user may choose the masses and charges of interacting nuclei, their spins and radii (the radii are used in the calculation of the proximity potential) for both the entrance and the exit channels as well as the transferred particle and the type of the reaction (*pick-up* or *stripping*).

The excitation energies E^* of the fragments and the Q-value of the transfer process for the exit channel may also be set. The energy of the relative motion in the exit channel is set automatically as $E'_{cm} = E_{cm} - Q$.

The button *G. S.* → *G. S.* (see the section *Bound states*) allows one to set the Q-value and the binding energies corresponding to the ground-state-to-ground-state transition (for this, the NRV database of

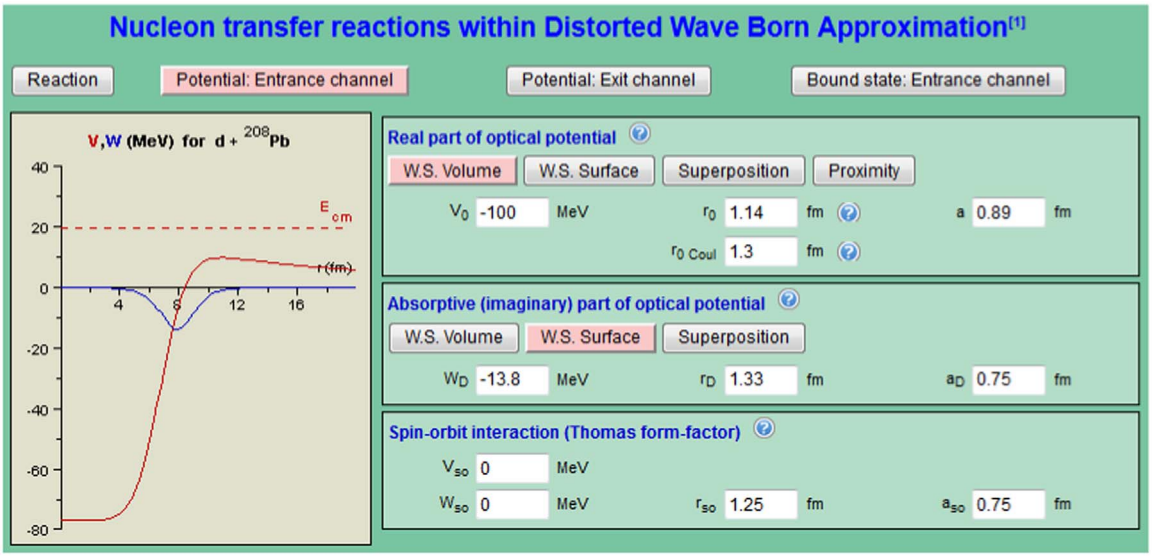

Fig. 7. NRV web dialog for setting the optical potential parameters for d + ^{208}Pb interaction in the entrance channel.

nuclear masses is used).

The calculation parameters include the center-of-mass angular range for the cross section: the starting angle θ_{min}, the angular mesh step $\Delta\theta$, and the number of steps N_θ. The value L_{max} is the maximum value of the orbital momentum taken into account. The quantities R_{max} and dR define the radial mesh used for numerical integration of the Shrödinger Eq. (3).

The combined spectroscopic factor $\mathcal{S}_a\mathcal{S}_B$ is used to normalize the DWBA cross section. The user may also choose either the prior or the post forms of the DWBA.

The button *DWUCK5* provides the input data in the proper format suitable for the code DWUCK5 [15] as well as the run output obtained after the code execution.

6.2.2. Potential: entrance (exit) channel

This section is used to set the parameters of the optical potential $U_{\alpha(\beta)}(r)$ (see Eq. (3) applied to the distorted wave calculation. The standard form of the point-sphere Coulomb potential is used

$$U_C(r) = Z_1Z_2e^2\begin{cases}\dfrac{1}{r}, & r > R_C,\\ \dfrac{1}{2R_C}\left(3-\dfrac{r^2}{R_C^2}\right), & r \le R_C,\end{cases} \tag{7}$$

where the Coulomb radius $R_C = r_{0.Cout}A_T^{1/3}$ may be specified by the user. The user may also choose one of the four different types of the real parts of the nuclear potential: the volume and the surface *Woods-Saxon*, and their *Superposition*

$$\mathrm{Re}\,U_N(r) = \frac{V_0}{1+\exp\left(\dfrac{r-r_0A_T^{1/3}}{a}\right)} - 4a_DV_D\frac{d}{dr}\frac{1}{1+\exp\left(\dfrac{r-r_DA_T^{1/3}}{a_D}\right)}, \tag{8}$$

or the *Proximity* potential [54]. The radii of nuclei required for the calculation of the proximity potential are set in the *Reaction* section next to the specific nucleus.

The imaginary part of the optical potential has the same options, but the proximity potential is not provided.

The spin-orbit interaction is chosen in the form

$$U_{SO}(r) = -(\mathbf{L}\cdot\mathbf{s})(V_{SO}+iW_{SO})\frac{1}{r}\frac{d}{dr}\left[1+\exp\left(\frac{r-r_{SO}A_T^{1/3}}{a_{SO}}\right)\right]^{-1}. \tag{9}$$

For convenience, the plot on the left panel shows the potential with the chosen parameters.

Note that the NRV provides the possibility of automatic setting of the potential parameters derived from the global parametrizations of the optical model parameters or by the analysis of experimental data on elastic scattering in the corresponding section of the knowledge base.

6.2.3. Bound state: exit channel

This section is used to specify the quantum state parameters and the interaction potential $V_{xA}(r'_x)$ for the composite system $B = (A + x)$ in the exit channel. Corresponding dialog is shown in Fig. 8. The quantity E_{bound} is the binding energy in MeV. The quantity N_r is the principal quantum number, J_{tr}, L_{tr}, and S_{tr} are the total angular momentum, the orbital momentum, and the spin of the transferred particle, respectively. These quantum numbers and potential completely define the wave function $\varphi_B(\mathbf{r}'_x)$ of the final state in the exit channel.

In this section the spin S_{tr} is fixed since it is the same as the spin of the transferred particle in the *Reaction* section. The total angular momentum $\mathbf{J}_{tr}$ is the result of the $\mathbf{L}_{tr} + \mathbf{S}_{tr}$ coupling. Note also that the total spin of the composite particle in the exit channel is the sum of the transferred particle momentum $\mathbf{J}_{tr}$ and the spin of the core particle. In the case shown in Fig. 8, these particles are the neutron in the $2g_{9/2}$ state (the transferred particle) and the led core with the zero spin. They form the total momentum $\frac{9}{2}$ of the ^{209}Pb nucleus.

In order to define the interaction potential V_{xA}, binding the clusters of the composite system, besides the Coulomb potential $V_C(r)$ the user may choose one of the two types of the nuclear term: the Woods-Saxon volume potential

$$V_{xA}(r) = V_C(r) + \frac{V_0}{1+\exp\left(\dfrac{r-R_v}{a_v}\right)} \tag{10}$$

or the Gaussian potential

$$V_{xA}(r) = V_C(r) + V_0\exp\left(-\frac{r^2}{R_v^2}\right). \tag{11}$$

The Coulomb interaction is chosen in the same form (7) as in the optical potential case.

The plot (Java applet) on the left panel shows the interaction potential $V_{xA}(r)$ and the bound state wave function $\varphi_B(r)$ for the exit channel. The wave function and the list of the levels found in the potential may be *saved* by the user in the text (tabular) or the graphical formats if user clicks on the plot.

In case the user changes any parameter, the Java applet also *adjusts* the potential depth V_0 automatically. In some cases the search routine

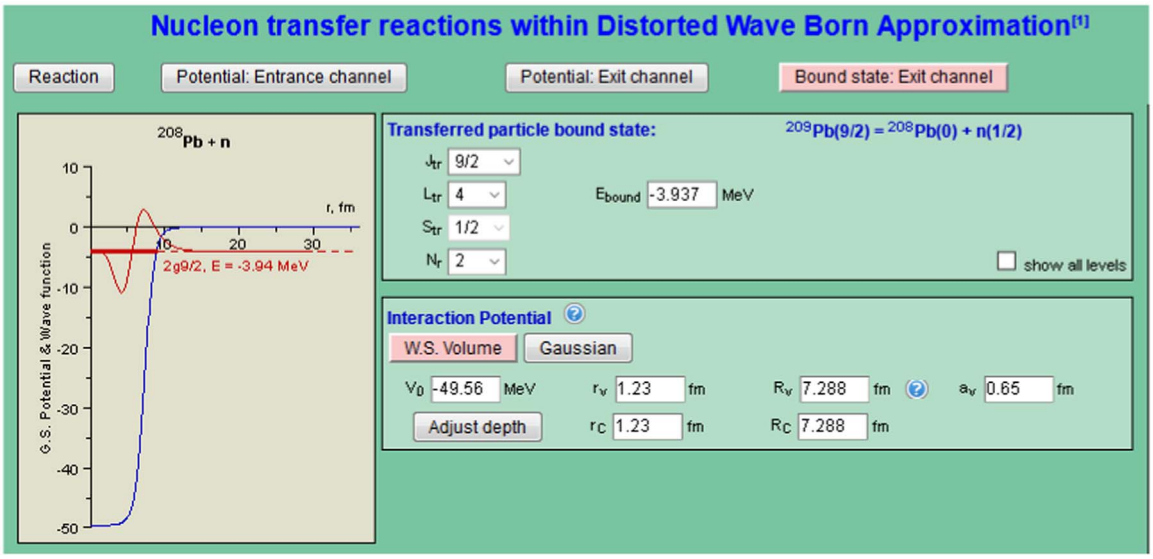

Fig. 8. NRV web dialog for setting the bound state parameters and the interaction potential in the exit channel for the system ^{209}Pb($\frac{9^+}{2}$, g.s.)= ^{208}Pb(0^+) + n($\frac{1^+}{2}$).

fails to find the appropriate potential depth. Then the user should set the initial value of the parameter V_0 manually in order to start the search routine again.

The bound state in the entrance channel may be specified in the same way in the section *Bound state: Entrance channel*.

6.2.4. Experimental data

In this section (Fig. 9) the user may enter the experimental data specifying the entrance channel, the transferred particle, and its final state in the exit channel. The collision energy and the scattering angles may be entered either in the laboratory or in the center of mass system.

The experimental data must be entered in the three-column format: the scattering angle θ in degrees, the differential cross section $d\sigma/d\Omega$ in the chosen units, and the percentage error of the cross section.

The experimental data are optional. The code DWUCK5 [15] does not require any experimental data to perform the calculation since it does not fit the theoretical curve to the data.

6.3. Calculation of transfer cross section

If all the parameters are set, the cross section calculation may be started by pressing the *Calculate* button. In this case the input parameters of the model as well as the entered experimental data are sent to the NRV server and saved in the user folder. Based on these parameters, the NRV server prepares the input file and runs the code DWUCK5 [15] on the server side. After the calculation the server passes the results to the Java applet located on the right side of the web dialog. The results are shown by the solid curve along with the experimental data. The integrated transfer reaction cross section is also shown in the plot.

The user may open an additional Java window with the differential cross section by clicking on the corresponding Java applet. This window is shown in Fig. 10. The plot in this window is the same as the plot in the web dialog, but additional options for processing of the data using the menu items are provided. For example, the user may save the data in the text (tabular) or the graphical formats (menu *File/Save as*...), plot the cross section *vs.* the scattering angle in the center

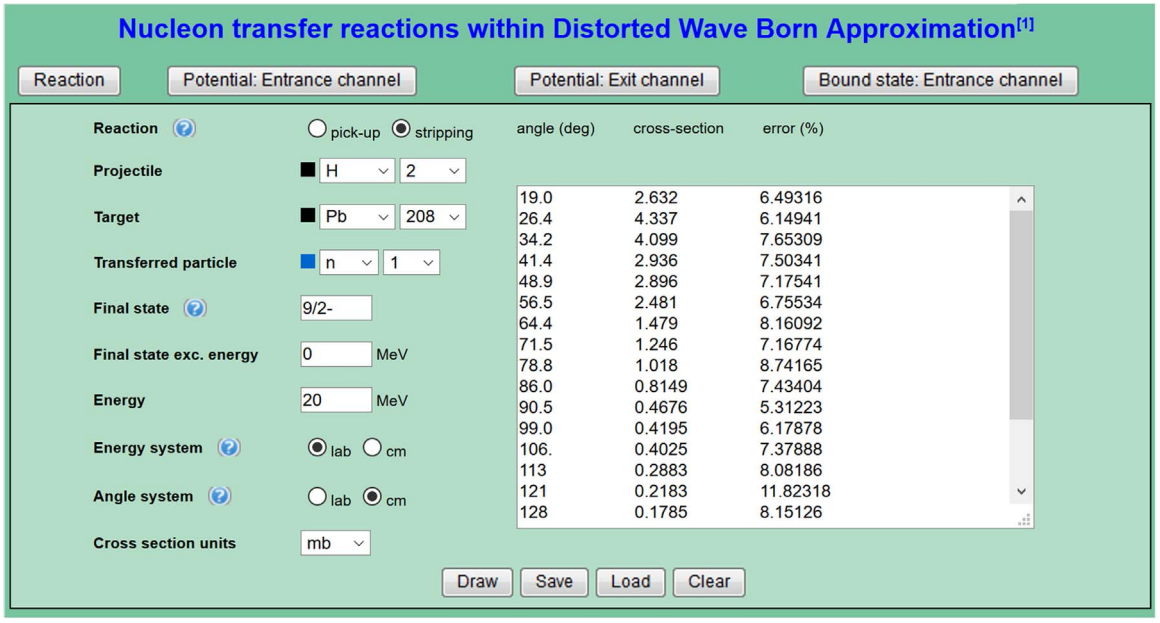

Fig. 9. NRV web dialog for entering experimental data for the transfer reaction. The experimental data for the ^{208}Pb(d, p) ^{209}Pb reaction is taken from Ref. [55].

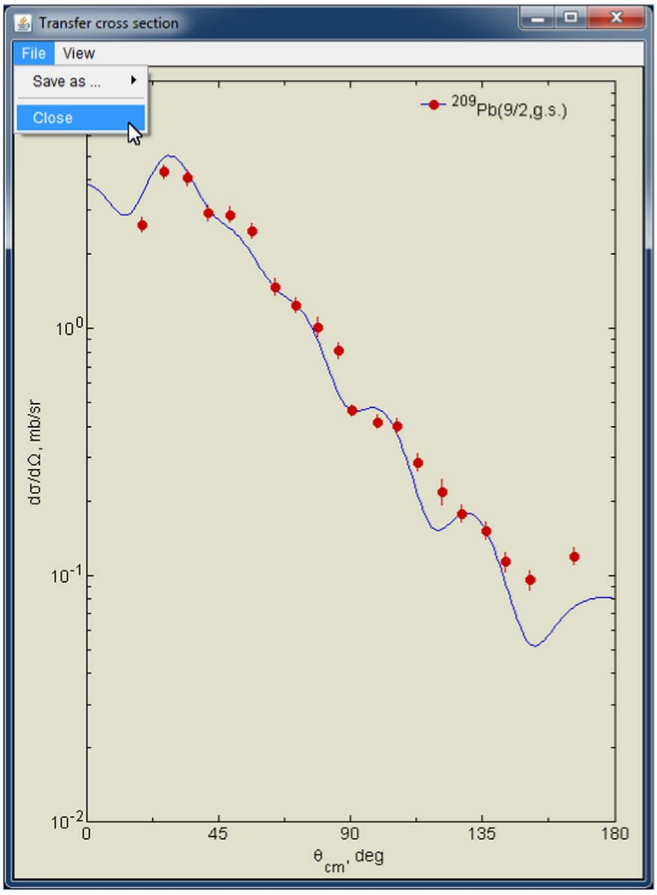

Fig. 10. Additional Java window for processing of the calculated cross section (curve) with the experimental data from Ref. [55] (points).

of mass or in the laboratory system, etc.

Note that the reaction and all the calculation parameters are stored in the personal user folder on the NRV server. Therefore, the next session will start with the previously calculated variant, if the same computer and the same Internet browser are used.

7. Summary and conclusions

The NRV web knowledge base on low-energy nuclear physics (http://nrv.jinr.ru/) has been developed in the Joint Institute for Nuclear Research. It integrates a large amount of experimental data with computational codes for modeling of nuclear properties and nuclear reactions. It also provides possibilities for planning experiments and analysis of experimental data. The knowledge base is available for any remote user via any web browser supporting the Java plugin. The main focus of the system is on modeling of nuclear reactions: elastic and inelastic scattering, nucleon transfer, fusion with subsequent decay of the excited compound nucleus, etc. The NRV knowledge base may be used for both scientific and educational purposes.

In this work the basic principles of the NRV knowledge base have been covered. The practical usage of the NRV knowledge base was demonstrated in detail on the example of the analysis of nucleon transfer reactions within the DWBA approach.

The further development of the NRV knowledge base is planned in the following directions: (1) filling and updating of the existing nuclear databases as well as adding new ones; (2) implementation of new physical models as well as extending the possibilities of the existing ones; (3) modernization of the user interface, in particular, transition from the use of Java applets to the use of new technologies, such as HTML5 and JavaScript.

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Appendix

Getting started with NRV

1. Browser compatibility

All sections of the NRV website work correctly in the following (current at the moment of paper submission) versions of browsers:

- Mozilla Firefox 50.1.0 (32-bit),
- Mozilla Firefox ESR 45.6.0 (32-bit),
- Microsoft Internet Explorer 11 (32/64-bit),
- Apple Safari 10.0.2,
- Pale Moon 27.0.3 (32/64-bit).

Microsoft Edge and the modern versions of Google Chrome and Opera are incompatible with the sections of NRV that still rely on Java. Older versions of Internet Explorer are not supported by Microsoft, therefore they are not tested for compatibility with NRV. Other browsers are not tested for compatibility with NRV due to low usage statistics. In general, based on our experience, we recommend to use Mozilla Firefox ESR (32-bit).

2. Installation of Java and enabling applets

At the moment, most of the sections of the NRV web knowledge base use Java to provide interactive user interface and display information. Depending on the version of the browser, 32- or 64-bit version of Java must be installed. After installation go to the *Java Control Panel*, open the *Security* tab, check *Enable java content in the browser*, and click *OK* to apply settings (Fig. A1).

On the first run in a particular browser a security warning will appear. Check *Do not show this again for apps from the publisher and location above* and click the *Run* button (Fig. A2). A Java applet will start. The same warning may also appear periodically later, often after the update of the browser or Java.

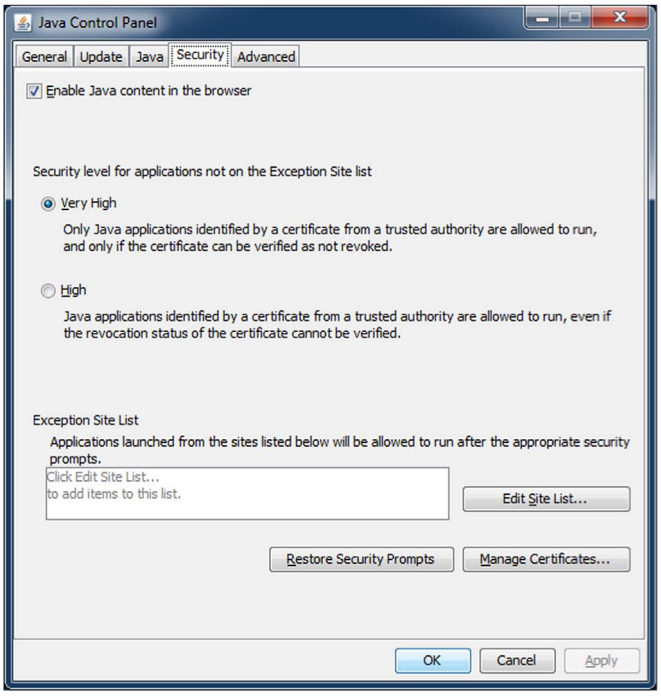

Fig. A1. *Java Control Panel* with the correct settings (Java 8 under Microsoft Windows 7).

Fig. A2. Security warning.

Please note that the actual look of the *Java Control Panel* and security warnings may vary.

More detailed and up-to-date information on Java installation, browser support, necessary settings, troubleshooting, etc. may be found on the Java website.

3. JavaScript

JavaScript must be enabled in order to work with the NRV website. JavaScript is usually enabled by default.

4. Pop-up windows

It is recommended to allow pop-up windows from the NRV website to ensure correct saving of data files, displaying of help files and model descriptions, etc. Pop-up windows are usually blocked by default. The necessary steps to allow pop-up windows vary depending on the browser used. Information on how to do it may be found on the websites of particular browsers. Note also that some ad-blocking or antivirus software may block pop-up windows.

5. Cookies

It is recommended to enable cookies for the NRV website to ensure automatic loading of the model parameters you used previously, which will make the work with NRV much more comfortable. Cookies are usually enabled by default. The necessary steps for enabling cookies are also browser-specific, therefore it is better to visit the websites of particular browsers for details on how to do it.

6. PDF viewer

It is recommended to have a PDF viewer (e.g., Adobe Reader) installed in your operating system for viewing help files and model descriptions. Note that some browsers have a built-in PDF viewer (e.g., Mozilla Firefox).

7. Support

More detailed and up-to-date information on work with NRV along with support contacts may be found on the NRV website.

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