ISSN 1063-7788, Physics of Atomic Nuclei, 2016, Vol. 79, No. 5, pp. 749–761. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © A.V. Karpov, A.S. Denikin, A.P. Alekseev, V.I. Zagrebaev, V.A. Rachkov, M.A. Naumenko, V.V. Saiko, 2016, published in Yadernaya Fizika, 2016, Vol. 79, No. 5, pp. 520–532.

NRV Web Knowledge Base on Low-Energy Nuclear Physics

A. V. Karpov[1),2)*], A. S. Denikin[1),2)], A. P. Alekseev[3)], V. I. Zagrebaev[†1),2)], V. A. Rachkov[1),2)], M. A. Naumenko[1)], and V. V. Saiko[1),2)]

Received December 21, 2015

Abstract—Principles underlying the organization and operation of the NRV web knowledge base on low-energy nuclear physics (http://nrv.jinr.ru) are described. This base includes a vast body of digitized experimental data on the properties of nuclei and on cross sections for nuclear reactions that is combined with a wide set of interconnected computer programs for simulating complex nuclear dynamics, which work directly in the browser of a remote user. Also, the current situation in the realms of application of network information technologies in nuclear physics is surveyed. The potential of the NRV knowledge base is illustrated in detail by applying it to the example of an analysis of the fusion of nuclei that is followed by the decay of the excited compound nucleus formed.

DOI: 10.1134/S1063778816040141

Dedicated to the memory of V. I. Zagrebaev

1. INTRODUCTION

The NRV web knowledge base on low-energy nuclear physics was created at the Joint Institute for Nuclear Research (JINR) and is being developed further [1–7]. This system, which operates through the Internet, is a vast body of digitized experimental data on the properties of nuclei and cross sections for nuclear reactions that is supplemented with a broad set of interconnected computer programs for simulating complex nuclear dynamics, which work directly in the browser of a remote user. At the present time, the NRV knowledge base is both a powerful tool for nuclear physics studies and an educational resource. The popularity of the system is growing steadily, as one can see from an ever increasing number of users queries to its resources and the number of references to this knowledge base in articles published in the most frequently quoted journals.

In what follows, we give an overview of the current situation in the field of employing network information technologies in nuclear physics, formulate basic principles of operation of the NRV knowledge base, and describe briefly its basic sections. The use of the NRV knowledge base in practice is demonstrated in detail by analyzing the example where the fusion of nuclei is followed by the decay of the excited compound nucleus formed.

†Deceased.
1)Joint Institute for Nuclear Research, ul. Joliot-Curie 6, Dubna, Moscow oblast, 141980 Russia.
2)Dubna International University for Nature, Society, and Man, Universitetskaya ul. 19, Dubna, Moscow oblast, 141980 Russia.
3)Chuvash State University, Moskovskii pr. 15, Cheboksary, Chuvash Republic, 428010 Russia.
*E-mail: karpov@jinr.ru

2. USE OF NETWORK INFORMATION TECHNOLOGIES IN NUCLEAR PHYSICS

2.1. Nuclear Data

An enormously large body of experimental information both about the properties of nuclei themselves and about cross sections for nuclear reactions has been accumulated over more than 100 years of nuclear physics studies. These data are contained in articles published in numerous nuclear physics journals. The creation of databases is the present-day means for accumulating and systematizing information of this type. Web versions of databases available through the Internet in a digitized form via browsers have been developed most vigorously in recent years. At the present time, the creation of electronic databases and the organization of access to them through the Internet are the commonly recognized line of the development of scientific information systems. Among such nuclear databases one should mention NNDC [8], CDFE [9], TUNL [10], NEA Data bank [11], NACRE [12], and NACRE-II [13].

The existing nuclear physics resources contain, as a rule, detailed information about the subject of study (properties of nuclei or reactions with them). Many of them are created either by large research centers (for example, the NNDC database [8] is supported by the Brookhaven National Laboratory, and the CDFE database [9] is supported by the Skobeltsyn Institute of Nuclear Physics at Moscow State University) or within international collaborations (for example, NEA [11], NACRE [12], and NACRE-II [13] databases). Focusing on specific narrow topics is the main drawback of the majority of nuclear databases. Moreover, they frequently do not provide well-developed tools for additional data analysis and description. Usually, information is presented in a text (tabular) form. This means that, even in order to obtain the simplest systematics of data, the user has to choose the necessary data manually, copy them into an individual file, and finally employ some graphical package for their representation.

2.2. Simulation of Nuclear Dynamics

A number of theoretical approaches that became commonly recognized by the physics community have been developed in the course of nuclear physics studies—in particular, investigations into dynamics of nucleus–nucleus collisions. They include the optical model of elastic scattering and the coupled-channel method for calculating nuclear fusion cross sections. Code packages (for example, FRESCO [14] and GRAZING [15]) providing the opportunity of simultaneous simulation of several competing processes accompanying nuclear collisions have been developed for many years. The majority of these code packages are written in the Fortran language and can be downloaded for free. An inconvenient interface is the main drawback of these codes. By interface, we mean here the way the user interacts with the code, for running of which it is necessary to prepare the input file correctly. As a rule, this is a text file that includes a large number of input parameters, the correct preparation of which requires studying complicated and sometimes incomplete descriptions. After the completion of the program, the user usually obtains a text file, for processing of which it is necessary to use separate graphical packages. As a result, an inexperienced user runs into serious difficulties in employing these codes. There are two basic means for solving this problem.

The first consists in creating systems for simulating nuclear dynamics in the form of a code downloaded to a specific computer of the user and running on a local computer within some operating system. These are, for example, TALYS [16], EMPIRE [17], LISE++ [18], and Windows-NRV [2]. All these codes have (or may have) a graphical interface for the preparation of input data, tools for an analysis of the results of simulations, a system of prompts and descriptions. This substantially facilitates the work of the user.

The second means consists in organizing the operation of computer codes on a single server (or a system of connected servers) that is accessible to the user through the Internet. The developers of the NRV web knowledge base (for a detailed description of it, see below) took the second path [1–7].

Either means has obvious drawbacks inherent in it. The first means, for example, proves to be dependent on the operating system. Moreover, its use entails problems connected with software update—in particular, with informing the user about new possibilities of the system, about the bug fixes, and so on. All these problems disappear upon choosing the second means, in which case there arise difficulties in organizing a much more complicated operation of the system on the Internet and in distributing computational problems under conditions of time-overlapping user requests.

3. PURPOSES OF CREATION AND BASIC COMPONENTS OF THE NRV KNOWLEDGE BASE

The free-access system developed by our group and called the NRV web knowledge base on low-energy nuclear physics is intended for combining nuclear databases with generally accepted theoretical approaches to simulating the dynamics of nuclear reactions on a single server with a unified graphical interface.

The creation of the system is aimed at improving the efficiency of employing a maximally broad set of experimental data, special codes for their processing, and fundamental models for describing the structure of nuclei and complex dynamics of nucleus–nucleus collisions. Its basis is formed by (i) a continuously updated experimental database of properties of nuclei (masses, electromagnetic properties, half-lives, decay modes, level schemes, and so on), (ii) a continuously updated experimental database of cross sections for various nuclear processes, (iii) an implementation of a large number of rather complicated (but simple in use) models and algorithms that describe various aspects of nuclear dynamics at low and intermediate energies, and (iv) the development of a unified, maximally friendly, user interface.

Within this project, complicated computer codes having a visual graphical interface for choosing input data along with a graphical representation and an analysis of the results become available through the Internet. This is achieved via the development of web applications that are special programs based on the client–server architecture. Their particular feature is that a web application resides and works on the server

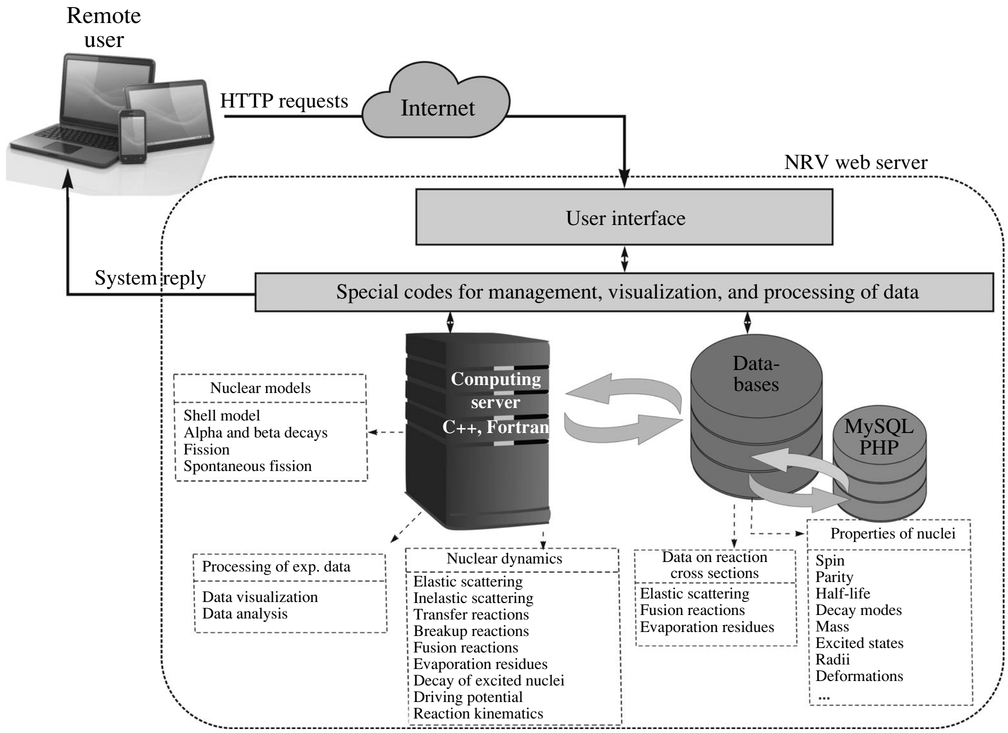

Fig. 1. Scheme of operation of the NRV knowledge base.

and that the client receives the results of this work through the Internet.

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

3.1. Web Server

The access to the system is accomplished using a web browser (for example, Internet Explorer or Mozilla Firefox) through the Internet. Owing to this, any user has an access to the NRV knowledge base from any point where there is a connection to the Internet. The interaction between the client and the server is organized via HTML forms. These forms are implemented by using JavaScript, PHP, and HTML languages. The creation and testing of numerous HTML forms requires the most laborious work, which has to be done individually for each new problem in order to render the interface the most interactive, to ensure convenient conditions for work, and to perform all necessary tests even at the stage of the preparation of data with the aim of rejecting unphysical requests.

The exchange of data between the server and client and the creation of the dynamical content is organized and implemented by means of the PHP language and the AJAX technology. Significant computer resources necessary for calculation of complex processes of nuclear dynamics (the time of such calculations may range between a few minutes and a few hours) require a special organization of the interaction between the remote user and the computing server. A special resident service starting computational programs, monitoring their execution, and sending intermediate information to the client operates on the server for this purpose. After the completion of the calculation, all of the results are sent to the user in the form of an HTML document for their further processing and analysis. This approach makes it possible to run the most complex computational algorithms through the browser and to obtain a final result even after a very long-term calculation.

3.2. Computing Server

Complicated computational programs are deployed and are executed on the side of the computing server. The user can monitor their launch and execution via HTML forms in the browser.

The developed software can be divided into two main groups: (i) computational codes that implement physical models of nuclear dynamics (in C++ and Fortran languages) and (ii) codes for processing of data and results of calculations and for representing them in the browser.

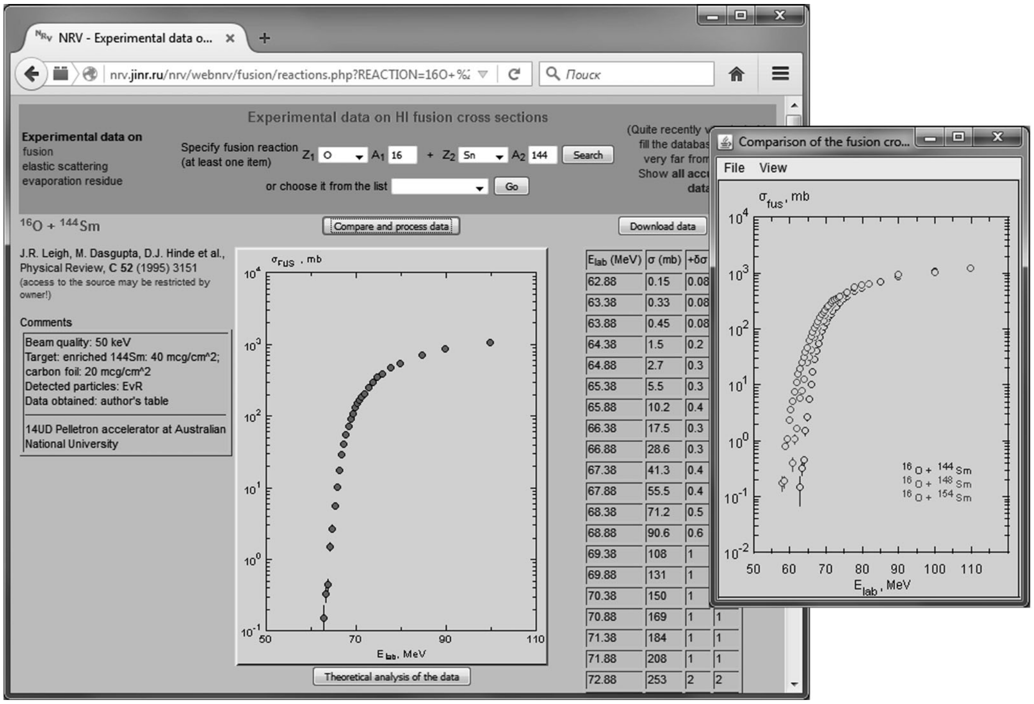

Fig. 2. Example of the representation of information about the experimental fusion cross section for $^{16}O+^{144}Sm$.

3.3. Database Server

Experimental data are stored using the MySQL relational database management system [19].

We fill experimental databases of properties of nuclei, employing predominantly the already existing and most recognized databases, such as NNDC [8] in Brookhaven, AMDC [20] in Orsay, and NUdat [21] in Lund. Also, we find part of information on properties of nuclei and enter it in databases independently, relying on original publications in journals (this primarily concerns data on properties of superheavy nuclei). In addition to experimental data on properties of nuclei, we independently create and fill digitized databases of cross sections for nuclear reactions, including angular distributions for the elastic scattering of light and heavy ions, excitation functions for processes of nuclear fusion, and cross sections for the formation of evaporation residues.

Thus, a browser is the interface of the NRV knowledge base, while the Internet plays the role of the medium via which the exchange of data occurs. This approach renders our knowledge base independent of the operating system and readily accessible to remote users. Note that, owing to the presence of convenient user interface, a straightforward application of generally recognized and extensively used nuclear dynamics algorithms becomes possible for any researcher (as well as any graduate or postgraduate student) involved in studies of low-energy nuclear physics.

4. NRV NOWADAYS

The following has been done to date by means of the approach outlined above (in the chronological order).

Databases of experimental properties of nuclei have been created and filled. Codes for their visual representation and for obtaining various systematics have been written. Web versions of the optical model and the classical model for the elastic scattering of nuclei have been developed. Relying on these versions and using a web browser, the user can choose the energy and the interaction parameters for the reaction of interest and obtain, various reaction features in a graphical and a text forms, including the differential cross section for elastic scattering, the S matrix, the trajectory field, the deflection function, and partial wave functions.

Codes intended for theoretical description of processes leading to the inelastic excitation of collective states, few-nucleon transfer reactions in heavy-ion collisions in the distorted-wave Born approximation (DWBA), and processes of nuclear fusion within empirical and quantum approaches have been written and deployed on the server. Finally, the work and continuous filling of the database of cross sections for the fusion of nuclei and for the production of evaporation residues have been organized; moreover, special codes for processing them have been written.

An example of the representation of information about the experimental fusion cross section for the

Statistics of the use of the NRV knowledge base over recent years (number of requests per year)

Year	Number of queries for nuclear data	Number of queries for performing calculations
2011	17 000	20 000
2012	36 000	21 000
2013	197 000	32 000
2014	199 000	36 000

^{16}O+^{144}Sm reaction is shown in Fig. 2. These data are represented in a graphical and in a text forms. Moreover, information about the source of the data (reference to the original publication) and a brief description of the respective experiment are given. The chosen data can be saved in a tabular form on user's computer (*Download data* option). There is also the possibility of comparing the fusion cross section for the reaction considered with data on other (similar) reactions from the database (*Compare and process data* option). The *Theoretical analysis of the data* option redirects the user to the section of a theoretical analysis of fusion cross sections for the chosen reaction (see below).

The work and a continuous filling of the database of cross sections for elastic scattering have been organized; special emphasis have been made on reactions involving light nuclei. The knowledge base includes codes for calculating single-particle levels in deformed nuclei on the basis of the shell model featuring a realistic mean field in the form of the Woods–Saxon potential, as well as on the basis of the two-center shell model, which makes it possible to calculate the system of single-particle levels for configurations from that of two separate nuclei to that of compact forms of a compound nucleus. An example of the calculation of single-particle levels in the ^{208}Pb nucleus is given in Fig. 3.

The system provides the possibility of calculating decay widths for excited nuclei on the basis of the statistical model. Moreover, models developed earlier for describing processes of nuclear fusion were combined with the statistical model. This made it possible to calculate cross sections for the formation of evaporation residues in heavy-ion reactions. The possibility of performing a kinematical analysis of nuclear reactions that have two- and three-body exit channels is implemented.

Some widely used systematics characterizing the process of nuclear fission (for the multiplicities of pre- and post-fission neutrons [22] and for the mean kinetic energy of fission fragments [22, 23]) were also included in the system. The possibility of calculating the mass and charge distributions of fragments for spontaneous and low-energy fission on the basis of the GEF code [24] was implemented, and the code package for calculating the half-lives of nuclei with respect to alpha decay, beta decay, and spontaneous fission was created.

The GRAZING code [15], which makes it possible to calculate cross sections for few-nucleon transfer reactions in the semiclassical approximation, was included in the knowledge base. In addition, the knowledge base provides the possibility of calculating cross sections for radiative capture reactions on the basis of the potential model [25] and incorporates codes for calculating and analyzing phase shifts for the elastic scattering of light nuclei, as well as the EPAX code [26] used to estimate yields of fragmentation processes.

The run of all of the software and the interaction of the software with the user is accomplished via ordinary web browsers. Because of this, the software proves to be independent of the operating system.

Throughout the time of existence of the NRV knowledge base, its usage statistics shows a steady growth. In particular, the total number of requests to the knowledge base over the year 2014 was, on average, more than 600 per day; of these, there were more than 500 queries per day to the databases and about 100 requests per day for performing calculations. In view of the fact that this project covers a rather narrow range of topics, this is a good indicator. Usage statistics of the NRV knowledge base is given in the table.

According to references and quotations in scientific journals, the list of countries where physicists vigorously use the NRV knowledge base includes, in addition to Russia, the United States of America, Germany, France, China, India, Italy, and Poland.

5. SYSTEM DEVELOPMENT STRATEGY

The NRV knowledge base is being developed along three main lines: (i) the filling and the updating of the existing databases, (ii) the addition of new models intended for describing the dynamics of nuclear reactions, and (iii) the modernization of user interface.

In order to represent and process user requests, we have been employing Java applets. In recent years, however, there appeared a trend showing that new browser versions gradually drop support of a virtual Java machine (and, hence, Java applets). Some browsers (for example, Google Chrome) no longer support a Java plugin, stating that it is not secure. Moreover, tablet PCs and other mobile devices, which

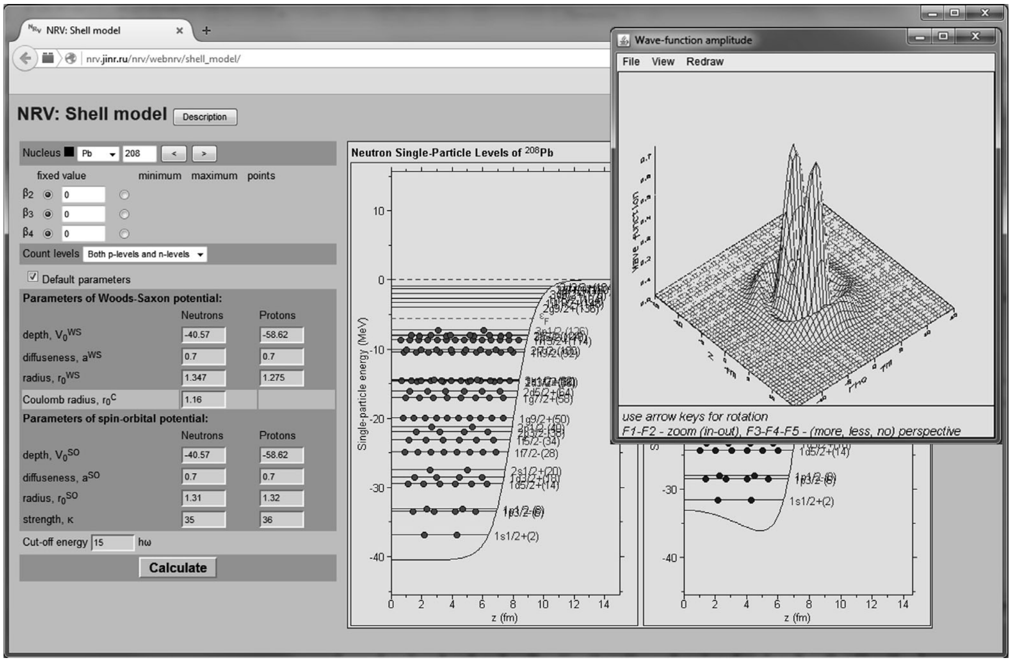

Fig. 3. Example of the calculation of single-particle levels in the ^{208}Pb nucleus.

became very popular, do not support a virtual Java machine. A gradual transition from the technology of Java applets to the JavaScript language, which is presently supported by all browsers without installing additional plugins, is one way to solve this problem. At the present time, the JavaScript technologies (in particular, AJAX), together with PHP and HTML5 Canvas, provide all tools necessary for a proper operation of our knowledge base: creation of controls, work with graphics primitives, and the exchange of data between client's device and the server. Thus, we consider the possibility of moving from Java applets to a JavaScript code.

In this respect, it should be noted that several interesting development tools based on open-source software have been created in recent years. They include Google Web Toolkit (GWT) [27], which enable a web developer to create AJAX applications on the basis of the Java language. When including new codes in the knowledge base that are intended for analyzing phase shifts in the elastic scattering of nuclei, we used the GWT package. In general, the experience of work with GWT may be considered successful. However, some disadvantages revealed in this package (in particular, the absence of a detailed documentation) made us consider the ASP.NET platform [28].

The use of the HTML5 language seems promising. A JavaScript code intended for plotting graphs on the basis of the Canvas element specified in the HTML5 standard has already been implemented. This code is used, for example, in the interface of the adiabatic rotational model (FRESCO [14]) in the *Inelastic scattering* section (see Fig. 4).

The search for the most efficient solution is a difficult challenge since this requires a detailed analysis of the potential and limitations of each technology and estimation of its development and support by IT community.

6. USE OF THE NRV KNOWLEDGE BASE FOR EDUCATIONAL PURPOSES

The NRV knowledge base can be used both in research and for educational purposes. On the basis of the existing knowledge base, nuclear physics students may study the dynamics of nuclear reactions and to analyze experimental data on the basis of generally recognized models (for example, the optical model of elastic scattering, the distorted-wave approximation as applied to reactions of inelastic excitation and transfer, and the channel coupling method for describing fusion reactions). In all of the aforementioned models, the dynamics of collisions between nuclei is determined by the potential of their interaction. In order to perform such an analysis, it is necessary to choose correctly the properties of nuclei (for example, their size), the interaction potential, and its parameters. For example, on the basis of an analysis of data on elastic scattering, one can draw conclusions about the sizes of nuclei. In the course of work on studying fusion reactions, one can analyze data at energies both above and below the Coulomb

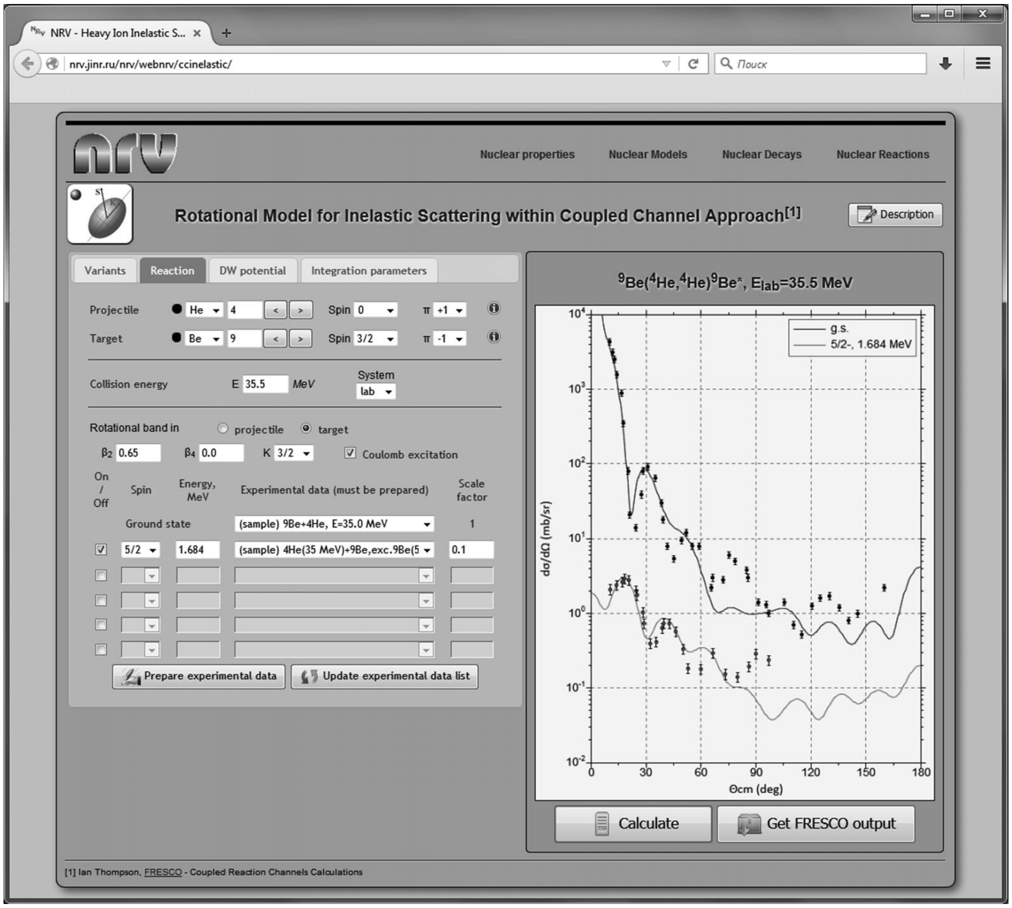

Fig. 4. Interface of the adiabatic rotational model (FRESCO [14]) from the *Inelastic scattering* section.

barrier. A comparison of the results of calculations based on the one-dimensional model with experimental data allows one to draw conclusions about the effect of other degrees of freedom on the process of nuclear fusion. The most important degrees of freedom contributing to the fusion cross section can be chosen on the basis of the structure of excited states of colliding nuclei. The effect of these degrees of freedom on the process of nuclear fusion can be taken into account both within a quantum and within a phenomenological approaches.

Thus, the NRV knowledge base is a convenient, easy-to-understand, and intuitive tool for acquiring and consolidating skills and experience in dealing with modern theoretical approaches to describing the properties of individual nuclides and simulating the dynamics of nuclear collisions, as well as the skills of work with experimental data and their systematization. The development of textbooks and recommendations for performing practical studies will make it possible to employ efficiently the NRV knowledge base in the the educational process of any higher institutions involved in the preparation of nuclear physics specialists.

7. USE OF THE NRV KNOWLEDGE BASE IN ANALYZING NUCLEAR FUSION REACTIONS AND DECAYS OF EXCITED COMPOUND NUCLEI

Reactions proceeding via near- and sub-barrier fusion of nuclei are complicated processes that depend on a large number of degrees of freedom. For many years, these reactions attracted the unceasing attention of both experimentalists and theoreticians. Fusion reactions play an important role in studying many processes, including those that lead to the formation of new superheavy elements produced in the fusion of two heavy ions. The fusion of light nuclei is of importance for nucleosynthesis in the Universe. The coupling of relative motion of colliding nuclei to other degrees of freedom, such as vibrations of the nuclear surface, a static deformation of colliding nuclei, and the redistribution of nucleons, may be of importance at energies below the Coulomb barrier. The

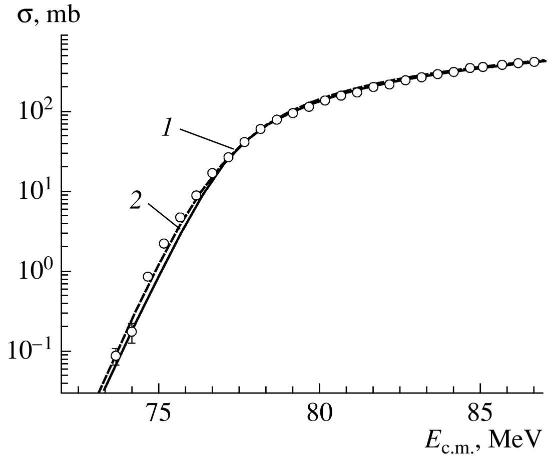

Fig. 5. Example of analyzing the cross section for the $^{36}S+^{90}Zr$ fusion reaction using the NRV knowledge base within the empirical [30] (curve *1*) and the quantum [29] channel coupling models (curve *2*). The displayed experimental data were taken from [32].

fusion of nuclei leads to the formation of an excited compound nucleus, which may thereupon undergo fission into two approximately equal parts or survive, emitting one or several light particles (predominantly neutrons) and/or gamma quanta.

The above range of nuclear dynamics problems can be comprehensively studied with the aid of the NRV knowledge base. The system includes experimental databases of fusion cross sections and cross sections for the production of evaporation residues. Fusion cross sections may be calculated within two basic models: the quantum channel-coupling model [29] and the empirical channel-coupling model [30]. The deexcitation of a compound nucleus is considered within the statistical model [31]. The fusion—fission cross sections and the cross sections for the production of evaporation residues can be calculated using the combination of the models for analyzing the fusion process followed by the decay of an excited compound nucleus. Below, we describe the main possibilities of the system in each of the sections and illustrate them by considering specific examples.

7.1. Nuclear Fusion Cross Sections

An analysis of processes of nuclear fusion is accessible via the *Fusion* section of the knowledge base. This section includes an experimental database of fusion cross sections and provides the possibility of simulating the fusion process within the coupled-channel method. The database of fusion cross sections is the most comprehensive compared to any other database of cross sections for nuclear reactions in the NRV knowledge base. At the present time, it contains more than 1500 excitation functions. An example of a data representation for a specific reaction is presented in Fig. 2.

In the NRV knowledge base, it is possible to calculate fusion cross sections on the basis of two versions of the channel coupling model: the quantum [29] and the empirical [30]. Either approach allows one to take into account the coupling of relative motion of colliding nuclei to their collective degrees of freedom (surface vibrations of spherical nuclei and/or the rotation of deformed nuclei). It is worth noting that the results produced by these two models are close to each other and are in good agreement with experimental data. This is illustrated in Fig. 5, where the fusion cross section for the $^{36}S+^{90}Zr$ reaction is analyzed within the empirical (curve *1*) and quantum (curve *2*) versions of the channel coupling model and compared with the experimental data from [32]. In the empirical version of the channel-coupling model, it is also possible to take into account neutron redistribution channels characterized by positive Q-values [33].

An example of a dialog for the preparation of input data is shown in Fig. 6. Similarly to the other sections of the knowledge base, the user is provided with the possibility of choosing the default input parameters of the model. This possibility is based on our experience of analysis of the respective process.

The dialog for preparation of input data contains several basic subsections.

Model. This subsection provides the possibility of choosing between the empirical and the quantum-mechanical versions of the channel coupling model. A description of the models is given in the *Description* subsection of the knowledge base.

Reaction. This subsection serves for the choice of projectile—target combination and the range of collision energies.

Experimental data. The user has the possibility of either avoiding the inclusion of experimental data in the analysis or choosing data for the analysis. In doing this, data can be either taken from the respective database or entered by the user manually. The experimental data included in the analysis are represented in the form of a graph in the left-hand part of the window (see, for example, Fig. 6).

Nuclear potential. The user may choose the most frequently used nucleus— nucleus interaction potentials (Woods—Saxon potential or proximity potential). The parameters of the Woods—Saxon potential can be chosen automatically according to the Akyüz—Winther systematics [34]. The dependence of the nucleus—nucleus potential on the distance between colliding nuclei is also shown in an individual Java

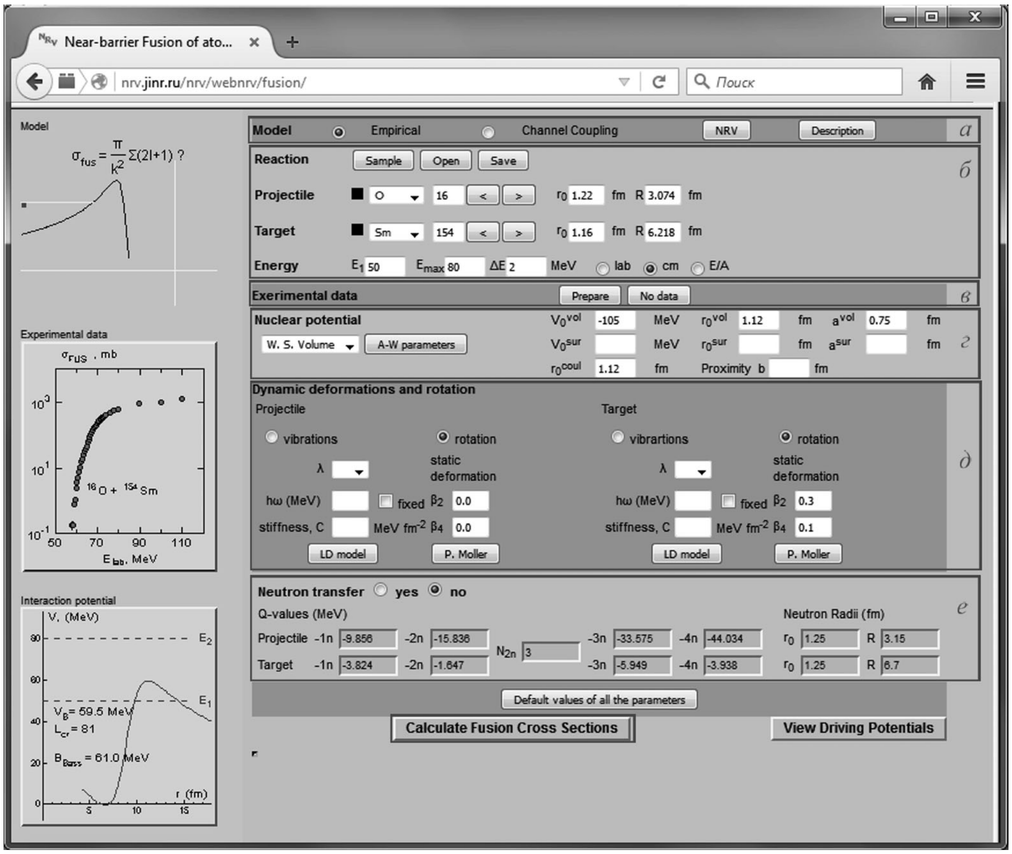

Fig. 6. Example of a dialog for the preparation of input data.

applet in the lower left part of the window. The horizontal dashed lines show the chosen range of collision energies.

Dynamic deformations and rotation. The user can select the collective degrees of freedom to take into account in the calculation and choose parameters of the respective excitation. The possibility of automatically determining values of respective parameters from the database of properties of nuclei is provided.

Nucleon transfer. This subsection is implemented only in the empirical version of the channel coupling model and allows one to take into account the effect of neutron transfer on the fusion cross section. All data necessary for this are determined automatically.

In order to run the computational code, it is necessary to click the *Calculate fusion cross sections* button. The NRV knowledge base provides the possibility of calculating and analyzing the following quantities related to one another: fusion cross sections, fusion barrier distributions, and partial fusion cross sections. Figure 7 shows an example of the analysis of the ^{4,6}He + ^{64}Zn fusion cross sections that was performed in [35] using the NRV knowledge base. Curve *1* stands for the fusion cross section calculated for the ^{4}He+^{64}Zn reaction within the empirical channel-coupling model without taking into account neutron transfers, while curves *2* and *3* represent the fusion cross sections calculated for the ^{6}He+^{64}Zn

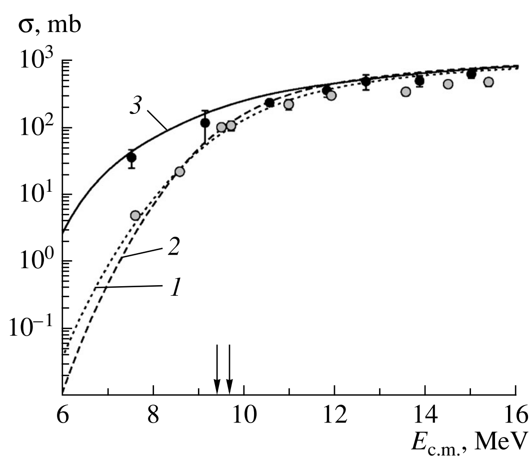

Fig. 7. Example of analyzing the fusion cross section for the ^{4,6}He+^{64}Zn reaction within the NRV knowledge base taken from Ref. [35], the displayed experimental data were taken from Refs. [36, 37].

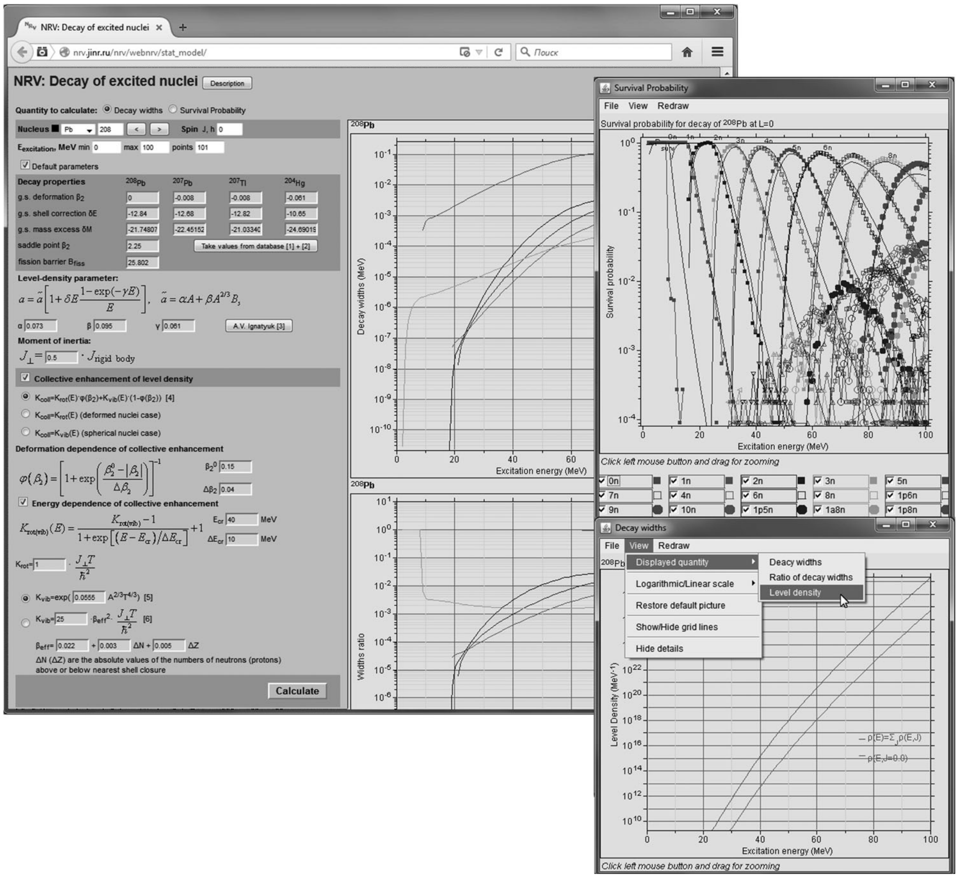

Fig. 8. Illustration of the possibilities of the *Decay of excited nuclei* section.

reactions without and with the transfer of neutrons, respectively. These results are compared with the experimental data from Refs. [36, 37].

7.2. Decay of an Excited Rotating Nucleus

The *Decay of excited nuclei* section of the NRV knowledge base is intended for simulating the decay of a highly excited rotating nucleus on the basis of the statistical model [31]. The level density in the excited nucleus under consideration (versus energy), the widths with respect to the emission of light particles from the excited nucleus (neutrons, protons, alpha particles, and photons), the fission width, and the survival probability for the nucleus in all possible channels are basic quantities calculated in this section. The statistical model is described in the *Description* subsection. An example of a dialog for the preparation of input data is shown in Fig. 8. The user can choose the calculated quantity: decay widths and level densities (*Decay widths*) or survival probability (*Survival probability*). After that, it is necessary to choose a nucleus, its angular momentum, and the range of excitation energies. For all parameters of the model (properties of the mother and daughter nuclei, as well as details of the calculation of the level densities), one can keep default values (*Default values*). The calculation starts after clicking the *Calculate* button. The survival probability can be calculated by the Monte Carlo method (in which case all possible channels involving the evaporation of neutrons, protons, and alpha particles are taken into account) or by the embedded-integral method (in which case only channels involving the emission of one to six neutrons are taken into account). The latter provides a higher speed of calculation—for example, in simulating the decay of excited superheavy nuclei, in which case the survival probability is extremely small. In all other cases, it is preferable to employ the Monte Carlo method, since it is more general.

The calculated decay widths for the chosen nucleus with respect to the emission of neutrons, protons, alpha particles, gamma quanta and with respect to fission are displayed in the main window of the browser (see Fig. 8). In this section of the NRV knowledge base one can also calculate the survival probability for the nucleus considered and the energy

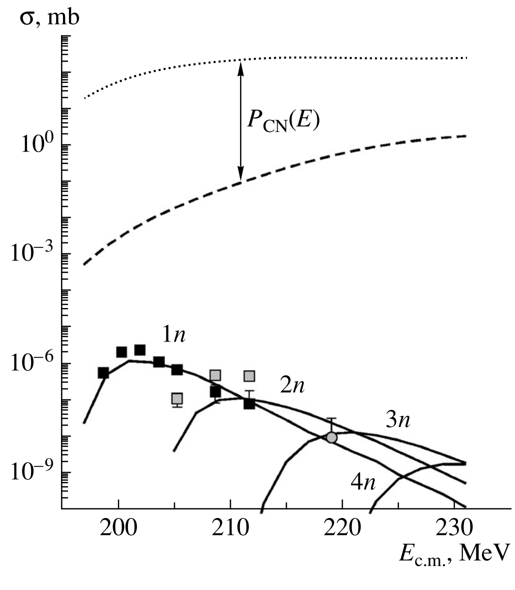

Fig. 9. Example of analyzing cross sections for the production of the superheavy element seaborgium in the fusion reaction $^{54}Cr + ^{208}Pb \rightarrow ^{262-x}Sg\,(x = 1{-}4)$ within the NRV knowledge base. The displayed experimental data were taken from [39].

dependence of the level density. These results are shown in individual windows.

7.3. Analysis of Fusion–Fission and Fusion–Survival Reactions

By combining within the knowledge base codes for calculating fusion cross sections with codes for simulating the decay of compound nuclei, it becomes possible to study fusion–fission and fusion–survival processes in the neutron, proton, and alpha-particle emission channels. A direct transition between the respective sections of the NRV knowledge base is implemented. A direct access is also possible from the main menu of the knowledge base (*Evaporation residues* section). The filling of the experimental database of cross sections for the production of evaporation residues is being continued. The data available in the knowledge base and the user data may be included in the analysis. For this, there is the option in the window that shows experimental data, as well as on the page for preparation of model parameters, displayed in Fig. 6. The dialog for preparation of model parameters is similar to the dialog of the *Decay of excited nuclei* section of the knowledge base (see above). It shows the reaction under analysis and the respective energy range. In order to change the reaction and/or the range of collision energies, it is necessary to go to the *Fusion* section and to calculate anew the fusion cross section for the required projectile–target combination.

The coupled-channel method makes it possible to calculate the so-called capture cross section, which, in the case of the fusion of not very heavy nuclei, is nearly coincident with the fusion cross section. For a number of reactions, however—for example, reactions leading to the production of superheavy nuclei—the probability P_{CN} for the production of a compound nucleus (CN) from the configuration of two touching nuclei may be substantially smaller than unity. The empirical formula proposed in [38] for P_{CN} is valid for cold fusion reactions, where lead or bismuth play the role of a target. This empirical relation can be taken into account within NRV in calculating cross sections for the production of evaporation residues (*use empirical formula for CN formation probability* option). An example of such a calculation performed within the NRV knowledge base for the reaction $^{54}Cr + ^{208}Pb \rightarrow ^{262-x}Sg\,(x = 1{-}4)$ is given in Fig. 9, where the capture cross section and the fusion cross section with taking into account P_{CN} are represented by, respectively, the dotted and dashed curves. The solid curves correspond to the cross sections calculated for the synthesis of superheavy nuclei in the $1n{-}4n$ evaporation channels. The displayed points stand for experimental data from Ref. [39].

The *calculate fission Z—N yield* option works only upon choosing the Monte Carlo method for simulating the decay of an excited nucleus and serves for calculating the two-dimensional charge–mass distribution of fragments originating from the fusion–fission reaction. The remaining dialog components do not differ from those that were described in the preceding section.

In Fig. 10, experimental data from Refs. [40, 41] on the cross section for the production of the isotope ^{46}Sc in the reaction $^{45}Sc(^{3}He, 2p)^{46}Sc$ are compared with the results of the calculations performed in Ref. [42] on the basis of the evaporation model incorporated in the NRV knowledge base. This figure shows that the theoretical curves agree reasonably well with the experimental data over the whole energy range.

As a further development of the set of codes already included in the NRV for simulating nuclear fusion followed by the decay of the product compound nucleus, it is planned to extend the number of reaction features available for the analysis. First of all, this concerns a calculation of the multiplicities and energy spectra of particles emitted both from survived nuclei and nuclei that undergone fission. In the latter case, it will become possible to analyze properties of both pre-fission particles, emitted from the compound nucleus, and post-fission particles, emitted from fission fragments.

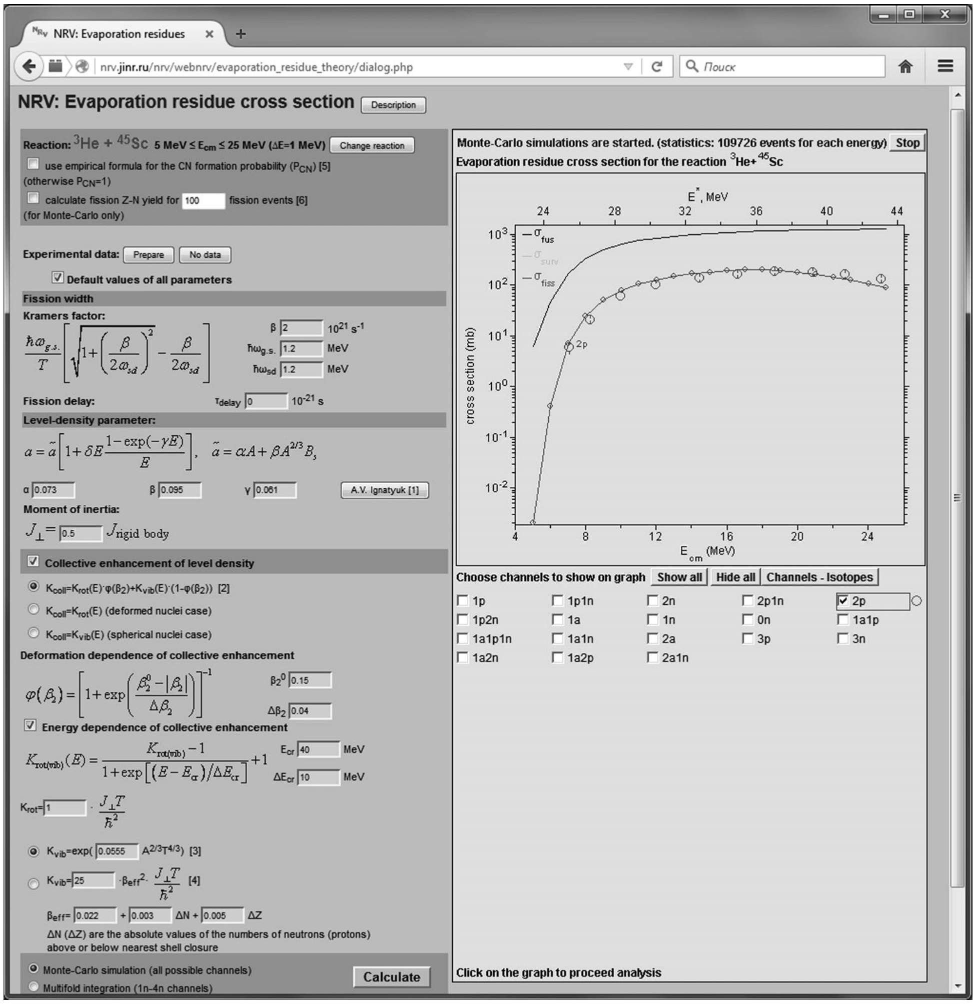

Fig. 10. Experimental data from Refs. [40, 41] on the cross sections for the production of the isotope ^{46}Sc in the reaction ^{45}Sc(^{3}He, $2p$)^{46}Sc along with the results of calculations performed in Ref. [42] on the basis of the evaporation model incorporated in the NRV knowledge base.

8. CONCLUSIONS

In the present article, we have analyzed the current situation in the field of employing network information technologies in nuclear physics, formulated basic principles of operation of the NRV knowledge base, and described briefly its main sections. The possibilities of the knowledge base have been illustrated in detail by considering the example of an analysis of processes of nuclear fusion followed by the decay of an excited compound nucleus.

The NRV knowledge base on low-energy nuclear physics provides a fast access to modern experimental data on the structure of nuclei and on cross sections for nuclear reactions and also makes it possible to analyze data and to simulate processes of nuclear dynamics within reliable theoretical approaches.

The NRV web knowledge database has several unique advantages over other nuclear databases. At the present time, it is extensively used not only in research but also as a valuable educational tool in the field of nuclear physics.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 15-07-07673-a).

REFERENCES

1. NRV web knowledge base on low-energy nuclear physics. http://nrv.jinr.ru/.
2. V. Zagrebaev and A. Kozhin, JINR Report No. E10-99-151 (JINR, Dubna, 1999).
3. A. S. Denikin, V. I. Zagrebaev, V. V. Samarin, et al., in *Proceedings of All-Russia Conference "Scientific Service in the Internet," Novorossiisk, 2003* (Mosk. Gos. Univ., Moscow, 2003), p. 14.

4. A. S. Denikin, A. P. Alekseev, V. I. Zagrebaev, et al., in *Proceedings of All-Russia Conference "Scientific Service in the Internet," Novorossiisk, 2006* (Mosk. Gos. Univ., Moscow, 2006), p. 211.
5. A. S. Denikin, A. V. Karpov, A. P. Alekseev, et al., in *Proceedings of All-Russia Conference "Scientific Service in the Internet," Novorossiisk, 2008* (Mosk. Gos. Univ., Moscow, 2008), p. 393.
6. A. S. Denikin, V. I. Zagrebaev, A. V. Karpov, et al., in *Proceedings of the 2nd South Africa–JINR Symposium on Models and Methods in Few- and Many-Body Systems* (Dubna, Russia, 2010), p. 145.
7. A. V. Karpov, A. S. Denikin, A. P. Alekseev, et al., in *Proceedings of All-Russia Conference "Scientific Service in the Internet," Novorossiisk, 2015* (Inst. Prikl. Mat. im. M. V. Keldysha, Moscow , 2015), p. 119.
8. NNDC, http://www.nndc.bnl.gov/index.jsp/.
9. CDFE, http://cdfe.sinp.msu.ru/index.en.html/.
10. TUNL, http://www.tunl.duke.edu/nucldata/.
11. NEA, Data bank http://www.oecd-nea.org/dbprog/.
12. NACRE, http://pntpm.ulb.ac.be/Nacre/.
13. NACRE-II, http://www.astro.ulb.ac.be/nacreii/.
14. FRESCO, http://www.fresco.org.uk/.
15. GRAZING, http://personalpages.to.infn.it/∼nanni/grazing/.
16. TALYS, http://www.talys.eu/.
17. EMPIRE, http://www.nndc.bnl.gov/empire219/.
18. LISE++, http://lise.nscl.msu.edu/lise.html/.
19. MySQL, http://www.mysql.com/.
20. AMDC, http://amdc.impcas.ac.cn/.
21. NUdat, http://www.nndc.bnl.gov/nudat2/.
22. M. G. Itkis and A. Ya. Rusanov, Phys. Part. Nucl. **29**, 160 (1998).
23. V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).
24. B. Jurado and K.-H. Schmidt, http://www.khs-erzhausen.de/GEF.html/.
25. P. Descouvermont, *Theoretical Models for Nuclear Astrophysics* (Nova Science, New York, 2003).
26. http://www-alt.gsi.de/documents/FRS-reference-2012-001.html/.
27. http://www.gwtproject.org/.
28. http://www.asp.net/.
29. V. I. Zagrebaev and V. V. Samarin, Phys. At. Nucl. **67**, 1462 (2004).
30. V. I. Zagrebaev, Phys. Rev. C **64**, 034606 (2001).
31. A. V. Karpov, V. I. Zagrebaev, and V. V. Saiko, Description of the Statistical Model. http://nrv.jinr.ru/nrv/webnrv/stat_model/description/description.pdf.
32. A. M. Stefanini, L. Corradi, A. M. Vinodkumar, et al., Phys. Rev. C **62**, 014601 (2000).
33. V. I. Zagrebaev, Phys. Rev. C **67**, 061601 (2003).
34. A. Winther, Nucl. Phys. A **594**, 203 (1995).
35. V. A. Rachkov, A. V. Karpov, A. S. Denikin, and V. I. Zagrebaev, Phys. Rev. C **90**, 014614 (2014).
36. M. Fisichella, V. Scuderi, A. di Pietro, et al., J. Phys.: Conf. Ser. **282**, 012014 (2011).
37. V. Scuderi, A. di Pietro, P. Figuera, et al., Phys. Rev. C **84**, 064604 (2011).
38. V. Zagrebaev and W. Greiner, Phys. Rev. C **78**, 034610 (2008).
39. S. Hofmann, F. P. Heβberger, D. Ackermann, et al., Nucl. Phys. A **734**, 93 (2004).
40. N. K. Skobelev, A. A. Kulko, Yu. E. Penionzhkevich, E. I. Voskoboinik, V. Kroha, V. Burjan, Z. Hons, J. Mrazek, Š. Piskoř, and E. Šimečkova, Phys. Part. Nucl. Lett. **10**, 410 (2013).
41. N. K. Skobelev, A. A. Kulko, Yu. E. Penionzhkevich, E. I. Voskoboynik, V. Kroha, V. Burjan, Z. Hons, J. Mrázek, Š. Piskoř, and E. Šimečkova, Bull. Russ. Acad. Sci. Phys. **77**, 795 (2013).
42. M. A. Naumenko, V. V. Samarin, Yu. E. Penionzhkevich, and N. K. Skobelev, Bull. Russ. Acad. Sci. Phys. **80**, 264 (2016).