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New Nuclear Charge Radii Database

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Abstract—Several large relational databases (DBs) containing various atomic nucleus parameters and nuclear reaction features were produced at the Centre for Photonuclear Experiments Data (Centr Dannyh Fotoyadernykh Eksperimentov (CDFE)) of the Skobeltsyn Institute of Nuclear Physics, Moscow State University). The sources are numerical data founds maintained by International Nuclear Data Centers Network of the International Atomic Energy Agency (IAEA) and produced by CDFE. The original CDFE product is the electronic “Chart of Quadrupole Nuclear Deformations” which includes ~2000 sets of data on nuclei quadrupole moments Q and quadrupole deformation parameters β_2 for ~1500 nuclei. At last time, in the frame of joint research with the Joint Institute for Nuclear Research (JINR) that electronic Chart was supplemented with the data on nuclear mean-root-square (MRS) charge radii (~900 isotopes of 90 elements (Z = 1–96, N = 0–152)) and therefore transformed into the “Chart of Nucleus Shape and Size Parameters”—complete collection of data under discussion. New Chart allows one to investigate the isotopic and isotonic behavior of nuclei quadrupole moments, parameters of quadrupole deformation and charge radii, and study the $R(Z, N)$ surface structure and $R(A)$ dependence of the fine structure.

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INTRODUCTION

During the last years, several complete relational databases (DBs) [1] have been produced at the Centre for Photonuclear Experiments Data (Centr Dannyh Fotoyadernykh Eksperimentov (CDFE)) of the Skobeltsyn Institute of Nuclear Physics, Moscow State University (MSU SINP). The sources are the following large numerical data founds: (i) international founds, organized and supported by the large International Nuclear Data Centers Network of the International Atomic Energy Agency (IAEA) [2], including CDFE, and (ii) original data prepared at CDFE in cooperation with other organizations.

Access of remote users to all DBs is performed through a specially develop Web interface. Efficient and flexible search systems of these DBs allow one to find quickly data, which correspond to a huge number of characteristics and their combinations, and process very complicated and sometimes unique requests. In addition, they make it possible to solve problems of physics of atomic nuclei and nuclear reactions, many of which can neither be solved without these DB nor even formulated. A large number of original investigations have been carried out and new interesting information about the nuclear properties and characteristics of nuclear reactions was obtained [1, 3] using the features available on the CDFE DB Web server (http://cdfe.sinp.msu.ru).

Recently, along with the complete systematics of the characteristics of nuclear levels and shells, much attention has been paid to the complete systematics of the data on the quadrupole moments Q of nuclei and the parameters β_2 of their quadrupole deformations (describing the nuclear shape) and charge radii.

The increased interest in the data on shape and size of atomic nuclei and their changes in nuclear transformations from the ground state to excited ones or in transitions from one nucleus to another, is related, first of all, to the investigation of new types of interactions between nucleons in a nucleus, which occupy shells with different quantum characteristics.

It was found that some kinds of such interaction influence not only the shape and size of a nucleus, but also the formation of a number of its properties and characteristics, which were earlier considered as belonging to only some special nuclei. New types of proton–neutron interaction result, e.g., in definite magic properties for a much larger number of nuclei than was believed previously [4, 5].

In view of this, the data on the quadrupole moments Q and quadrupole deformation parameters β_2 of atomic nuclei were earlier systematized into a special electronic collection. Based on this collection, a radically new relational base of discussed data on the nucleus shape was produced: the electronic “Chart of Quadrupole Nuclear Deformations” (http://cdfe.sinp.msu.ru/services/defchart/defmain.html) [6], which included the systematized data of discussed type (~2000 data sets for ~1500 nuclei) from three authoritative international sources [7–9].

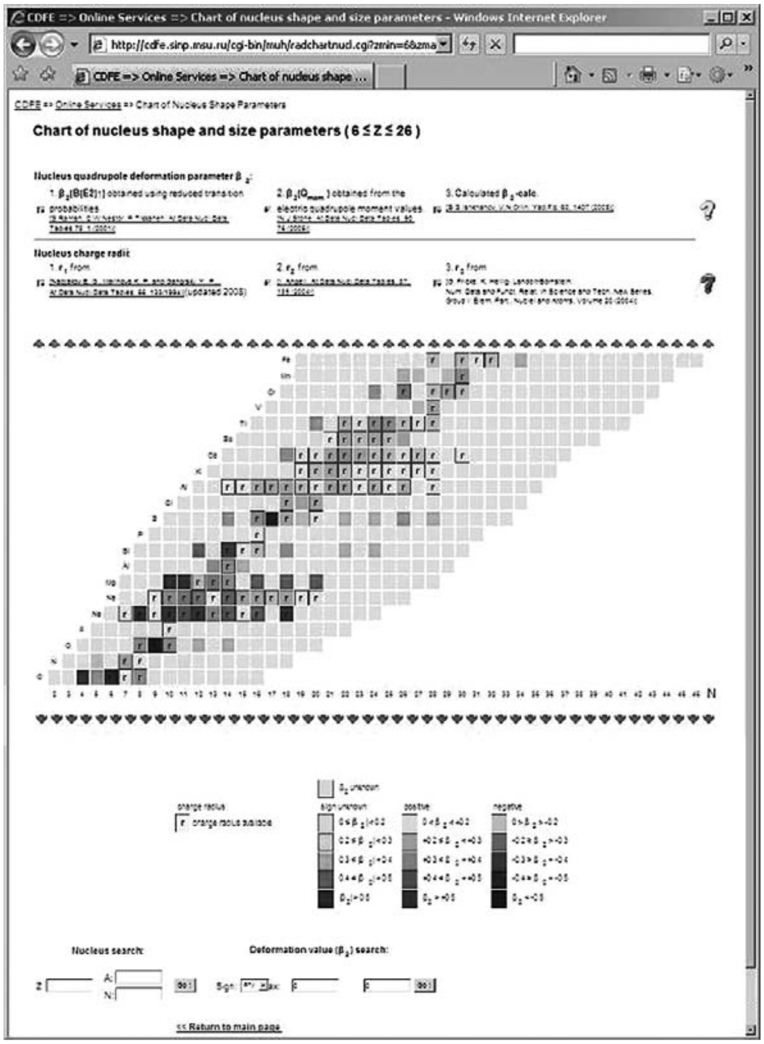

Fig. 1. Principles of information presentation for the Chart scale 3rd level.

Recently this DB was added with data on nucleus charge radii and thus actually reorganized into a new DB: "Chart of Nuclear Shape and Size Parameters" (http://cdfe.sinp.msu.ru/services/radchart/radmain.html). This new DB on the charge radii of atomic nuclei is presented in this paper.

1. SOURCES OF INFORMATION ON CHARGE RADII OF NUCLEI

The root-mean-square charge radius (RMSCR) $R = \langle r^2 \rangle^{1/2}$ is a fundamental characteristic of atomic nucleus; its change with a change in the number of nucleons (protons and neutrons) in a nucleus often indicates a change in the fundamental properties of nuclear matter.

Four experimental methods are used to determine this parameter with a satisfactory accuracy, which are based on the use of peculiarities of electromagnetic interactions between a nucleus and its electronic shells; these methods can be combined into two groups. Experiments on determination of the transition energies in muonic (μ^-) atoms and measurement of spectra of elastically scattered electrons (e^-) make it possible to determine the absolute values of charge radii $R(A) = \langle r^2 \rangle^{1/2}$. However, it is applicable only to a limited number of stable or long-lived isotopes. The second group includes measurements of optical isotopic shifts and *KX*-ray energy shifts. They contain information about the differences in charge radii $\delta\langle r^2 \rangle^{A', A} = \langle r^2 \rangle^{A} - \langle r^2 \rangle^{A'}$ of two compared isotopes, *A* and *A*'. In particular, modern optical laser spectroscopy can be applied to a wide range of isotopes located far from the drip line. These types of experiments supplement each other: using the absolute values of charge radius *R* of a stable isotope *A*' for a given element and the radius change $\delta\langle r^2 \rangle^{A', A}$ between *A*' and a radioactive isotope *A*, one can determine *R*(*A*) for any isotope *A* in a long isotopic chain on the basis of the simple dependence

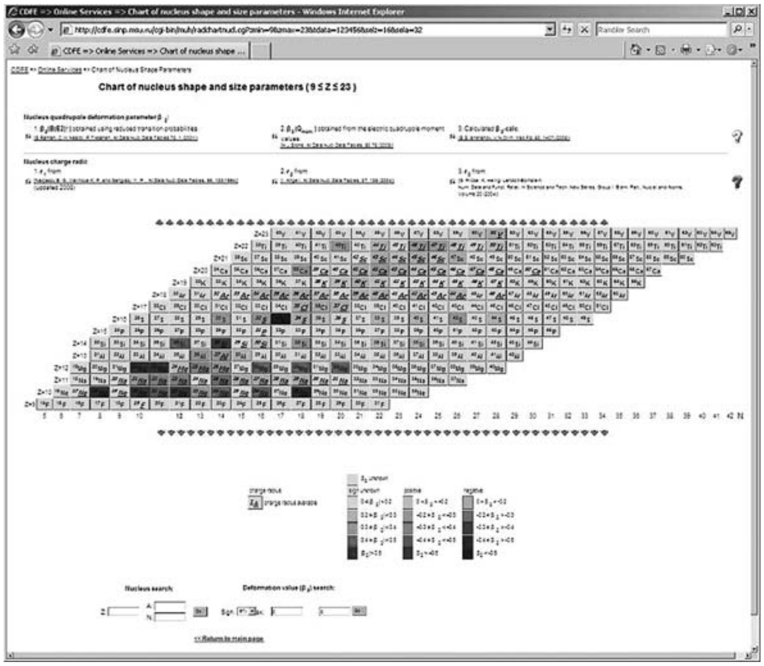

Fig. 2. Principles of identifying the presence of charge radius data in the DB.

$$R^2(A) = R^2(A') + \delta\langle r^2\rangle^{A'A}.$$

In [10–12], various algorithms for joint analysis of data on $R(A)$ and $\delta\langle r^2\rangle^{A'A}$ have been elaborated. The RMSCR values obtained were included in the DB. They cover data for a wide range of stable and radioactive nuclei: more than 850 isotopes of 76 elements ($Z = 1–96$, $N = 0–152$),

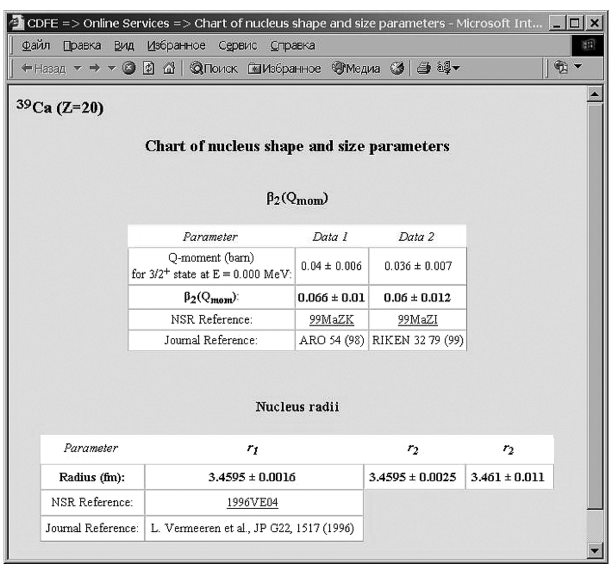

Fig. 3. Example of presentation of tabular data on the quadrupole moment Q, quadrupole deformation parameter β_2, and charge radius r of the ^{39}Ca nucleus from different publications (there are direct references to unique identifiers of NSR DB documents on publications). The tabular values for r_2 and r_3 were obtained by Angeli [11] and Fricke [12], respectively.

2. DATA ACCESS ORGANIZATION

To represent the Chart data, we used the same convenient graphical form as in [4]: disposition of data sets in the "number of protons Z"–"number of neutrons N" coordinates. To make easier the search and identification of data for a nucleus (or group of nuclei) with definite deformation (and corresponding shape), special coloring of DB elements according to the quadrupole nuclear moments is applied, which is similar to that traditionally used for geographic maps. Namely, brown color ("mountains") denote the nuclei with positive deformation (i.e, extended), blue color ("sees") is for the nuclei with negative deformation (i.e., flattened), and green color ("plains") is for the nuclei with an unknown or zero deformation.

Five grades of each color are used, which help to identify the deformation parameters by the absolute value: the maximum value corresponds to the most intensive color. Such representation of the discussed physical information allows a user to find very quickly nuclei of characteristic shape: significantly or, vice versa, insignificantly extended or flattened ones. In addition, there are possibilities of using four scale levels and a Fast Search panel for a given charge Z and a number of neutrons N of a specific nucleus. The principle of information representation is illustrated in Fig. 1 for the third Chart scale level.

The presence of data on the charge radii in DB is denoted as follows: with an additional slash (diagonal)

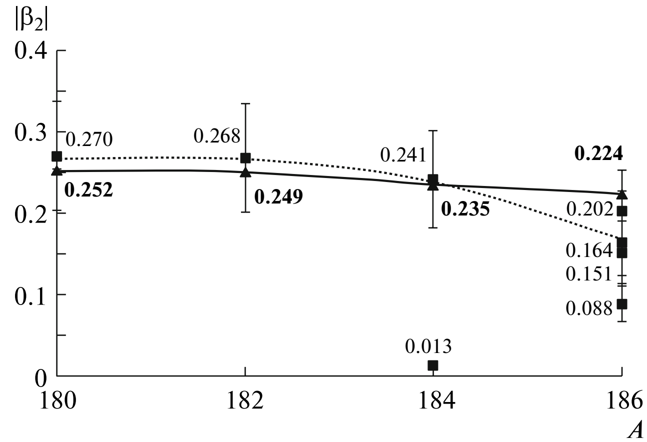

Fig. 4. Nearly coincident data on the quadrupole deformation parameter β_2, obtained by different methods for the W nucleus (group of Ti, Cr, Zr, Nd, Sm, Gd, Dy, Er, and W nuclei): the solid and dotted lines connect, respectively, the data obtained from reduced probabilities of the $B(E2\uparrow; 0^+ \to 2_1^+)$ transition and the quadrupole moments Q.

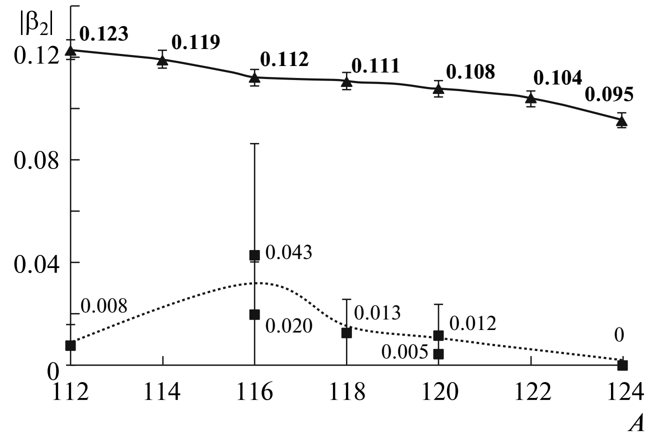

Fig. 5. Significant systematic discrepancies of the data on the quadrupole deformation parameter β_2, obtained by different methods for Sn nuclei (group of C, Si, Ar, Ca, Fe, Ni, Zn, Ge, Se, Kr, Sr, Mo, Ru, Pd, Cd, Sn, Te, Ba, Yb, Hf, Pt, and Pb nuclei), designations are the same as in Fig. 4.

on the small scale, with the character *r* on the intermediate scale, and with underlined italics for the element name on the large scale (Fig. 2).

After selection of nucleus on the largest Chart scale, all the data corresponding to the previously chosen information sources are shown in an additional window (Fig. 3, example for the ^{39}Ca nucleus). All the values of quadrupole moments Q and quadrupole deformation parameters β_2 (with indication of energies and spin–parities of nuclear states to which they refer) and also the charge radii of nuclei are accessible.

In each data set of nuclear shape and size parameters, bibliographic references are given in the form of unique DB CDFE identifiers for publications (NSR) [13]; the corresponding hyperlinks give a direct access to the documents of this bibliographic reference DB. This DB plays a special role in the CDFE information system, since it links all factographic DBs. Thus, a user can enter the system via a request for a certain DB (on nuclear reactions (EXFOR), nuclear spectroscopy (ENDSF), on giant dipole resonance (GDR) parameters, on nuclear shape and size parameters, etc.) and then pass via the reference DB (NSR) to any other DB of the system with subsequent return or turn to any other DB.

3. DBs PREDICTION AND ANALYTICAL POSSIBILITIES

As was mentioned above, the efficient and flexible search systems of these DBs allow one to find quickly data corresponding to a huge number of characteristics and their combinations and process very complicated, sometimes unique requests. Combination of these possibilities of such search systems with large datasets makes it possible to solve problems of atomic nucleus and nuclear reactions physics (many of which cannot be solved in another way) and thus get new data, new information, and finally new knowledge. In fact, specifically this circumstance allows us to speak about certain DB prediction and analytical possibilities. First of all, we should note the possibilities of revealing or predicting previously unknown dependences of data from some DB section on the data from other sections.

3.1. Systematic Discrepancies of the Data on Quadrupole Nucleus Deformation Parameters Obtained by Different Methods

The relational DB (Chart of Nuclear Deformations [6]) was used to reveal obvious systematic discrepancies of the data on quadrupole nucleus deformations, obtained by two traditional methods (see above): from the probability of transition from the ground state to the first state with $J^\pi = 2_1^+$ and from the quadrupole moments of nuclei. It was found that two groups of nuclei can be selected [13], for which the obtained deformation parameters distinctly differ by the derivation method. Figure 4 indicates that the quadrupole deformation parameters for the nuclei of one group (W isotopes) nearly coincide, while Fig. 5 shows significant systematic discrepancies of these values for the nuclei of another group (Sn isotopes). Such a distinct separation of all known nuclei into two groups, in one of which different methods give close values, while the data for the second group differ substantially (in favor of the former method) may indicate manifestation of zero oscillations of the surface of nuclei in the ground state in the second group [14, 15]. However, we should note another possible cause of the discrepan-

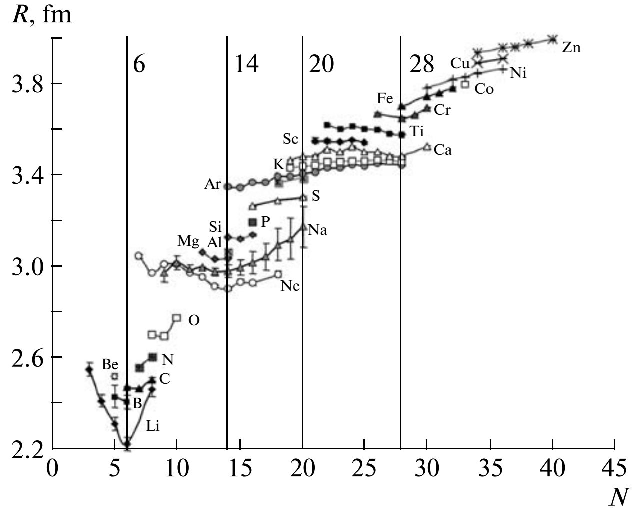

Fig. 6. Example of isotopic RMSCR dependence $R_Z = R_Z(N)$ for nuclei with the proton number $Z = 3–30$. Features for the neutron numbers $N = 6$, 14, and 28 can be seen well; however, the classical magic number $N = 20$ does not manifest itself in the isotopic behavior of charge radius (see [16, 17]).

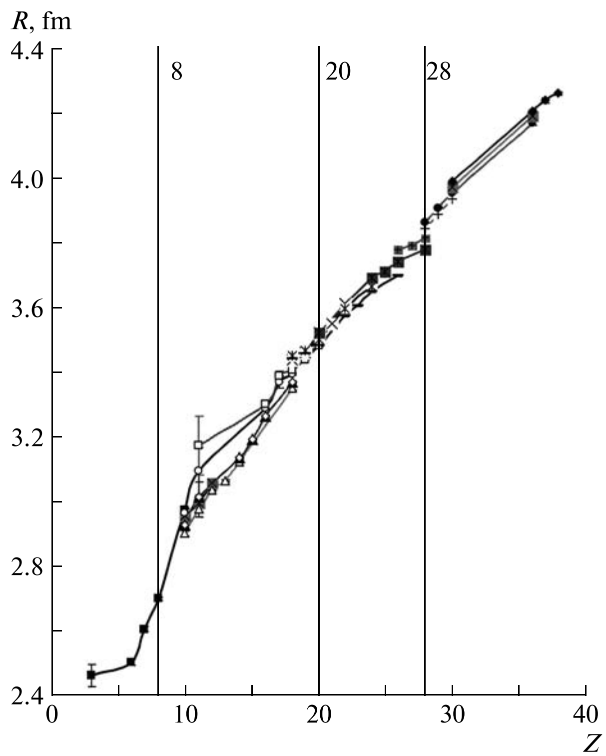

Fig. 7. Example of isotonic RMSCR dependence $R_N = R_N(Z)$ for nuclei with the neutron number $N = 8–40$. Features for the proton numbers $Z = 8$, 20, and 28 can be seen well.

cies. It is related to the method for determining the parameter β_2. Generally, the so-called projection formula is used, which relates β_2 and Q; its validity is significantly limited.

3.2. Systematic Regularities of the Data on the Charges of Nucleus Radii

The new relational DB—electronic Chart of Data on Charge Radii of Nuclei—allows one to investigate very efficiently the general structure of the $R(Z, N)$ surface and study the isotopic and isotonic behavior of charge radii. This is illustrated by an example of light nuclei data in Figs. 6 and 7, respectively. In both figures, the peculiarities of RMSCR dependences on numbers of nucleons in the intermediate vicinity of the magic (classical or non-traditional) numbers of neutrons (N) and protons (Z) can be seen distinctly. These peculiarities manifest themselves as a change in the curve slope, e.g., a distinct minimum (Fig. 6) or steps (Fig. 7). It is planned to carry out a detailed analysis of all RMSCR data, although such an analysis has already been performed for some nuclei.

Figure 8 shows RMSCR values for the isotopes and isotones that neighbor a new magic nucleus, ^{96}Zr. It was shown previously [18] that this new magic nucleus has many peculiarities inherent in classical magic nuclei: a high energy $E(2_1^+)$ of the first state with $J^\pi = 2^+$; a small ratio of energies of the first 4^+- and 2^+ states, $E(4_1^+)/E(2_1^+)$; and a very small quadrupole deformation parameter β_2. In addition, this nucleus is characterized by very large energy gaps between the corresponding proton and neutron subshells and characteristic peculiarities of the nucleon emission energies. Figure 8 indicates that the RMSCR for the ^{96}Zr nucleus is smaller than for the neighboring nuclei.

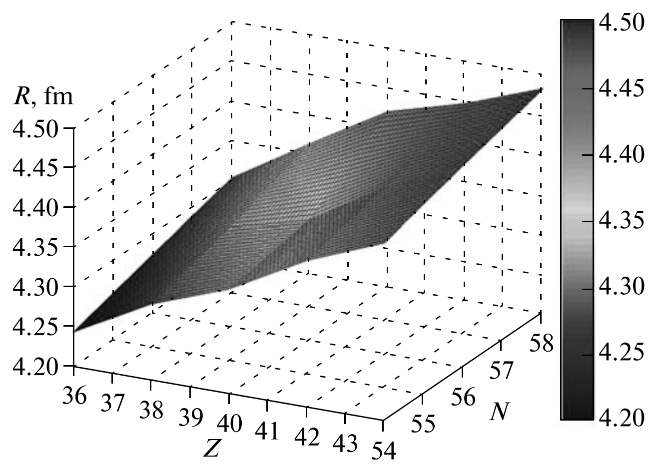

Fig. 8. Local minimum of RMSCR values in the range of isotopes and isotones neighboring the new magic nucleus ^{96}Zr.

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