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The role of neutron pairs in nuclear collective properties

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Abstract. The role of surface neutrons in nuclear properties was examined by comparing rigidities of nuclear collective vibrations and charge radii of even-even nuclei. Correlations of peaks in rigidities and minimal values of $r_0 = R_{ch} \cdot A^{-1/3}$ parameters were revealed.

Eighty years of nuclear investigations have revealed a large variety in nuclear characteristics, their consistent theoretical interpretation is up to now only partly successful. For example, the theory of multipole giant resonances (MGR) observed experimentally in the cross sections of different reactions on even-even nuclei cannot explain in full extent a great variety of their forms and widths. E.g., in the region of middle-mass nuclei the giant $E1$ resonance has a complicated structure. It is a well-known phenomenon and many more or less successful attempts were made to describe the GR structure in magic and semi-magic nuclei. However, as one can see from experimental data, sometimes addition of a couple of neutrons drastically changes the envelope of resonance peak.

One may assume that one of the sources of diversity in the resonance shape is a variety of rigidities of nuclear surface. This characteristic of nuclei was discussed already at the dawn of nuclear physics when liquid drop model of nuclei was created [1, 2].

In the collective coordinate representation the Hamiltonian of the nuclear surface vibrations reads [1]

$$H_S = T + V = \sum_{\lambda\mu} \left[\frac{1}{2B_\lambda} |b_{\lambda\mu}|^2 + \frac{C_\lambda}{2} |a_{\lambda\mu}|^2 \right], \qquad (1)$$

where the momenta $b_{\lambda\mu}$ conjugate to collective coordinates $a_{\lambda\mu}$ which describe the deformation of nuclear surface. The coefficient B_λ is the vibrational mass parameter. The rigidity C_λ which determines the potential energy of nuclear deformation is connected with the nuclear surface tension. For the quadrupole surface vibrations ($\lambda = 2$) the connection of rigidity with the surface tension σ of a nucleus having the charge and radius Ze and R, respectively, has the form

$$C = 4R^2\sigma - \frac{3Z^2e^2}{10\pi R} \qquad (2)$$

It was already mentioned in [1] that the nuclear rigidity (deformability) may considerably vary from nucleus to nucleus and is strongly influenced by its shell structure. Nuclear rigidity as regards to quadrupole vibrations is connected with the energy of the first collective 2_1^+ state and the mean squared deformation of a nucleus β

$$C = \frac{5h\omega}{2\beta^2} \qquad (3)$$

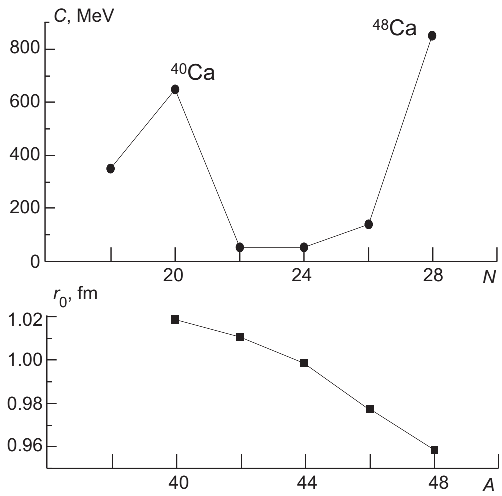

Figure 1. The rigidity C and the charge radius parameter r_0 for Ca isotopes.

The values of β were estimated and listed in [3] for all at that time available even-even nuclei. The estimations were based on the measured probabilities of quadrupole transitions to the ground states $B(2_1^+ \rightarrow 0_{g.s.}^+)$. Certainly, the results are model dependent and the variations in the root-mean-square deformation estimations is less than 20%.

In this work, we present the results of comparison of the calculated rigidities with the charge radii parameters for several isotopic chains of even-even nuclei. The data on the nuclear charge radii are taken from [4]. The dependence of nuclear charge radii on the neutron number is shown in [5].

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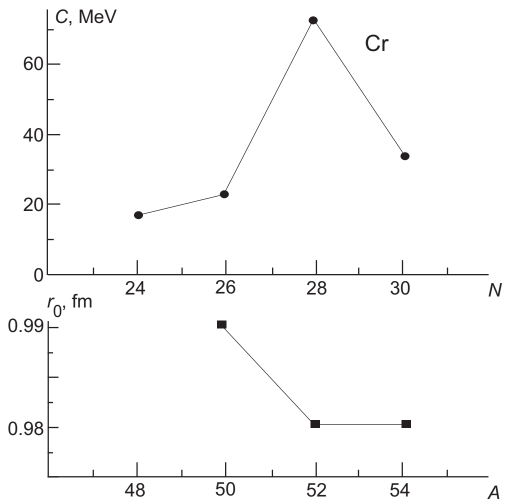

Figure 2. The rigidity C and the charge radius parameter r_0 for Cr isotopes.

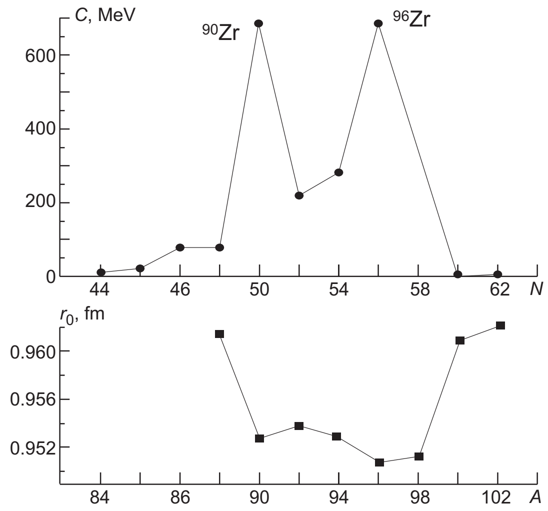

Figure 3. The rigidity C and the charge radius parameter r_0 for Zr isotopes.

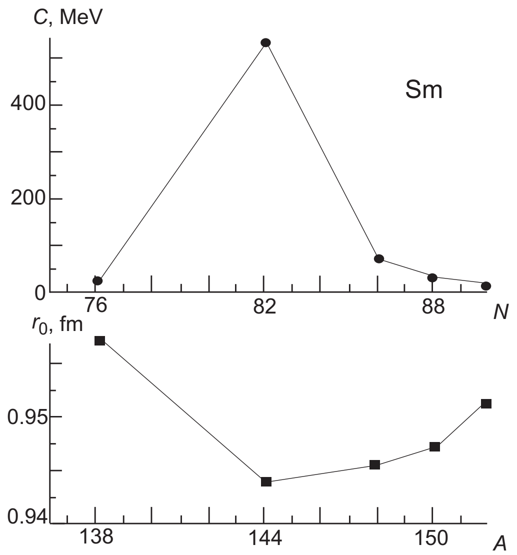

Figure 4. The rigidity C and the charge radius parameter r_0 for Sm isotopes.

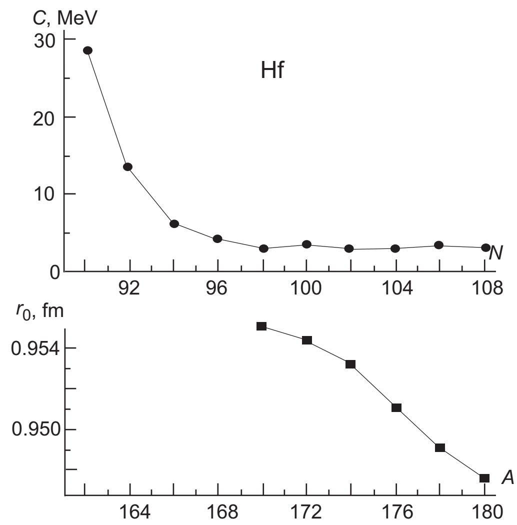

Figure 5. The rigidity C and the charge radius parameter r_0 for Hf isotopes.

Figures 1–5 display the results of calculation of the rigidity C together with values $r_0 = R_{ch}A^{-1/3}$ for the nuclear charge radii in several chains of even-even isotopes. Only a part of the results is shown (for other examples of this calculations see [6]). The most interesting result is that the maxima of rigidity and minima of the parameters r_0 are highly correlated. Since the nuclear density is inversely proportional to third power of r_0, the reduction of its values corresponding to the compression of the proton component of nuclear matter.

In Fig. 1, the rigidities for even-even calcium isotopes with $38 \leq A \leq 48$ are shown. The peaks of C correspond to well known magic numbers 20 and 28. It should be noted that the rigidity of ^{48}Ca is higher than one of the ^{40}Ca and reaches the maximal value for the nuclei with $A < 50 - C(^{48}\text{Ca}) \approx 800$ MeV. It should be noted that the ratio of rigidities of Ca isotopes extracted from the data on the mean-square deformations, does not agree with the corresponding results of the collective model calculations [7]. The latter, based on a specified scheme for quantum numbers and energy levels, have concluded that $C(^{40}\text{Ca}) > C(^{48}\text{Ca})$.

Rigidities for the even-even Cr isotopes with $A = 24 \div 30$ demonstrate the same tendencies (see Fig. 2). The rigidity is maximal whereas parameter r_0 is minimal in the isotope ^{52}Cr with the completely filled neutron shell $1f_{7/2}$ ($N = 28$).

It seems that a rigidity is a nuclear property with a strong sensitivity to the neutron number. The plots of $r_0 = R_{ch}A^{-1/3}$ in Figs. 1–5 demonstrate that nuclei with closed neutron subshells have maximal rigidities. After adding a couple of neutrons to the closed shell r_0 decreases, it means that the proton matter is compressed more. This tendency is revealed for all even-even nuclei with Z up to 40.

The number of neutrons in nuclei with maximal rigidity corresponds to well known magic numbers 8, 20, 28, 50. However, comparison of the C and r_0 values for the Zr isotopes (Fig. 3) reveals that at $N = 56$ the two parameters reach their extrema: C has the maximum whereas r_0 goes through deep minimum. It is worth noting that the neutron number $N = 56$ was revealed and discussed as the "new magic" one from quite different point of view in Ref. [8].

For all medium and heavy nuclei with $A \geq 100$ which are spherical in the ground state, a correlation between the rigidity maxima and minima of the charge radius parameter r_0 was found (see Ref. [6] where even-even isotopes of Xe, Ba, Ce, Nd, Sm were considered). The position of the rigidity maximum in all these nuclei corresponds to the magic number of neutrons $N = 82$. Figure 4 shows the values of C and r_0 for Sm isotopes. Qualitatively results for isotopes of Xe, Ba, Ce, Nd are the same.

The value of C is connected with a nuclear deformability. For well-deformed nuclei in the ground states the C values appear to be by 10 – 100 times smaller than for the magic nuclei. E.g., for the Hf isotopes (Fig. 5) the maximal value of C (^{162}Hf) is ~30 MeV whereas for the lead isotopes ^{208,210}Pb $C \simeq 3000 \div 4000$ MeV.

The correlation between the nuclear rigidity and the nuclear charge radius is one of manifestations of the important role of the nuclear surface tension σ. The closed neutron shells correspond to the large rigidities which means growing of surface tension σ and the stronger pressure p of nuclear matter. This follows from the classical Laplace formula $p = \sigma[(1/R_1 + 1/R_2)]$.

It should be stressed that the parameters r_0 are extracted from the charge radii of nuclei and consequently reflect the characteristic of the nuclear proton distributions. The decrease of r_0 means a slight grow of the nuclear proton density. The effect is certainly small but it leads to increasing of difference in the proton and neutron wells with growing neutron numbers.

For all nuclei with closed neutron shells the rigidity C goes through maximum. Attention is drawn to the fact that among the considered isotopic chains the maximal C values have isotopes of Ca and Zr. Just these two chains contain two isotopes each with the magic neutron numbers – ^{40,48}Ca and ^{90,96}Zr (about "magic" features of the neutron number $N = 56$ see [8]).

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