Mean-square charge radius of the magic nucleus ^{146}Gd

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The isotope shifts of gadolinium isotopes with $A = 146$–160 have been determined by the method of resonance photoionization of atoms. The isotope change of the charge radii was calculated from the measured isotope shifts. These calculations, along with the known charge radii of stable Gd nuclei, were used to determine for the first time the mean-square charge radius of the ^{146}Gd magic nucleus: $\langle r^2\rangle^{1/2}(^{146}\text{Gd}) = 4.984$ fm.

The magic nature of ^{146}Gd nucleus has recently been the subject of a vigorous discussion. A large body of experimental data such as the structure of the excitation spectrum of ^{146}Gd, the presence of a large gap in the single-particle proton spectrum, a discontinuity of the mass surface at $Z = 64$ and $N = 82$, energy systematics of the 2^+ and 3^- levels for the neighboring nuclei, and so forth (see, e.g., Ref. 1) constitute evidence in favor of the assumption that ^{146}Gd is a magic nucleus.

To test any theoretical model, it is highly desirable to have as much information as possible on this "new" magic nucleus. In particular, characteristics of magic nuclei such as the charge radius and binding energy determine the optimum parameters of the effective nucleon-nucleon forces on the basis of the Hartree-Fock method.[2] This stems from the fact that in the case of magic nuclei the dynamic effects influence the characteristics under consideration only slightly.

Since ^{146}Gd nuclei are unstable, and since they cannot be produced in large quantities, the conventional methods of measuring the mean square charge radii (by means of electron scattering or from analysis of mesic-atom spectra) are not suitable for measuring $\langle r^2\rangle$ (^{146}Gd) since their sensitivity is low.

This problem can be solved by analyzing the optical isotope shifts of Gd isotopes. Since the charge radii of stable Gd isotopes such as ^{154}Gd have been accurately measured in experiments with mesic atoms, the unknown charge radius of ^{146}Gd can be calculated by determining the quantity

$$\Delta\langle r^2\rangle_{146,\,154} = \langle r^2\rangle(^{154}\text{Gd}) - \langle r^2\rangle(^{146}\text{Gd}) \qquad (1)$$

for the measured isotope shifts. We have carried out such a calculation.

To measure the isotope shifts, we used the method of resonant photoionization of atoms. This method, the experimental setup, and the measuring procedure are described elsewhere.[3,4] The isotope shifts were measured for the transition with a wavelength of 585.16 nm. The isotope shifts of the optical line under study, $\Delta\nu_{A,A'}$ can be represented for a pair of isotopes with mass numbers A and A' as a sum[5]:

$$\Delta \nu_{A,A'} = F\lambda_{A,A'} + M\frac{A'-A}{AA'},$$

where

$$\lambda_{AA'} = \Delta\langle r^2\rangle_{A,A'} + C_1\Delta\langle r^4\rangle_{A,A'} + C_2\Delta\langle r^6\rangle_{A,A'} + \ldots$$

and the constants C_k decrease rapidly with increasing k. In determining F and M for the optical transition we have used the data on the isotope shifts of x ray K lines[6] and s levels of mesic atoms,[7] as well as data on the isotope shifts of stable Gd isotopes in other optical lines.[8]

Figure 1 shows differential variation of the charge radii of Gd nuclei with $N \geqslant 82$. Also shown in this figure are the quantities $\Delta\langle r^2\rangle_{A,A=2}$, which were measured previously for the neighboring even-proton $_{62}$Sm nucleus (Ref. 5) and $_{66}$Dy nucleus (Ref. 9). The isotope dependence $\Delta\langle r^2\rangle$ for Gd nuclei by and large is similar to the corresponding dependences for Sm and Dy nuclei. In particular, a jump in $\Delta\langle r^2\rangle_{A,A=2}$ with $N = 88$–90, which is associated with an abrupt change in the deformation of the corresponding nuclei, is clearly discernible. A discontinuous change in the deformation near $N = 88$–90 is seen only for nuclei with Z close to $Z = 64$ (Refs. 6 and 9), which, according to the authors of Refs. 1, 9, and 10, is attributable to the magic nature of the number $Z = 64$. As can be seen in Fig. 1, the jump of $\Delta\langle r^2\rangle$ at $N = 88$–90 is maximum in comparison with the neighboring even-proton nuclei.

To determine the value of the charge radius of the ^{146}Gd magic nucleus, we used relation (1), where the value of $\langle r^2\rangle(^{154}\text{Gd})$ was taken from the results of the mesic-atom experiments[7]: $\langle r^2\rangle(^{154}\text{Gd}) = 26.239(42)$ fm^2 and the value $\Delta\langle r^2\rangle_{154,146} = -1.40(12)$ fm^2 was obtained by us. As a result, we found

$$\langle r^2\rangle(^{146}\text{Gd}) = 24.84(16)\ \text{fm}^2 \quad \text{and} \quad \langle r^2\rangle^{1/2}(^{146}\text{Gd}) = 4.984(16)\ \text{fm}.$$

The principal contribution to the error of the mean-square charge radius of ^{146}Gd

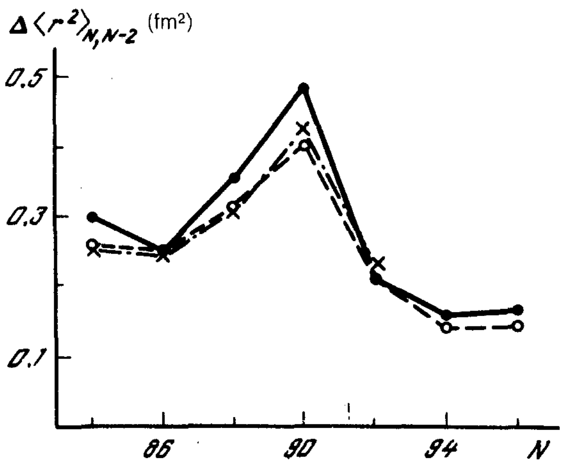

FIG. 1. Differential variation of the mean-square charge radii of $_{62}$Sm nucleus (crosses; Ref. 5), $_{64}$Gd nucleus (filled circles; our results), and $_{66}$Dy nucleus (open circles; Ref. 9).

magic nucleus comes from the error in $\Delta\langle r^2\rangle_{154,146}$, which in turn is almost completely determined by the errors of the constants F and M.

The charge radius of ^{146}Gd magic nucleus can be used in the search for parametrization of the effective forces. We have compared the experimental value obtained by us with the results of calculations based on the Hartree-Fock method, with various effective forces. The SkM′ (Ref. 11) and SG2 (Ref. 12) forces proved to be the best forces from the standpoint of the description of $\langle r^2\rangle$ (^{146}Gd) (4.992 fm and 4.980 fm, respectively) and the worst were the $S3$ force (Ref. 2) (5.045 fm) and the $S6$ force (Ref. 2) (5.060 fm). The agreement between theory and experiment obtained for the SkM′ forces is evidence in favor of the fact that these forces can legitimately be used for calculations in the region of unstable nuclei. The value of $\langle r^2\rangle$ (^{146}Gd) determined by us may prove to be very important for the further refinement of the parameters of the effective interaction, since this is the only presently known value of the mean-square charge radius of magic nuclei far from stability.

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