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THE EFFECT OF DEFORMATION AND THE NEUTRON SKIN ON RMS CHARGE RADII

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Abstract

Droplet Model predictions for nuclear RMS charge radii are compared with measured values in order to determine whether or not there is any evidence for volume shell effects. After corrections for deformation, diffuseness, and the central depression have been applied, some evidence for such effects remains, but it is at about the same level as the experimental uncertainty.

1. Introduction

In 1977, Angeli and Csatlos compiled all the data on nuclear RMS charge radii that were available at that time[1,2]. They presented these data in a particularly interesting way that seemed to show that there were substantial shell effects in the measured quantities. Similar general observations have been made by Fricke[3] and Sick[4]. Other authors have discussed the shell effects in radii for particular isotopic sequences[5].

Our analysis of these data shows that most (if not all) of the apparent shell effects are due to deformations rather than actual variations in the spatial extent of the nuclear charge distribution[6]. In order to establish this conjecture we have compared the measured nuclear RMS charge radii with Droplet Model predictions[7-9], after first making an approximate correction using calculated values for the nuclear deformation[10]. We have also compared the corrected RMS radii with liquid drop model predictions. Rather large systematic deviations remain in this case, because the model contains no provision for the influence of the neutron skin on the charge radius.

2. The Droplet Model

In the Droplet Model the effective sharp radius of the nuclear density distribution (neutrons plus protons) is given by the expression[8],

$$R = R_0(1 + \bar{\varepsilon}) \tag{1}$$

where

$$R_0 = r_0 A^{1/3} \quad , \tag{2}$$

$$\bar{\varepsilon} = (-2a_2 A^{-1/3} + L\bar{\delta}^2 + c_1 Z^2 A^{-4/3})/K \quad . \tag{3}$$

The expression for the effective sharp radius of the proton distribution is

$$R_z = R - \frac{N}{A} t \quad , \tag{4}$$

and for the neutron distribution it is

$$R_n = R + \frac{Z}{A} t \quad . \tag{5}$$

The neutron skin thickness t (R_n minus R_z) is given by

$$t = \frac{2}{3}(I - \bar{\delta})R \quad . \tag{6}$$

The quantity $I = (N - Z)/A$ is the global nuclear asymmetry, and $\bar{\delta}$ is the average value of the local asymmetry, $\delta = (\rho_n - \rho_z)/\rho$, over the central region of the nucleus[7]. The expression for $\bar{\delta}$ is

$$\bar{\delta} = [I + \frac{3}{16}(c_1/Q)ZA^{-2/3}]/[1 + \frac{9}{4}(J/Q)A^{-1/3}] \quad . \tag{7}$$

In all of these expressions, we have used the following values for the Droplet Model coefficients[8]:

$$\begin{aligned} r_0 &= 1.18 \text{ fm} \quad , \\ a_2 &= 20.69 \text{ MeV} \quad , \\ c_1 &= 0.73219 \quad , \\ J &= 36.8 \quad , \\ Q &= 17 \quad , \\ K &= 240 \quad , \\ L &= 100 \quad . \end{aligned} \tag{8}$$

3. Geometrical Considerations

Once the effective sharp radius of the charge distribution is known, the RMS radius can be calculated from the expression:

$$\langle r^2 \rangle = \langle r^2 \rangle_s + 3b^2 + \Delta \quad , \tag{9}$$

where $\langle r^2 \rangle_s$ for a proton distribution having a sharp surface and uniform central density depends upon deformation according to the expression,

$$\langle r^2 \rangle_s = \frac{3}{5}R_z^2 \left(1 + \alpha_2^2 + \frac{5}{9}\alpha_4^2\right) \quad . \tag{10}$$

We have calculated the deformation parameters α_2, α_4 using the expressions,

$$\begin{aligned} \alpha_2 &= \frac{5}{6} Q_2/[Z\cdot(1.16A^{1/3} \text{ fm})^2] \quad , \\ \alpha_4 &= \frac{3}{2} Q_4/[Z\cdot(1.16A^{1/3} \text{ fm})^4] \quad , \end{aligned} \tag{11}$$

and the tabulated values of the multipole moments Q_2, Q_4 from ref. [10]. The second term in eq. (9) is the correction for diffuseness based on the idea that any sharp distribution may be made diffuse by convolution[11]. The coefficient b has the approximate value,

$$b = 1 \text{ fm} \quad . \tag{12}$$

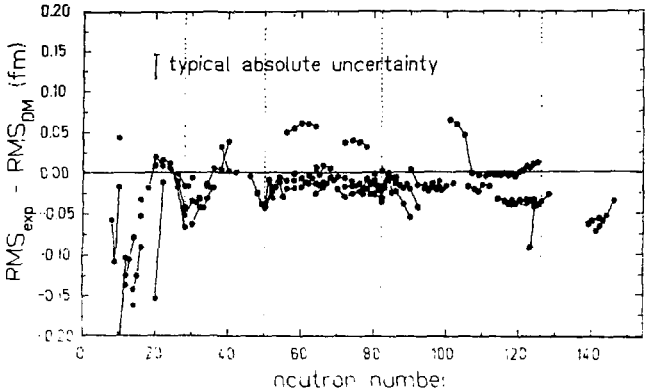

Fig. 1 The difference between measured RMS radii and the Droplet Model predictions of eq. (9).

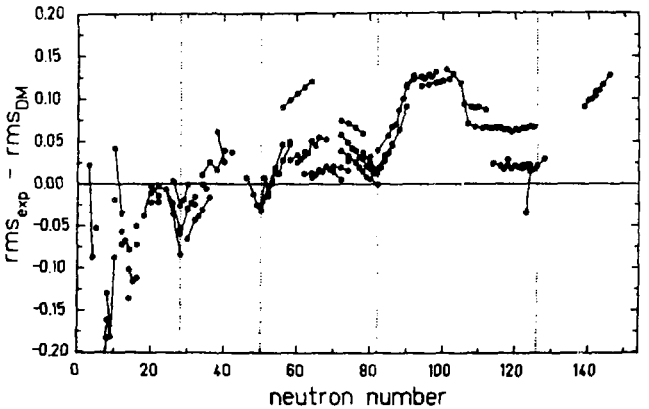

Fig. 2 The same as Fig. 1 but without the corrections for deformation and redistribution.

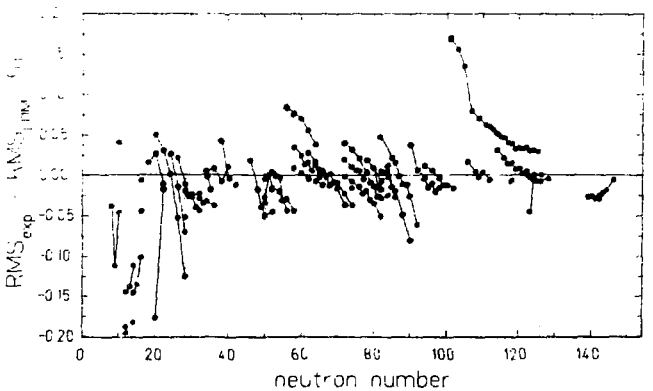

Fig. 3 The same as Fig. 1 but using the liquid drop model expression of eq. (15) instead of the Droplet Model.

The third term in eq. (9) is added to account for the contribution to $\langle r^2 \rangle$ of the central depression in the proton distribution due to Coulomb repulsion (and the consequent increase in charge at the surface). This term, which is an integral part of the Droplet Model description of nuclear density distributions, is not usually included when the liquid drop model is used. Its value may be obtained from the expression[9],

$$\Delta = \frac{6}{175}\left(\frac{9}{2K} + \frac{1}{4J}\right) Ze^2 R_z \quad , \qquad (13)$$

where J and K are given in (8) and $e^2 = 1.44$ MeV fm.

4. Comparison with Experiment

In fig. 1 we have plotted the difference between the measured RMS radii from ref. [2] and the predictions of eq. (9). Most of the plotted points lie near, but slightly below, the zero line, suggesting that the Droplet Model nuclear radius constant r_0 should probably be reduced by about one-half percent. At this stage it isn't possible to determine whether the remaining structure is evidence for shell effects or merely due to the approximate nature of the calculated deformation corrections.

In fig. 2 the same comparison is made, but without the corrections for deformation or for the central depression. The larger mid-shell RMS radius values associated with deformations can be clearly seen. The general upward slope of the points toward heavier nuclei is expected because of the charge redistribution associated with the Coulomb repulsion that creates the central depression.

Figure 3 is a comparison of measured and calculated RMS radii similar to fig. 1, except that the liquid drop model has been used instead of the Droplet Model. The actual expression employed was

$$RMS_{LD} = \sqrt{\frac{3}{5}}\, Q_z \sqrt{(1 + \alpha_2^2 + \frac{5}{9}\alpha_4^2)} \qquad (14)$$

where

$$Q_z = (1.15 + 1.80A^{-2/3} - 1.20A^{-4/3})A^{1/3} \text{fm} \quad , (15)$$

corresponding to a nuclear radius constant r_0 = 1.15 fm, a diffuseness b = 0.98 fm, and no central depression[1]. In almost every isotopic sequence the differences plotted slope steeply downward to the right because the effect of the neutron skin thickness is not included in the liquid drop model.

5. Conclusion

The three figures above serve to illustrate the importance of deformations and the neutron skin in the calculation of RMS charge radii. Meticulous care will have to be taken to assess the accuracy of the measured values and the values of the deformations that are used in the calculations before it will be possible to determine whether or not there are volume shell effects. At present, most of remaining differences lie within the experimental uncertainty.

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