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**ANALYSIS OF COULOMB DISPLACEMENT ENERGIES AND
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NUCLEI**

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Analysis of Coulomb displacement energies and its relation to the proton halo structure of nuclei

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Abstract: We investigate the Coulomb displacement energies of the nuclear systems ^{16}O core plus several nucleons. This analysis is performed in order to search for peculiarities of the nucleus ^{20}Mg which was experimentally found to be a candidate for the occurrence of a proton halo. The structure of ^{20}Mg is discussed on the basis of this analysis. Some evidence is presented that proton correlations play an important role in the structure of this nucleus.

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Experimental investigations of high-energy interaction cross-sections [1, 2] have indicated that ^{17}Ne and ^{20}Mg have larger radii than their neighbours in the corresponding isobaric sequences and may thus possess a proton halo. In these studies, the effective root-mean-square radii of the nucleon density distribution were deduced by using Glauber model calculations for the analysis of interaction cross-sections obtained from transmission measurements with relativistic ^{17}Ne and ^{20}Mg beams [1, 2], respectively. In this short note, we investigate the Coulomb displacement energies, and discuss the relation of this analysis to the proposed occurrence of a proton halo.

Coulomb energy differences between members of isospin multiplets (ΔE_c) have extensively been used to estimate nuclear radii as well as to determine the radial extent of the neutron excess in nuclei whose charge radii are known (see e.g. [3]). In this context the halo phenomenon was explicitly mentioned.

In resuming this discussion, we note that the binding energy of two protons in ^{17}Ne (0.96 MeV) is larger than the proton binding energy of ^{17}F (0.60 MeV) whose radius was found to be smaller than that of ^{17}Ne [1]. Since a comparison of the Coulomb interaction in ^{17}F and ^{17}Ne also gives no hint for the occurrence of a proton halo in the latter nucleus, it was suggested [1] that a lower centrifugal barrier is responsible for a halo formation and the large radius in ^{17}Ne . The ground state configuration of ^{17}F ($T=1/2$), with a spin parity assignment of $J^\pi = 5/2^+$, is interpreted as being due to the last proton in the $1d_{5/2}$ orbital [4]. The centrifugal barrier for $L=2$ suppresses significantly the tail of the proton density distribution. These arguments suggest that a proton halo of ^{17}Ne can only be explained by demanding the last two protons in this nucleus to be abnormally in a $2s_{1/2}$ orbital around a ^{15}O core ($J^\pi = 1/2^-$).

In order to check whether the same effect is responsible for the large radius of ^{20}Mg , we inspect the Coulomb displacement energies (Table 1) by using atomic masses and excited-level energies of the systems under consideration from refs. [4, 5]. We assume that the five members of the $T=2$ isospin multiplet from ^{20}O to ^{20}Mg have the same structure or, in other words, that the only

charge-dependent force is the Coulomb force. The lowest two states in the $A=17$, $T=1/2$ isospin multiplet are $5/2^+$ (d orbital) and $1/2^+$ (s orbital). These levels lie close to each other and are well separated from neighboring states. The ΔE_c value for the $2s$ orbital is lower by 375 keV than that of the d state, as can be seen from Table 1. This reflects the fact that the proton in the d orbital is effectively closer to the core, which allows one to estimate the orbital momentum value directly from ΔE_c .

The ΔE_c value for $^{18}F - ^{18}O$ ($T=1$) is 60 keV less than that for the d state in $^{17}F - ^{17}O$ ($T=1/2$), which indicates that there is a significant $2s$ shell admixture. The anomalous behavior of the $A=18$ triplet is well known (see e.g. ref. [6]), and this triplet has therefore been excluded from a shell model analysis of Coulomb displacement energies [6, 8]. The admixture of different shells is one of the possible explanations of this anomaly [6].

The ΔE_c values for $^{19}F - ^{19}O$ ($T=3/2$) and for $^{20}F - ^{20}O$ ($T=2$) are also approximately 50 keV lower than that for the d state in $^{17}F - ^{17}O$ ($T=1/2$), this effect being probably also connected with an admixture of the $2s$ state. However, in all these cases ΔE_c decreases by only 1.5%. These changes are much smaller than the difference observed between the radii of ^{20}O and ^{20}Mg .

Table 1: Coulomb displacement energies, ΔE_c (keV), for the pairs $^{17}F - ^{17}O$ ($T=1/2$), $^{18}F - ^{18}O$ ($T=1$), $^{19}F - ^{19}O$ ($T=3/2$), and $^{20}F - ^{20}O$ ($T=2$).

$T; J^\pi$	Nuclei	ΔE_c
$1/2; 5/2^+$ d-state	$^{17}F - ^{17}O$	3543(1)
$1/2; 1/2^+$ s-state	$^{17}F - ^{17}O$	3168(1)
$1; 0^+$	$^{18}F - ^{18}O$	3480(1)
$3/2; 5/2^+$	$^{19}F - ^{19}O$	3503(3)
$2; 0^+$	$^{20}F - ^{20}O$	3487(3)

This is surprising since one would expect the radii of the two mirror nuclei ^{20}Mg and ^{20}O to reflect the behavior of ΔE_c of members of the isospin multiplet $T=2$ (see Fig.1).

In the model of uniformly charged spheres an increase of the radius implies a decrease in the average two-body Coulomb interaction. This statement is valid for most of the stable light nuclei, as it was shown, for example, in ref.[7]. Results of calculations performed with a semiclassical uniform charge sphere model [7] are displayed in Fig.1 (dotted line). The behavior of $\Delta E_c/Z_<$ ($Z_<$ is the lower of the two charges of an isobaric pair) seems to contradict the fact that the radius of ^{20}Mg has been observed to be larger than that of ^{20}O . However, as mentioned in ref.[8], the uniform charge sphere model might be insufficient in the present case of a nucleus with few nucleons above closed shell. Therefore we consider a model in which N_p valence protons are in an orbital of constant rms radius R , with the rms radius $\langle r_c^2 \rangle^{1/2}$ of the core being constant. Under these assumptions the Coulomb two-body matrix elements are independent on N_p as long as correlations between valence protons are negligible. This conclusion is valid in spite of the fact that the charge radius increases with the number of valence protons. Correspondingly, the difference ΔE_c obtained between the core and a nucleus with N_p valence protons takes the form:

$$\Delta E_c = \frac{N_p \cdot Z_c e^2}{R} + \sum_{i \neq j}^{N_p} \frac{e^2}{r_{ij}} \quad (1)$$

where Z_c is the charge of the core nucleus and r_{ij} the distance between the members of a pair of protons. We replace further $\frac{1}{r_{ij}}$ by the characteristic average distance between the members of a pair of valence protons $\langle \frac{1}{r_{pp}} \rangle$. The first part of the expression contains the interaction of the valence protons with the core nucleus, the second term accounts for the interaction between valence protons ΔE_c^{pp} . We note that the value of $R = 3.3 \text{ fm}$, estimated from the Coulomb difference between ^{20}O and ^{20}F , corresponds to the position of the dominant peak in the zero range form-factor for two-nucleon transfer to

^{16}O [9]. Without correlations between protons, i.e. $\langle \frac{1}{r_{pp}} \rangle = \frac{1}{R}$, the reduced Coulomb energy shift $\Delta E_c/Z_\zeta$ remains constant for all members of an isospin multiplet. However, this model assumption fails to describe the experimental $\Delta E_c/Z_\zeta$ values, as can be seen from Fig. 1 (dashed line).

Figure 1: Dependence of the reduced Coulomb displacement energies $\Delta E_c/Z_\zeta$ on the Z_ζ . The experimental data are shown by circles with the uncertainties. The dotted line corresponds to results obtained from a uniform charge sphere model calculation. The solid and the dashed lines indicate results of independent particle model calculations performed with and without valence proton correlations, respectively.

In order to take proton correlations into account we increased $\langle \frac{1}{r_{pp}} \rangle$ by 13 %. This approach yields a lower limit for the strength of valence proton correlations due to the fact that the proton wave function must be antisymmetrized (which leads to a decrease of ΔE_c^{pp}). This calculation is in good agreement with the experimental data (see Fig. 1, solid line).

Within the independent-particle model, which assumes nucleons orbiting around an inert core nucleus, one may introduce, in analogy to the pairing energy, a proton quartet energy ϵ_{4p} . This quantity can be derived from binding energies as:

$$\epsilon_{4p} = B(Z + 4) - B(Z) - 4(B(Z + 1) - B(Z)) \quad (2)$$

For the ^{20}Mg case ϵ_{4p} amounts to ≈ 4.5 MeV. This value is larger than the largest value known for the proton pairing energy which is another indication for the importance of proton correlations.

We have the following expression for the rms matter radius of ^{20}Mg in our model:

$$\langle r_{matter}^2 \rangle = \frac{A_c}{A_c + N_p} \langle r_c^2 \rangle + \frac{N_p}{A_c + N_p} R^2 \quad (3)$$

In this case the positions of the center of mass (cm) coordinates for the core nucleons (A_c) and the four valence protons are the same. For the ^{20}Mg radius obtained is still less than experimentally observed [2], one needs to assume a shift of the cm coordinate of the core relative to that of the valence protons on the level of ≈ 1 fm to explain the experimental data.

The results of our considerations can be summarized as follows:

- The comparison of Coulomb displacement energies for the members of the T=2 multiplet with those of the T=1/2 nuclei in $2s_{1/2}$ and $1d_{5/2}$ states does not show any significant influence of the possible admixture of a $2s$ state in the T=2 multiplet. This effect alone can thus not explain the large radius of ^{20}Mg .

- The uniform charge sphere model demands a decrease of the nuclear radii with increasing Z for the members of the $T=2$ multiplet. This is in contradiction with the experimental data.
- The independent-particle model with protons moving on a well defined orbit around an inert core yields agreement with the ΔE_c versus Z dependence observed experimentally if a strong correlation between the valence protons is included in the calculations.
- Evidence for valence proton correlations is found also from considering the proton quartet energy. Roughly speaking, a tetra-proton cluster is bound in the core field by 4.5 MeV.
- The large radius of ^{20}Mg can be explained only when the valence proton correlations are taken into account.

All these points lead us to the conclusion that ^{20}Mg has a very specific structure characterized by a ^{16}O core and a tetra-proton cluster. It is evidently not the admixture of low orbital momentum states, but the correlations between the valence protons, arising from their mutual interaction, which determine the existence of a proton halo. This halo is not a uniform proton distribution around the core nucleus, but a specific structure due to strong correlations between the valence protons.

On the basis of this interpretation, one may expect – in terms of mean field models – a much larger deformation for the charge distribution of ^{20}Mg than that of the corresponding neutron distribution. It is interesting to note, that the ΔE_c^{pp} value of ^{18}Ne (708 keV) is abnormally large, which reflects the surface clusterisation of two nucleons outside a closed shell. Calculations [10], which are based on this assumption and demand additionally a strong $2s$ shell admixture, show that the two valence protons create a very compact cluster with an average distance of 2.5 fm between the protons. ^{18}Ne might thus be a good candidate for a proton halo nucleus as well.

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