Eur. Phys. J. A **5**, 371–372 (1999)

THE EUROPEAN PHYSICAL JOURNAL A

No Tetra-proton cluster in ^{20}Mg

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Received: 14 May 1999
Communicated by B. Povh

Abstract. Despite a recent suggestion of Chulkov, et al., we find no evidence for a tetra-proton cluster in ^{20}Mg. The binding energy and radius are easily understood without such a cluster.

PACS. 21.10.Dr Binding energies and masses – 21.10.Sf Coulomb energies – 21.60.Gx Cluster models

1 Introduction

Based upon the measured interaction cross sections [4], the matter radius of ^{20}Mg is slightly larger than that of ^{20}O. Chulkov, Roeckl, and Kraus [1] computed Coulomb energies in a simple model and concluded "The large radius of ^{20}Mg can be explained only when valence proton correlations are taken into account", and "^{20}Mg has a very special structure characterized by an ^{16}O core and a tetra-proton cluster." If true, this claim would be extremely significant. The phenomenon of two-nucleon clustering is well known. Most of the evidence is for clustering of isospin T=1 nucleon pairs, but to a lesser extent (and in light nuclei) some clustering of T=0 pairs is observed. And, of course, evidence abounds in light nuclei for alpha clustering, i.e. a T=0 tetra-nucleon cluster. There is virtually no information concerning tetra-nucleon clusters with T=1 or 2. Hence, we have chosen to investigate the claims of Chulkov, et al.

Actually, two questions are involved:

1. Does ^{20}Mg exhibit evidence of a tetra-proton cluster that is not present in ^{20}O as a tetra-neutron cluster?
2. Do the A=20, T=2 nuclei exhibit evidence of a T=2 tetra-nucleon cluster?

With an ^{16}O core, the T=1, 0^+ ground states of ^{18}O, ^{18}F, and ^{18}Ne do exhibit some two-nucleon clustering [2]. The Coulomb energies of these nuclei can be understood [3] only by careful consideration of the relevant configuration mixing in these nuclei. It is possible that pairing correlation of two neutrons coupled to the ^{18}O ground state (which already contains some two-nucleon clustering), could masquerade as four-neutron clustering. We investigate whether Coulomb energies and matter radii in the A=20 quintet can be understood in terms of independent nucleons and pairing only.

2 Coulomb shifts

The simplest computation is to couple a $1d_{5/2}$ nucleon to a $5/2^+$ A=19, T=3/2 core - e.g. ^{20}O=^{19}O $\otimes$ n, ^{20}F=0.25 [^{19}O $\otimes$ p] + 0.75 [^{19}F (T=3/2) $\otimes$ n)], etc. These results are listed in Table 1. For these calculations, we used a Woods-Saxon potential with r_0=1.25 fm, a=0.65 fm, and a well depth chosen to give correct binding for ^{20}O=^{19}O $\otimes$ n. For the other nuclei, the Coulomb potential of a uniformly charged sphere was included. The differences (calculated minus experimental) are only 41, 59, 39, and -21 KeV respectively - quite small considering the simplicity of the model. For the $T_z=\pm 2$ nuclei of primary interest here, the simple model correctly accounts for the ^{20}Mg - ^{20}O Coulomb energy difference of 16905 keV to within 21 keV. A very small change in radius or diffusivity completely removes the discrepancy.

To compare, the Coulomb difference for the ^{18}Ne-^{18}O pair is missed by more in this simple model. Inclusion of configuration mixing gives a much better result for A=18, but still misses by -44 KeV. Uncertainty in the experimental ^{20}Mg mass is 27 KeV, and in ^{19}Na is 13 KeV. Coulomb shifts computed for ^{19}Na starting with ^{19}O, miss ^{19}Na by + 20 keV. We miss ^{20}Mg by -21 keV which is within the experimental uncertainties in the masses. The calculated minus the experimental value for the difference in

Table 1. Excitation Energies (keV) of lowest 0^+, T=2 states for A=20

	^{20}O	^{20}F	^{20}Ne	^{20}Na	^{20}Mg
Calc.	0	6560	16792	6573	-21
Exp.	0	6519(3)	16733(3)	6534(13)	0(27)
Calc.-exp.	0	41	59	39	$-21(27)$

Table 2. Calculated Matter Radii (fm) in ^{20}O and ^{20}Mg

		^{20}O	^{20}Mg	Difference
Present		2.770	2.811	0.041
Brown & Hansen		2.80	2.85	0.05
Kitagawa	Sph	2.784	2.818	0.034
	Def	2.805		
Descouvemont	V2	2.83	2.87	0.04
	MN	2.78	2.80	0.02
SKX		2.778	2.823	0.045
Exp (ref 4)		2.64±0.03	2.86±0.06	0.22

the masses of ^{20}O=^{18}O + n + n and ^{20}Mg=^{18}Ne + p + p is -1 ± 27 keV. This result is consistent with little two-nucleon correlations for ^{18}O + 2n and ^{18}Ne + 2p, and hence consistent with only two-nucleon clustering in ^{20}O and ^{20}Mg.

3 Matter Radii

Interaction cross sections for T=2, A=20 nuclei were measured by Chulkov, et al. [4], and converted to matter radii by them and by others. Their later conclusions [1] about tetra-proton clustering makes use of these radii. We and others have computed radii for nuclei just above ^{16}O in a model that takes account of neutron and proton parentage of the states.

Our matter radii for ^{20}O and ^{20}Mg, computed with the model of Sherr [5], turn out to be 2.77 fm and 2.81 fm respectively, compared to "experimental" values [4] of 2.64 $\pm$ 0.03 and 2.86 $\pm$ 0.06. It is to be expected the proton rich mirror will have a slightly larger matter radius than its neutron-rich parent. Several others have computed these radii, in a variety of different models, including Brown and Hansen [6], Kitagawa [7] and Descouvemont [8]. They are summarized in Table 2. We have updated the Hartree-Fock Calculation of Brown and Hansen by considering the results obtained from the SKX Skyrme-type interaction [9]. The SKX interaction considered the displacement energy for the mirror pair ^{48}Ni-^{48}Ca where it was found that it was preferable to leave out the Coulomb exchange interaction in order to obtain agreement with the empirical value. The results for the A=20 displacement energy are 16.98 MeV with SKX (without the Coulomb exchange term) and 15.42 MeV with SKXce (with the Coulomb exchange term). Compared to the experimental value of 16.90 MeV the deviations are 0.5% with SKX and 8% with SKXce, again showing the practical importance of removing the exchange term. We note that the present Woods-Saxon calculations for the displacement energy also do not include the Coulomb exchange. (It has recently been shown that the introduction of a charge-symmetry breaking interaction in the Hartree-Fock hamiltonian can also reproduce the experimental displacement energies [10]). The matter radii obtained with SKX are 2.778 fm for ^{20}O and 2.823 fm for ^{20}Mg, in agreement with the present results.

We conclude that there is nothing anomalous about the radius of ^{20}Mg. All the calculations reproduce it reasonably well. However, the so-called ^{20}O experimental radius is far too small. All models give 0.02 - 0.04 fm for the ^{20}Mg - ^{20}O radius difference, not 0.22 fm as claimed experimentally [1]. We suspect that the measured cross section and hence the interaction radius derived from it for ^{20}O is in error.

This expectation is supported by the calculations of Kitagawa [7], who uses the SGII force of Giai and Sagawa [11] and a Glauber scattering model to compute interaction cross sections. His result of 1145 mb for ^{20}Mg is fairly close to the measured value of 1150 $\pm$ 10 mb. However, he computes 1129 mb for ^{20}O, very much larger than the measure value of 1078 $\pm$ 10 mb.

In conclusion, we find nothing unusual about the energy or matter radius of ^{20}Mg. We find no need for a tetra-proton cluster. We suggest the measured interaction cross section for ^{20}O is too small. It should be re-measured.

Support for this work was provided from US National Science Foundation grant number PHY-9605207.

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