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MAGNETIC NUCLEAR FORCES, AN ISING NUCLEAR MODEL, AND ASYMMETRIC FISSION

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An extensive study of hadron resonances^{1,2} has led to a geometry for nucleons, Figure 1, which is radically different from the geometry usually attributed to these particles. This nucleon geometry in turn leads to a geometry for the atomic nucleus which is radically different from our usual notions about atomic structure. Conventionally, the nucleon is pictured as a more-or-less spherical object, and the atomic nucleus is pictured as a collection of these spherical nucleons bound together in an effectively central potential, so that the nucleus is also more-or-less spherically symmetric. Even when the nucleus is described in terms of α -particle clusters, as in the model of Linus Pauling³, the α clusters are assumed to be spherical, and they are packed together in a spherical fashion³. However, the nucleons shown in Figure 1 are not spherical: they are cylindrical. And they bind together, as shown for example in Figure 2, in a planar manner. Hence, from the present results, we logically expect collections of nucleons to form two-dimensional nuclear layers, with each layer being two fermis thick - the height of the nucleons shown in Figure 1. Since nucleons, as we will show, seem to be bound together magnetically, these two-dimensional nuclear layers are directly analogous to the two-dimensional Ising layers that occur in magnetic materials. Thus we finally arrive at an Ising model for the atomic nucleus.

The present short report is written to sketch the manner in which the transition is made from hadron structure to nuclear structure, and not to go into

the details of this Ising model for the nucleus. To illustrate the connection between hadron phenomenology and the phenomenology of atomic nuclei, we briefly discuss two aspects of nuclear structure - nuclear forces, and the α particle. We also give one application of this nuclear Ising model by showing how it accounts in a simple and natural manner for one of the major unsolved puzzles in nuclear physics, namely the problem of asymmetric fission.

I. The nature of the nuclear force.

In reconstructing the metastable hadron resonances, we were led^{1,2} to the use of three types of binding energy - hadronic ($\sim 4\%$), magnetic ($\sim 1\%$), and coulomb ($\sim 1\%$) (see Table VII in Ref. 2). The strong hadronic binding energy, which operates between particle-antiparticle pairs, as for example in Figure 2, does not seem to operate between particle-particle pairs. Thus if we seek to apply the present formalism for hadronic binding energies also to collections of nucleons in an atomic nucleus, we are left only with magnetic and coulomb interactions. Furthermore, since coulomb forces in an atomic nucleus are repulsive, magnetic interactions must necessarily supply the attractive component of the nuclear force.

There are several systematic results which suggest that the attractive component of the nuclear force is in fact magnetic:

(1) From the observed nucleon magnetic moments, we have

$$\begin{aligned} p &= +2.8 \text{ nuclear magnetons} \rightarrow p \equiv \uparrow_s^n, \\ n &= -1.9 \text{ nuclear magnetons} \rightarrow n \equiv \uparrow_n^s, \end{aligned} \tag{1}$$

where we now picture the nucleons, for binding energy purposes, as small cylindrical bar magnets.

(2) If nucleons cluster side-by-side, as in Figure 2, then pairing interactions in atomic nuclei will be via the spin 0 pairs

$$p \uparrow p \uparrow \equiv \uparrow_s^n \downarrow_n^s \quad \text{and} \quad n \uparrow n \uparrow \equiv \uparrow_n^s \downarrow_s^n, \tag{2}$$

as observed experimentally; this pairing characteristic of protons and neutrons is in fact one of the dominant aspects of atomic nuclei. The bound state of the deuteron is the spin 1 pair

$$d \equiv p \uparrow n \uparrow \equiv \begin{matrix} n & s \\ \uparrow & \uparrow \\ s & n \end{matrix} . \quad (3)$$

(3) Side-by-side nucleon clustering is also suggested by the fact that the magnetic moments of light nuclei are obtained as the sums of the constituent nucleon magnetic moments.

(4) Hadronic forces are EXTRAORDINARY in the sense that hadronic bonds cannot be broken kinematically (the composite proton is stable even at cosmic ray energies). Electromagnetic forces and nuclear forces, on the other hand, are both ORDINARY in the sense that the binding is broken if the binding energy is exceeded. This suggests that nuclear forces are electromagnetic rather than hadronic.

(5) The magnetic and coulomb binding energies described in Table I of reference 2 are not sufficient to give a quantitative theory of nuclear forces⁴, but they do lead to a solution of the most critical problem of nuclear forces, namely to account for the binding energy of the α particle. What is equally important, they also lead to an indication of the manner in which α particles (and other light-element clusters) bind together magnetically to form atomic nuclei.

II. The α particle.

Quantitatively, the crucial problem of nuclear forces is to account for the large binding energy of the α particle. We can construct the α particle, in analogy with Figure 2, as the spinor cluster

$$\alpha \equiv \begin{matrix} p \\ n & n \\ p \end{matrix} \equiv \begin{matrix} & S-S-S \\ & S-S \\ S & S-S \\ & S-S-S \end{matrix} , \quad (4)$$

where $S-S$ denotes an intranucleon hadronic bond between spinor pairs SS .

If we assume the charge and spin assignments

$$\alpha \equiv \begin{array}{ccccccc} & S^+ & & S^- & & S^+ & \\ & \uparrow & & \downarrow & & \uparrow & \\ S^+ & & S^+ & & S^+ & & S^+ \\ \uparrow & & \downarrow & & \downarrow & & \uparrow \\ & S^+ & & S^+ & & S^+ & \\ & \uparrow & & \downarrow & & \uparrow & \\ & S^+ & & S^+ & & S^+ & \\ & \downarrow & & \uparrow & & \downarrow & \\ & S^+ & & S^+ & & S^+ & \\ & \downarrow & & \uparrow & & \downarrow & \end{array}, \quad (5)$$

then the calculated magnetic binding energy for the α is -23.8 MeV (using a magnetic binding energy of ± 1.7 MeV per adjacent singly-charged spinor pair, as obtained from rule (8) of Table I in Ref. 2), and the calculated coulomb energy is +0.8 MeV (using the coulomb energies of Table I in Ref. 2). Thus the net binding energy calculated in Eq. (5) for the α particle is -23 MeV, as compared to the experimental value of -28 MeV. If we increase the spinor pair magnetic binding energy from ± 1.7 MeV per singly-charged pair to ± 2.1 MeV per pair, a step for which there is some phenomenological justification⁴, then the binding energy of the α particle is given correctly.

To see how two α particles bind together in an atomic nucleus, we can write down a North pole and South pole magnetic diagram corresponding to Eqs. (4) and (5). Viewing the α particle from above, we have

$$\alpha \equiv \begin{array}{ccccc} N & N & N & & \\ & S & S & S & \\ & N & N & N & \cdot \\ & S & S & S & \end{array} \quad (6)$$

Thus the magnetic poles line up in a layered fashion. Hence attractive α - α binding energies can be obtained by placing α particles side by side, or end to end, or stacked one on top of the other. The triton T appears as⁴

$$T \equiv \begin{array}{c} p \\ n \quad n \end{array} \equiv \begin{array}{ccccc} & S & - & \bar{S} & - & S \\ & S & - & \bar{S} & & S \\ & S & / & \bar{S} & - & S \end{array} \equiv \begin{array}{ccccc} N & N & N & & \\ S & S & S & & \\ N & N & N & & \end{array}, \quad (7)$$

so that α particles and tritons can combine together magnetically to form Ising cluster layers in a nucleus. From this viewpoint, it is of interest to note that high energy pion bombardment on atomic nuclei results in the ejection of apparently real α particles and tritons from these nuclei⁵.

The α particle that is described in Eqs. (4) - (6) is not spherical; it is a hexagonally-close-packed "brick", with a height of 2 fermis and a length and width 3.6 fermis by 4.8 fermis (as determined from the dimensions of the nucleons shown in Figure 1). Thus the α particle has an electric quadrupole moment, in spite of the fact that it is an even-even nucleus. However, since its net magnetic field (at a distance) is zero, it does not couple vectorially to atomic electrons in the helium atom, and hence there is no practical way that this electric quadrupole moment can be observed. We note in a similar situation that the deformed even-even nucleus U^{238} also has an electric quadrupole moment⁶.

III. Asymmetric fission in ${}_{92}U^{238}$.

Asymmetric fission is a process that has been difficult to account for from the viewpoint of the liquid drop model of the nucleus. However, it emerges naturally from the viewpoint of nuclear Ising layers, as is demonstrated by the following line of reasoning.

(1). Assume that atomic nuclei are composed of magnetically-bound Ising layers, with each layer being 2 fermis thick.

(2). In large nuclei, coulomb forces create a strong repulsive potential ($V_c \sim +300$ MeV) between the centermost Ising layers. The limit of nuclear stability against fission is reached when the magnetic attraction between Ising layers just counterbalances the coulomb repulsion.

(3). In ${}_{92}U^{238}$, the net nuclear binding energy is about -1800 MeV, and the coulomb repulsion energy (assuming a uniform charge distribution) is about +900 MeV, so that the attractive magnetic binding energy is -2700 MeV. Of this magnetic binding energy, -1300 MeV can be attributed to intra- α and intra-He⁶ binding energies ($He^6 = T + T$), and perhaps another -400 MeV to α - α and α -He⁶ binding energies within Ising layers. Thus about -1000 MeV of magnetic binding occurs at the Ising layer interfaces. If U^{238} has eight Ising interfaces (see (5) below), then the two centermost interfaces, where the collective magnetic

field is the strongest, will each have roughly -300 MeV of magnetic binding energy, and it can be seen that the U^{238} nucleus is right at the limit of stability against fission. This has the consequence that (low energy) neutron bombardment will result in scission right at a central Ising interface.

(4). If a fissioning nucleus has an even number of Ising layers, then scission will be into two equal parts, and if a fissioning nucleus has an odd number of Ising layers, scission will be into two unequal parts. However, if the bombarding energy is large enough to shatter an Ising layer (roughly 5 - 10 MeV), then scission will occur more-or-less symmetrically.

(5). The shape of the ${}_{92}U^{238}$ nucleus is known to be prolate⁶, with a total length of 18 fermis and a diameter at the waist of 14 fermis. If this nucleus is divided into two-fermi-thick Ising layers, it will contain nine layers. If these layers are close-packed with nucleons, then from volume arguments the nucleon occupation numbers for the nine layers are approximately

$$8, 24, 30, 36, 42, 36, 30, 24, 8 . \quad (8)$$

Low-energy fission will occur at a central interface, and it will divide the U^{238} nucleus into two unequal parts, one containing 98 nucleons and the other containing 140 nucleons. Experimentally⁷, these are in fact the most probable mass numbers for the fission fragments from the low-energy or spontaneous fission of U^{238} . High energy bombardment results in symmetric fission.

(6). After a U^{238} nucleus has divided into two parts, each of the two final fission fragments has about the same magnetic binding energy per nucleon (-11.5 MeV) as did the original U^{238} nucleus, but the fission fragments have smaller repulsive coulomb potentials (roughly +300 MeV each as against +900 MeV for U^{238}). Thus the net binding energy per nucleon is larger in the fission fragments than in the U^{238} nucleus. This surplus energy appears mainly as kinetic energy of the two fission fragments. The range of the magnetic attraction at a central Ising

interface (from the collective nature of the attraction) is roughly 5 fermis, so that when the two fission fragments have moved 10 fermis apart, the magnetic attraction has fallen to zero. At this distance, which is a center-to-center fragment separation of 19 fermis, the coulomb potential is +160 MeV, which is about equal to the observed kinetic energy of the two fission fragments.

IV. Suggestions for Ising cluster systematics.

As viewed in the present framework, the atomic nucleus appears to consist of magnetically-bound layers, with each layer formed from α particles, tritons, He^3 nuclei, and other light particles. Thus this Ising model is in essence a "laminar cluster model" of the nucleus. In contrast to the single-particle picture of the nucleus, in which internal orbital rotations are ascribed to an unmatched nucleon, internal orbital rotations in the Ising model seem to involve an entire Ising layer.

The light nuclei D, T, He^3 , He^4 , He^6 , and Li^6 are accurately reproduced (spins, parities, and magnetic moments) as S-state Ising cluster configurations. In rotational modes, if the cluster configurations $\alpha+n$, $\alpha+p$, $\alpha+T$, $\alpha+\text{He}^3$ are formed in $J^\pi = 3/2^-$ rotational states, these configurations accurately reproduce the He^5 , Li^5 , Li^7 , and Be^7 ground states. The four cluster configurations ($\alpha + n$ or p or T or He^3) appear to be basic Ising layer configurations in the sense that we can now form nuclear quartets as the series expansion

$$\text{odd-A nuclei} = K\alpha + (\alpha + n \text{ or } p \text{ or } T \text{ or } \text{He}^3), \quad (9)$$

with K running from 1 to 9, and accurately pair off the ground states spins and parities for these quartets (the parities change sign at the magic numbers). Thus one of the successes of this Ising model, just as for the nuclear shell model, lies in the correlation of ground-state spins and parities in odd-A nuclei. The systematics of Eq. (9) gives a hint as to the manner in which α particle symmetries in an atomic nucleus are related to the magic numbers (note the fact that the symmetry of the magic numbers with respect to Z and N, the proton and

neutron occupation numbers, indicates a basic nuclear building block the α particle, that is also symmetric in Z and N).

One of the most direct ways to obtain information about individual Ising layers in heavy nuclei is to study asymmetric fission in detail, since the nucleon difference between the large and small fragments in asymmetric fission is just the nucleon content of the central Ising layer of the fissioning nucleus.

References.

- (1). M. H. Mac Gregor, Physical Review D9, 1259 (1974).
- (2). M. H. Mac Gregor, Physical Review D (in press).
- (3). L. Pauling, Phys. Rev. Lett. 15, 499 (1965); Science 150, 297 (1965).
- (4). From the arguments in Figure 22 in Ref. 2, the spinor pair magnetic binding energy is determined to be ± 1.7 MeV. However, it could also be argued that in the Σ^0 resonance the magnetic and coulomb repulsion keeps the two S^+ spinors somewhat separated (although they are held fairly close together by the hadronic bonds to the 4^-). In the limit of this latter argument, the Σ^0 would only have +2 magnetic pairs, so that the magnetic interaction energy difference in the $\Sigma^0 \rightarrow \Lambda + \gamma$ decay becomes $(+2) - (-1) = (+3) = 6.9$ MeV, which gives a magnetic pair energy of ± 2.3 MeV instead of ± 1.7 MeV. The mass accuracy of Table VII can still be maintained with this change, since compensating changes occur in other parameters. An intermediate value, ± 2.1 MeV, correctly reproduces the α particle binding energy for the configuration shown in Eq. (5). However, the calculated binding energy for the triton configuration of Eq. (7) is -14.5 MeV, as compared to the experimental triton binding energy of -8.5 MeV. The He^3 and D nuclei are similarly overbound, so it is apparent that the short-ranged magnetic force is not fully operative for clusters lighter than the α particle. Phenomenologically, this indicates that we do not yet have a complete theory for the attractive nuclear force.

- (5). V. G. Lind et al., Phys. Rev. Lett. 32, 479 (1974).
- (6). F. K. Mc Gowan et al., Phys. Rev. Lett. 27, 1741 (1971).
- (7). For example, see R. D. Evans, The Atomic Nucleus, Mc Graw-Hill, New York (1955), Table 3.5, page 392.

Figure 1. The proton and neutron. These are both formed as Fermi-Yang spinor clusters, $N = \bar{S}\bar{S}\bar{S}$, where each spinor S consists of an aligned array of three oblate spheroids. A spinor S has an overall height of 2 fermis and equatorial radii equal to 0.6 fermi. Thus the effective shape of the spinor S is cylindrical, and spinors bind together in a side-by-side manner. The spinor S has the same electromagnetic properties (except for its integral charges) as the nucleon quark of Gell-Mann and Zweig, but it has different particle and antiparticle properties. As described in Ref. 2, the configurations shown here for the proton and neutron accurately reproduce the masses, spins, and charges of these particles, and also the magnetic moment ratio. Stripes on a spinor S represent (integral) equatorial charge distributions. In order to reproduce the masses of the hadron resonances, three kinds of binding energy are required - hadronic, magnetic, and coulomb. The magnetic binding energy that was deduced from the systematics of the hadron resonances (see Ref. 2) also appears to account for the attractive component of the nuclear force.

$\bar{p}n$ BOUND STATE

Figure 2. The $\bar{p}n$ bound state. This state, which has the largest binding energy ever observed for any physical system (4.4%), illustrates the manner in which nucleons and antinucleons cluster together in a laminar manner. Atomic nuclei, in contrast to the $\bar{p}n$ bound state, are composed entirely of particles, and the strong (4%) hadronic force does not seem to be operative between particle-particle pairs. Thus the extranucleon forces that operate between spinors in adjacent nucleon-nucleon pairs must be electromagnetic - magnetic and coulomb, and the attractive components of these forces must be primarily magnetic. The same laminar clustering seems to occur in atomic nuclei as is illustrated here for the $\bar{p}n$ hadron resonance: magnetic forces bind clusters of nucleons together into two-dimensional Ising layers, and a large nucleus contains a number of such layers.

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