A Case for Neutron Isotopes

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Recent studies of the binding of neutron pairs and quartets, together with studies of neutrons in halo nuclei, suggest that clusters of five or more neutrons are strongly bound.

For ordinary nuclei, the masses of the various isotopes can be described by a liquid drop model. Although that model does not reflect the fine distinctions of the nuclear shell structure, it comes sufficiently close to serve as a useful approximation. In this analysis I suggest a liquid drop model for neutron isotopes and their decay products, in anticipation that such a model may have similar utility for quantifying the properties of these nuclei. For neutron isotopes ^{A}n I suggest a simple liquid drop formula for their mass excesses,

$$\Delta(^{A}n) = A\Delta(n) - a_v A + a_s A^{2/3} \, . \qquad (1)$$

In this formula all terms are in units of MeV. $\Delta(^{A}n)$ is the mass excess of isotope ^{A}n and $\Delta(n)$ is the mass excess of a single neutron. A volumetric term $-a_v A$ represents the nuclear binding energy of a droplet of A neutrons, and a surface energy term $+a_s A^{2/3}$ reduces the magnitude of the binding energy of the droplet by an amount proportional to its surface area.

Recent evidence [1] has shown that a di-neutron ^{2}n, which is bound when confined to the nucleus ^{16}Be, becomes unbound when removed from ^{16}Be. The two neutrons then fly apart with kinetic energy 1.35 MeV. This indicates that, when ^{2}n is freed of interaction with other components of a nucleus in which it is embedded, its mass excess is

$$\Delta(^{2}n) = 2\,\Delta(n) + 1.35 \text{ MeV}. \qquad (2)$$

Other evidence [2] suggests that the tetra-neutron ^{4}n is either very weakly bound, or very weakly unbound. Zero binding appears to be the best currently available estimate, giving

$$\Delta(^{4}n) = 4\,\Delta(n) + 0 \text{ MeV}. \qquad (3)$$

The experimentally determined relationships (2) and (3) are sufficient for determining the liquid drop parameters a_v and a_s in formula (1),

$$a_v = 2.597 \text{ MeV} \qquad (4)$$
$$a_s = 4.122 \text{ MeV}.$$

These values for a_v and a_s are about 1/4 of those for ordinary nuclei as given by Krane [3], indicating that neutron isotopes are relatively weakly bound.

Table 1 lists the binding energies $E_B = -a_v(A) + a_s(A^{2/3})$ and mass excesses $\Delta(^A n)$ of neutron isotopes for selected values of A, based on formula (1) with values of a_v and a_s from equation (4), rounded to two digits following the decimal point. The smallest bound isotope is ^5n, and the binding energy per neutron strengthens asymptotically to −2.60 MeV for very large A.

Table 1

Calculated binding energies E_B and mass excesses $\Delta(^A n)$
for selected neutron isotopes $^A n$ in units of MeV

A	E_B	$\Delta(^A n)$
2	+1.35	17.49
3	+0.78	25.00
4	0.00	32.28
5	−0.93	39.42
6	−1.94	46.45
7	−3.10	53.40
8	−4.29	60.28
9	−5.54	67.10
10	−6.84	73.87
100	−170	636
1000	−2180	5890
Large A limit	−2.60A	5.47A

Although bound and stable against strong decay, neutron isotopes are not stable against beta decay in which a neutron changes into a proton. In considering the stability of neutron isotopes and their beta decay products, I assume that the nuclear binding strength of a mixed droplet of neutrons and protons is independent of the proportions of neutrons and protons in the mix. This implies that the strength of the strong interaction between any pair of nucleons is the same, independent of whether they are interacting as two protons, two neutrons, or one proton and one neutron. And because the isospin T of a cluster of A neutrons has maximum value $T_{max} = A/2$ it follows that any cluster of A nucleons belongs to the $T_{max} = A/2$ isospin multiplet.

Equation (1) then can be rewritten for a mix of A−Z neutrons and Z protons (this mix is an isotope of the element having nuclear charge Z),

$$\Delta(^A Z) = (A-Z)\Delta(n) + Z\Delta(^1H) - a_v A + a_s A^{2/3} + a_c Z(Z-1)A^{-1/3}. \quad (5)$$

The term $a_c Z(Z-1)A^{-1/3}$ represents the coulomb energy of a drop containing Z protons. I expect the density of nucleons in a T_{max} nucleus to be about 1/8 the density of ordinary nuclei, comparable with the density in the halos of halo nuclei [4]. This implies a value of $a_c = 0.360$ MeV for T_{max} nuclei, about half that of ordinary nuclei [3]. Altogether

$$\begin{aligned} a_v &= 2.597 \text{ MeV} \\ a_s &= 4.122 \text{ MeV} \\ a_c &= 0.360 \text{ MeV}. \end{aligned} \quad (6)$$

An isolated neutron is unstable against beta decay, in which the neutron changes into a proton with emission of an electron and an antineutrino,

$$n \rightarrow p^{+} + e^{-} + \text{antineutrino} \qquad (7a)$$

which is customarily written

$$n \rightarrow {}^{1}H + 0.782 \text{ MeV} \qquad (7b)$$

with the proton and electron combined in a hydrogen atom and the antineutrino understood. Because the antineutrino is practically massless, its energy is mostly undetected kinetic energy included in the 0.782 MeV total energy release.

I assume that neutron isotopes decay similarly by conversion of a neutron into a proton,

$$^{A}n \rightarrow {}^{A}H_{T} + 0.782\text{MeV}. \qquad (8)$$

The subscript T on $^{A}H_{T}$ indicates that the wave function of $^{A}H_{T}$ is a member of the isospin T_{max} = A/2 multiplet. The isotope $^{A}H_{T}$ is stable against strong decay, but is capable of the beta decay

$$^{A}H_{T} \rightarrow {}^{A}He_{T} + (0.782 - 0.720A^{-1/3}) \text{ MeV}. \qquad (9)$$

The decay energy released is reduced by $0.72A^{-1/3}$ from (8) because of the coulomb energy accompanying addition of the second proton. Subsequent beta decays lead to maximum-isospin isotopes with increasing numbers of protons,

$$^{A}n \rightarrow {}^{A}H_{T} \rightarrow {}^{A}He_{T} \rightarrow {}^{A}Li_{T} \rightarrow {}^{A}Be_{T} \rightarrow {}^{A}B_{T} \rightarrow \ldots \qquad (10)$$

and so on until the increment of coulomb energy increase becomes too great for further decay. The maximum changes achievable by sequential beta decay are shown in Table 2.

Table 2

Mass Excesses of T_{max} Isotopes

[Table to come]

Isotopes $^{A}Z_{T}$ with charge $Z \geq 2$ are unstable with respect to alpha decay

$$^{A}Z_{T} \rightarrow {}^{A-4}(Z-2)_{T} + {}^{4}He \qquad (11)$$

in which an ordinary helium atom is emitted.

The mass excesses of T_{max} isotopes can be tabulated as a supplement to the Wallet Cards [5]. This is done in Table 2, which shows mass excesses and decay products for all T_{max} isotopes based on Equation (5). The table shows also the mass excesses and other properties of a few ordinary isotopes that can be products of T_{max} isotope decays, or that for illustrative purposes are discussed below. Examination of Table 2 shows that all reaction products of T_{max} isotopes having A>6 are also T_{max} isotopes. Only isotopes having A≤6 have decay products that are ordinary isotopes.

Many reactions are possible between T_{max} isotopes and ordinary particles or nuclei. Three types of reactions may have consequences of particular interest.

Neutrons interact strongly with every $^{A}Z_{T}$, being absorbed in the exothermic reactions

$$n + {}^{A}(Z)_{T} \rightarrow {}^{(A+1)}Z_{T}. \qquad (12)$$

There is no coulomb barrier to any of these reactions, which can occur between neutrons and every T_{max} nucleus in Table 2. As a consequence, a T_{max} nucleus located in an environment that contains free neutrons will grow indefinitely so long as neutrons are available. This may be of interest to astrophysics. During the first few minutes after the big bang there comes a time when baryonic antimatter has disappeared and space is filled with a mixture of photons, electrons, positrons, muons and anti-muons, and neutrons. Although the rate of formation of ^{5}n is small, it is expected to be finite. And because neutrons are more strongly bound in ^{A}n and in $^{A}Z_{T}$ than in deuterium, the growth of ^{A}n and $^{A}Z_{T}$ droplets will diminish the formation of deuterium. A significant accumulation of very large $^{A}Z_{T}$ would be expected. Astrophysicists may wish to consider this possibility, as it may influence the relative proportions of ^{1}H and ^{2}H established in the first few minutes. If enough T_{max} nuclei are formed, and if they absorb enough neutrons, the $^{A}Z_{T}$ that are created could later sink into the cores of stars, providing more mass to stars than suggested by their energy output.

Neutron isotopes can also interact with deuterium without a coulomb barrier,

$$^{A}n + {}^{2}H \rightarrow {}^{A+1}n + {}^{1}H \qquad (13)$$

producing hydrogen and increasing the size of the neutron isotope. And neutron isotopes can react with many massive ordinary isotopes ^{D}Z, transferring neutrons to them and correspondingly reducing the size of the neutron isotope:

$$^{A+B+C}n + {}^{D}Z \rightarrow {}^{A+B}n + {}^{C+D}Z. \qquad (14)$$

It can also happen that the neutron isotope can fission:

$$^{A+B+C}n + {}^{D}Z \rightarrow {}^{A}n + {}^{B}n + {}^{C+D}Z. \qquad (15)$$

In combination reactions (13) and (15) allow the possibility of a chain reaction in a star. This could be of interest to astrophysicists in examining the process of element creation in stars.

The chain reaction might also be of interest for the detection of dark matter. If large $^{A}Z_{T}$ isotopes do have a role in dark matter, it may be possible to construct an instrument containing deuterium gas and (for example) argon gas in which a chain reaction having macroscopic detectability could be triggered by a single ^{A}n in the flux of particles arriving from distant sources. Evidence for triggering could be provided by identifying the ordinary isotopes produced in the chain reaction. This instrument could also be used in a search for neutron isotopes that may be created in laboratory experiments.

Overall, the possible existence of the family of T_{max} nuclei, based on the experimental data for tetra-neutrons and di-neutrons and summarized in Table 2, exemplifies how a wide area of physics may be opened by evidence from a few key experiments.

References [to be done correctly]

1. [authors], First Observation of Ground State Dineutron Decay: Be16,

2. F. M. Marques, N. A. Orr, H. Al Falou, G. Normand, N. M. Clarke, On the possible detection of ^{4}n events in the breakup of ^{14}Be, arXiv:nucl-ex/0504009v1, 6 Apr 2005.

3. Krane

4. Halo nuclei

5. Wallet cards