Typeset with jjap2.cls <ver.1.0> **Regular Paper**

Neutron Isotope Reactions

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I suggest that neutron clusters of sufficient size are bound and stable against strong decay and that these massive neutron isotopes can react with ordinary nuclei by transferring neutrons to them, accepting neutrons from them, binding with them to form nuclear molecules, and in other ways. The implications of this enlarged scope of nuclear physics are explored. These include reactions with ^{18}O, ^{6}Li, ^{7}Li, and ^{2}H that produce energy, ^{4}He, ^{3}H and other nuclear products. This approach provides a natural explanation for a range of novel nuclear phenomena for which evidence has been accumulatng over the past fifteen years. It provides a theoretical framework for guiding future research and for exploring potential applications to energy generation and to other nuclear processes.

KEYWORDS: neutron isotope, polyneutron, transmutation, chain reaction, energy generation

1. Introduction

This is a speculative assessment of the possible existence, properties, and reactions of neutron isotopes. There is little direct evidence for such isotopes although there has been a preliminary report of tetraneutrons.[1)] Indirect evidence is derived from experiments that were designed to prove, disprove, or clarify the claim of "cold fusion" during electrolysis. Although the fusion interpretation has been discredited the results of well-done experiments should not be discarded because experimenters were mistaken in their interpretation of what they observed.

The most widely studied electrolysis systems consist of a glass cell containing an electrolyte of LiOD, Li_2SO_4 or D_2SO_4 dissolved in D_2O or H_2O, a palladium cathode, and a platinum anode. Beginning with the pioneering work of Fleischmann, Pons and Hawkins[2)] these systems have povided evidence for the generation of energy in excess of amounts that are explainable by electrochemical processes[3)4)] and for production of substantial amounts of ^{4}He.[5)] Small amounts of tritium have been observed.[6)] Energetic charged particles have been observed by means of detectors immersed in the electrolyte.[7)8)] and in the vapor over the electrolyte.[9)] The review prepared by Storms[10)] provides a broad overview of research in these areas.

In seeking an explanation for these various observations we first rule out nuclear fusion because the required reaction products are not observed. Theory rules it out as well because at room temperature there is insufficient thermal energy to overcome the coulomb barrier. Indeed the coulomb barrier rules out every low-temperature nuclear reaction between charged

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particles, leaving only neutral particles as possible mediators. Neutrons play this role in the commercial low-temperature reactors that provide energy for electric power generation and ship propulsion, but neutrons cannot be the mediators in electrolysis experiments because measurement shows that they are not present in sufficient numbers.

Neutral particles of a different kind are required. Here we explore the possibility that they may be massive neutron isotopes, although searches for neutron isotopes have so far met with limited success. In particular the dineutron is not bound. There is a substantial potential well for a pair of neutrons in close proximity but it is not quite deep enough to bind them and they show a resonance with energy about 0.1 MeV above that of a pair of free neutrons. Most searches for heavier isotopes have produced negative results and it is clear that ^{3}n is not bound. If bound isotopes do exist they must be more massive.[11)] The lightest may be the tetraneutron ^{4}n recently reported.

Theoretical analyses have led to suggestions that isotopes ^{64}n and larged might be bound, or that ^{114}n and larger might be bound.[11)] These analyses did not consider the additional binding that can result from collective condensation of neutron pairs analogous to the electron-pair condensation in superconductivity. Collective binding of neutron pairs is expected to be much stronger than that of electron pairs. Neutrons attract each other forcefully and directly, rather than weakly and indirectly through the agency of phonons as for electrons. The momentum space available for neutron pairing is not limited to a thin shell at the fermi surface. With such strong interaction and full access to momentum space, relatively small isotopes will be bound.

2. Notation

A neutron isotope will sometimes be referred to as a polyneutron or as a neutron droplet. The ground state of a neutron isotope containing A neutrons is denoted by ^{A}n. It is assumed to be a paired collective state analogous to the BCS paired electron state that is responsible for superconductivity. Its isospin is $T = A/2$, the maximum possible value for an assemblage of A nucleons. The 3-component of isospin is $T_3 = -A/2$, the minimum possible value for an assemblage of A neutrons.

Rotation in isospace replaces one or more neutrons with protons but leaves unchanged the number of nucleons and the nuclear symmetry of the droplet. The minimal isospace rotation increases the 3-component of isospin to $T_3 = -A/2 + 1$ with a single proton in interaction with A−1 neutrons. Because the nuclear symmetry is unchanged the isospin remains $T = A/2$. The isotope with this minimally isorotated nucleus is designated by $(^{A}H)_{max}$. The H indicates a hydrogen isotope with its single proton in the nucleus and the subscript reminds us that the isospin retains its maximum value. Further isorotation gives successive nuclei with $T_3 = -A/2 + 2$, $-A/2 + 3$, ..., the corresponding isotopes being designated $(^{A}He)_{max}$, $(^{A}Li)_{max}$, ... Because the nuclear symmetry is unaffected the energies of these nuclei receive

identical contributions from nuclear interactions. Their total energies differ only because of differing numbers of lighter-mass protons and because multiple protons lead to coulomb energy contributions.

In situations where all potential transfers of neutrons between an ordinary nucleus and a neutron isotope are endothermic we can have composites such as $^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n}$ where an ordinary nucleus and a neutron isotope are bound to each other and are stable against strong decay. Composite nuclei are written in the form customary for molecules with the individual constituents $^{16}\mathrm{O}$ and $^{\mathrm{A}}\mathrm{n}$ written adjacent to each other. I expect that the configuration of a composite resembles that of a droplet of oil and a droplet of water bound to each other by a reduction of surface energy over the area of contact. Following initial contact neutrons flow between the droplet and the ordinary nucleus until the energy reaches a minimum and further neutron transfer is endothermic.

The mass excess of atom $^{\mathrm{A}}\mathrm{Z}$ composed of A nucleons, Z protons, and Z orbital electrons is defined as the mass of $^{\mathrm{A}}\mathrm{Z}$ minus A/12 times the mass of an atom of $^{12}\mathrm{C}$. It is written $\Delta(^{\mathrm{A}}\mathrm{Z})$. Mass excesses are commonly tabulated for the isotopes and can be used in place of masses for determining reaction energies.

The elementary beta decay is $\mathrm{n} \longrightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}$ in which a neutron is transformed into a proton, an electron, and an antineutrino. The antineutrino achieves its maximum energy when p^+ and e^- are combined to form the atom $^1\mathrm{H}$ at rest, $\mathrm{n} \longrightarrow {}^1\mathrm{H} + \bar{\nu}$. This reaction can be abbreviated $\mathrm{n} \longrightarrow {}^1\mathrm{H} + E$ where $E = \Delta(\mathrm{n}) - \Delta(^1\mathrm{H})$ is the energy released by the reaction and where the presence of the $\bar{\nu}$ is understood. Most beta reactions below are abbreviated simply $\mathrm{n} \longrightarrow {}^1\mathrm{H}$ in which the energy term is also understood and its partition among p^+, e^- and $\bar{\nu}$ is not specified.

3. Initial Polyneutron

Because neutron isotopes are not stable against beta decay they cannot be present in nature, but must somehow be generated at the time and in the place where they are to react. We begin by outlining a process by which this may occur.

Consider an oxygen nucleus $^{16}\mathrm{O}$ and a neutron droplet $^{\mathrm{A}}\mathrm{n}$ that come into contact to form a nuclear molecule or composite $^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n}$. Assume that the interfacial energy between the two is smaller than the sum of the surface energies of the free constituents and that the $^{16}\mathrm{O}$ and the $^{\mathrm{A}}\mathrm{n}$ stick together analogously to drops of immiscible oil and water. Now we ask for the decay channels for this composite and for its lifetime. Let $\Delta(^{\mathrm{A}}\mathrm{n})$ be the mass excess of droplet $^{\mathrm{A}}\mathrm{n}$ and let D be the difference in mass excess between $^{\mathrm{A+1}}\mathrm{n}$ and $^{\mathrm{A}}\mathrm{n}$, a quantity that is a slowly varying function of A,

$$D = \Delta(^{\mathrm{A+1}}\mathrm{n}) - \Delta(^{\mathrm{A}}\mathrm{n}). \tag{1}$$

Assume that $-0.79 < D < 1.98$ Mev for all A. Then no strong decay channels are available

because reactions of the form

$$^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16\pm\mathrm{X}}\mathrm{O}\,^{\mathrm{A}\mp\mathrm{X}}\mathrm{n} \tag{2}$$

that transfer neutrons to or from ^{16}O are all endothermic.

It is shown below that, for all values of A of significance in electrolysis experiments, beta decay of the composite is ruled out by the associated increase in coulomb energy. The only available decay channels involve double beta decay and simultaneous alpha emission occurring as a coordinated process in reactions that include

$$^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,^{\mathrm{A-4}}\mathrm{n} + {}^{4}\mathrm{He} \tag{3}$$

and the polyneutron-producing reaction

$$^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,^{\mathrm{A-4-B}}\mathrm{n} + {}^{4}\mathrm{He} + {}^{\mathrm{B}}\mathrm{n}. \tag{4}$$

The alpha particle and the two electrons from beta decay are combined to form atomic ^{4}He and the two antineutrinos are understood. The composite nucleus $^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n}$ has a long lifetime because of the double beta decay and the coulomb barrier that inhibit alpha emission. Subsequent decays have increasingly longer lifetimes because as the composite shrinks the coulomb barrier increases. The lifetime between successive alpha decays grows ever longer.

Following the discussion of chain reactions it is suggested that composites $^{16}\mathrm{O}\,^{\mathrm{A}}\mathrm{n}$ are continuously generated at active sources in nature and are present at low concentration in the atmosphere and in the hydrosphere. Polyneutrons produced in reaction channel (8) are suggested as the sources of the initial polyneutrons required to initiate chain reactions that occur during electrolysis. Now the question of the origin of the initial polyneutron moves back through time and we ask for the source of the polyneutrons that ignited the earth's first natural reactors. They may have been very long-lived composite nuclei that formed in the neutron-rich environments of supernova explosions.

4. Chain Reactions

Consider first a chain reaction in which oxygen is the fuel. A single polyneutron $^{\mathrm{A}}$n is sufficient to initiate a chain in interaction with ^{18}O (the heaviest naturally-occurring oxygen isotope, with 0.2% natural abundance). It begins with growth of the initial polyneutron in the reaction

$$^{18}\mathrm{O} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O} + {}^{\mathrm{A+2}}\mathrm{n} \tag{5}$$

which is exothermic for $D < 1.98$. Growth can continue by iteration of this reaction, adding a pair of neutrons to the polyneutron at each step and releasing ^{16}O and energy at each step.

Growth of a single polyneutron proceeds far too slowly to account for the observed rate of energy production. A multiplication reaction must be available to sustain a chain reacton and thereby to enable the build-up of a large concentration of neutron isotopes. Fission of large

polyneutrons is required for this step,

$$^{18}\mathrm{O} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O} + {}^{\mathrm{B}}\mathrm{n} + {}^{\mathrm{A-B+2}}\mathrm{n}. \tag{6}$$

(In a related reaction the polyneutron $^{\mathrm{A}}$n is split into three parts, one of which combines with the ^{16}O to form a composite nucleus and the other two emerge as free polyneutrons.)

If reactions (5) and (6) were the only ones available we would have a runaway chain of strong reactions in contrast to the bounded reaction rates that have been observed. Other reactions must come into play. The reaction

$$^{18}\mathrm{O} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,{}^{\mathrm{B}}\mathrm{n} + {}^{\mathrm{A-B+2}}\mathrm{n} \tag{7}$$

creates a composite nucleus $^{16}\mathrm{O}\,{}^{\mathrm{B}}\mathrm{n}$ that because of its charge cannot participate in further strong reactions other than with polyneutrons. The reactions with polyneutrons include

$$^{16}\mathrm{O}\,{}^{\mathrm{B}}\mathrm{n} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,{}^{\mathrm{B+C}}\mathrm{n} + {}^{\mathrm{A-C}}\mathrm{n} \tag{8}$$

resulting in major shrinkage of the polyneutron and enlargement of the composite. They also include

$$^{16}\mathrm{O}\,{}^{\mathrm{B}}\mathrm{n} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,{}^{\mathrm{B+A}}\mathrm{n} + \gamma \tag{9}$$

which captures a polyneutron and removes it from the system. As a chain reaction proceeds the concentration of $^{16}\mathrm{O}\,{}^{\mathrm{B}}\mathrm{n}$ rises. Reaction (8) increasingly prevents the growth of polyneutrons to a size where they can fission, and reaction (9) incresingly removes them. When the rate of removal exceeds the rate of fission the chain reaction comes to a halt, poisoned by its reaction products.

We see that reactions (8) and (9) can quench the chain of reactions (5) and (6). This is a requirement that must be satisfied for otherwise we would expect liquid oxygen to explode. Now we consider how electrolysis can constrain reactions (8) and (9) to limit the rate of the chain reaction without quenching it. During electrolysis hydrogen or deuterium atoms are generated at the cathode surface. There they combine to produce molecules that supersaturate the electrolyte to a level that supports homogeneous bubble nucleation. Many tiny bubbles appear in the electrolyte near the cathode and trigger a maelstrom of competitive growth. Surface tension requires that bubbles of different sizes be in equilibrium with different levels of saturation, small bubbles with a high level and large bubbles with a lower level. At any given level bubbles larger than a critical size will grow and smaller bubbles will shrink. The situation is unstable. Minor differences in size and in local hydrogen or deuterium concentration in the electrolyte enable a few bubbles to take the path of runaway growth while the majority shrink and vanish. Then growth of the large bubbles slows as they move away from the region of bubble nucleation.

Now consider the fate of a polyneutron that finds itself in the electrolyte near the surface of a bubble in its rapid growth stage. There it ignites a chain reaction and the concentration of

$^{16}O\,^{A}n$ reaction products begins to rise. The cloud of products that would have built up and would have quenched the reaction in a quiescent fluid gets stretched tangentially and shrunk radially into a thin spherical shell. The thickness of the active region tends to increase because of the continuing reaction, but it is held in check by the thinning action of the expansion. Reaction can continue as long as bubble growth is rapid, but ultimately a bubble moves into a region with a lower concentration of dissolved gas and the growth rate slows. The thinning rate becomes insufficient to stop buildup of composite nuclei and reaction at that bubble is quenched. But this is not the end of the story. The reaction from an active bubble can be transferred by polyneutron diffusion to rapidly growing bubbles behind it, igniting them, and the process can continue indefinitely with the result that a bounded rate of reaction can be maintained near the surface of the cathode where bubble nucleation and rapid growth occur. The situation near the anode is similar, with supersaturated oxygen as the driving force for bubble growth. In summary, a single polyneutron that is released near a rapidly growing bubble in an electrolysis experiment can ignite a reaction that will persist near an electrode as long as electrolysis persists, whereas in contrast the chain reaction in a quiescent electrolyte is quenched by localized buildup of composite nuclei.

Other means than electrolysis are expected to be capable of maintaining the high fluid shear rate necessary for dispersing composite nucleus poisons and for providing a steady input of fresh reactant for maintaining a reaction. Preliminary studies suggest that mechanically produced shear serves this purpose.[12)13)] We can expect that here and there in nature where sufficiently high shear rates exist, chain reactions are proceeding with ^{18}O from water or air as fuel and are providing ongoing sources for $^{16}O\,^{A}n$ composite nuclei. Chemically these nuclei are massive oxygen isotopes that mix into the oceans and the atmosphere. There they shrink at an ever slowing rate through successive coordinated beta and alpha decays and occasionally they generate neutron isotopes as in reaction (4), providing in nature a steady low production rate of neutron isotopes capable of triggering chain reactions.

Composite nuclei $^{16}O\,^{A}n$ that are produced during electrolysis are dispersed throughout the electrolyte by fluid agitation. There they decay by correlated double beta and alpha emissions emitting alpha particles that can be recorded on detector chips immersed in the electrolyte.[7)8)] Composites also move into the oxygen-hydrogen vapor above the electrolyte and decay there, most often via reaction (3) but occasionally via reaction (4) which produces a free polyneutron that can initiate a chain reaction. Evidence for such chain reactions has been obtained by detection of particle showers in the vapor above a light-water electrolyte in an active electrolysis cell.[9)] A pair of plastic detector chips (CR-39 plastic commercially available for alpha particle detection) were suspended in the vapor facing each other at a distnce of about 1 cm. A shower of approximately 150,000 alpha particles orginated in the vapor between the detectors, which recorded about 30,000 tracks on the one nearest the

origin of the shower and about 10,000 tracks on the more remote one. Analysis of the track densities on the detector surfaces and of track orientations showed that the shower initiated in a compact source between the detectors, and that it decayed in intensity as it drifted with convection currents in the vapor. These observations can be understood as a very rapid buildup of polyneutrons in the early stages of a chain reaction, then cessation of the chain reaction as the concentration of composite nuclei rises and quenches it, followed by progressively less rapid decay of the composite nuclei as their lifetimes increase in consequence of their shrinkage. The shower is consistent with the production of about 1000 composite nuclei containing about 600 neutrons each (or another number of composites with an appropriate number of neutrons to aggregate 600,000 neutrons). After the composites have decayed the 600,000 neutrons have been repackaged as 150,000 alpha particles.

5. Other Polyneutron Reactions

Reactions with ^{2}H are particularly interesting. This isotope can support polyneutron growth in the reaction

$$^{2}\mathrm{H} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{1}\mathrm{H} + {}^{\mathrm{A+1}}\mathrm{n} \tag{10}$$

and it also can support polyneutron shrinkage and generate tritium in the reaction

$$^{2}\mathrm{H} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{3}\mathrm{H} + {}^{\mathrm{A-1}}\mathrm{n} \tag{11}$$

which is exothermic for $D > 1.82$. Recalling that reaction (5) is exothermic for $D < 1.98$ we have the requirement $1.82 < D < 1.98$ for both reactions (5) and (11) to be exothermic. The intermediate value $D = 1.90$ lies within 4% of the bounds and represents a good approximation to the value of D for large polyneutrons whose binding energy per neutron is independent of neutron number. In the absence of binding the increase of of energy per neutron in a neutron aggregate is the mass excess of a free neutron $\Delta(\mathrm{n}) = 8.07$ MeV/neutron. With full binding it is 1.90 MeV/neutron indicating a binding energy of magnitude 6.17 MeV/neutron, about 40% of the nuclear binding energy per nucleon in ordinary nuclei.[14)]

The situation is different for small polyneutrons. The binding energy is near zero for ^{4}n and it grows in magnitude as the number of neutrons increases until the droplet reaches a size beyond which the pairing wave function loses coherence. There is little empirical data to support an estimate of the rate of increase of binding strength in this region beyond the fact that none of the isorotated nuclei $(^{\mathrm{A}}\mathrm{H})_{\mathrm{max}}$, $(^{\mathrm{A}}\mathrm{He})_{\mathrm{max}}$, etc. appears to be stable for any value of A$\geq$4. It is shown below that all polyneutrons are unstable with respect to beta decays that lead to $(^{\mathrm{A}}\mathrm{Li})_{\mathrm{max}}$. If this isotope were stable it would likely have been observed in searches for massive low-Z isotopes. Its non-observation suggests that the decay

$$(^{\mathrm{A}}\mathrm{Li})_{\mathrm{max}} \longrightarrow (^{\mathrm{A-4}}\mathrm{H})_{\mathrm{max}} + {}^{4}\mathrm{He} + (4D - 1.56)\ \mathrm{MeV} \tag{12}$$

is exothermic for all values of A, with the consequence that isolated polyneutrons can decay

to helium in iterated instances of reaction (12). For reaction (12) to be exothermic in the small polyneutron region we must have $D > 0.39$ limiting the range of D to $0.39 < D < 1.90$. The coherence number is the value of A for which $\Delta(^{\mathrm{A}}\mathrm{n}) = 1.90\mathrm{A}$ (the relationship for large polyneutrons) equals $\Delta(^{\mathrm{A}}\mathrm{n}) = 4(8.07) + (\mathrm{A}-4)D$ (the relationship for small polyneutrons with $\mathrm{A} \geq 4$). This occurs at $\mathrm{A} = (32.28-4D)/(1.90-D)$ which ranges from A=20 for D=0.39 to A$\rightarrow\infty$ for $D = 1.90$. I tentatively assume $D = 0.70$, which suggests a coherence number of about 25 neutrons. In subsequent analyses I therefore assume

$$\begin{aligned} \Delta(^{\mathrm{A}}\mathrm{n}) &= 29.48 + 0.70\mathrm{A} && (\mathrm{A} < 22) \\ \Delta(^{\mathrm{A}}\mathrm{n}) &= 1.90\mathrm{A} && (\mathrm{A} \geq 22) \end{aligned} \tag{13}$$

This makes possible the determination of the energies generated in the polyneutron growth reactions sustained by the isotopes ^{18}O, ^{7}Li, ^{6}Li and ^{2}H.

$$\begin{aligned} ^{18}\mathrm{O} + {}^{\mathrm{A}}\mathrm{n} &\longrightarrow {}^{16}\mathrm{O} + {}^{\mathrm{A+2}}\mathrm{n} && +2.56/0.16\ \mathrm{MeV} \\ ^{7}\mathrm{Li} + {}^{\mathrm{A}}\mathrm{n} &\longrightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{\mathrm{A+2}}\mathrm{n} && +3.79/1.39\ \mathrm{MeV} \\ ^{6}\mathrm{Li} + {}^{\mathrm{A}}\mathrm{n} &\longrightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{\mathrm{A+1}}\mathrm{n} && +3.67/2.47\ \mathrm{MeV} \\ ^{2}\mathrm{H} + {}^{\mathrm{A}}\mathrm{n} &\longrightarrow {}^{1}\mathrm{H} + {}^{\mathrm{A+1}}\mathrm{n} && +5.14/3.94\ \mathrm{MeV} \end{aligned} \tag{14}$$

Here the first energy value corresponds to the small A region and the second to the large A region. In the presence of oxygen all of these reactions can contribute to a chain reaction and to energy production during electrolysis, but it is not yet known whether lithium and deuterium can support chain reactions on their own in the absence of oxygen.

We now turn to consideration of decay mechanisms for polyneutrons and for composite nuclei. According to the liquid drop model for ordinary nuclear matter[14] the coulomb energy associated with nuclear charge Z and nucleon number A is $E_c = 0.711\,\mathrm{Z}\,(\mathrm{Z}-1)\mathrm{A}^{-1/3}$. For a neutron droplet the volume per neutron is larger by a factor of α yet to be determined. The coulomb energy is smaller and the coefficient 0.711 must be replaced by $0.711\,\alpha^{-1/3}$. Assuming $\alpha = 2$ the coulomb energy term for neutron droplets and isorotated droplets is

$$E_c = 0.56\,\mathrm{Z}\,(\mathrm{Z}-1)\,A^{-1/3}. \tag{15}$$

At each step in the cascade of beta decays in the chain $(^{\mathrm{A}}\mathrm{n})_{\max} \rightarrow (^{\mathrm{A}}\mathrm{H})_{\max} \rightarrow (^{\mathrm{A}}\mathrm{He})_{\max} \rightarrow (^{\mathrm{A}}\mathrm{Li})_{\max} \rightarrow (^{\mathrm{A}}\mathrm{Be})_{\max} \rightarrow (^{\mathrm{A}}\mathrm{B})_{\max}$ there is an energy decrease of 0.78 MeV because a neutron is replaced by a lighter proton. And at each step there is an energy increase of $E_c(Z) - E_c(\mathrm{Z}-1) = 1.12\,(\mathrm{Z}-1)\,A^{-1/3}$ where Z is the charge of the product nucleus. For product atoms $(^{\mathrm{A}}\mathrm{H})_{\max}$, $(^{\mathrm{A}}\mathrm{He})_{\max}$, and $(^{\mathrm{A}}\mathrm{Li})_{\max}$ the coulomb energy is small and the beta reactions are exothermic for all values of A. For $(^{\mathrm{A}}\mathrm{Be})_{\max}$ the beta reaction is exothermic for A$>$ 80 and for $(^{\mathrm{A}}\mathrm{B})_{\max}$ it is exothermic for A$>$ 3000.

We see that all polyneutrons can decay spontaneously to $(^{\mathrm{A}}\mathrm{Li})_{\max}$ and that sufficiently

large ones can decay to $(^{\mathrm{A}}\mathrm{Be})_{\max}$ or to $(^{\mathrm{A}}\mathrm{B})_{\max}$. The atoms $(^{\mathrm{A}}\mathrm{He})_{\max}$, $(^{\mathrm{A}}\mathrm{Li})_{\max}$, etc. all can decay by emission of alpha particles in the reactions $(^{\mathrm{A}}\mathrm{He})_{\max} \rightarrow (^{\mathrm{A-4}}\mathrm{n}) + {}^{4}\mathrm{He}$, $(^{\mathrm{A}}\mathrm{Li})_{\max} \rightarrow (^{\mathrm{A-4}}\mathrm{H})_{\max} + {}^{4}\mathrm{He}$, etc. Hence every free polyneutron will decay away completely by successive (β, β, α) decays. Although we do not know the decay rates, they must be sufficiently slower than the polyneutron growth rate in reaction (5) that they do not quench the chain reaction.

The increment of coulomb energy associated with transformation of a single neutron to a proton in an ordinary nucleus with nucleon number B and initial charge Z is equal to $0.711\,(2\mathrm{Z})\,\mathrm{B}^{-1/3}$. This expresses the energy required to move a unit electric charge from infinity to a distance $\mathrm{A}^{1/3}$ from the center of the nuclear charge. The energy required to move a polyneutron with unit electric charge into contact with an ordinary nucleus is smaller because the distance between the two centers of charge is increased to $\mathrm{B}^{1/3} + (\alpha\mathrm{A})^{1/3}$. The associated energy increment is $\Delta E_c = 0.711\,(2\mathrm{Z})\,(\mathrm{B}^{1/3} + (\alpha\mathrm{A})^{1/3})^{-1}$ on transformation of the composite nucleus ${}^{\mathrm{B}}\mathrm{Z}\,{}^{\mathrm{A}}\mathrm{n}$ to ${}^{\mathrm{B}}\mathrm{Z}\,(^{\mathrm{A}}\mathrm{H})_{\max}$. [Note that ΔE_c is the increment of energy for two components that barely touch; if they bond more strongly and the area of contact is appreciable, the value of ΔE_c will be larger because the distance between charge centers will be smaller.] For beta decay of the composite ${}^{16}\mathrm{O}\,{}^{\mathrm{A}}\mathrm{n}$ we have

$$^{16}\mathrm{O}\,{}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,(^{\mathrm{A}}\mathrm{H})_{\max} + \Big(-0.78 + 0.711\,(16)\left(16^{1/3} + (2\mathrm{A})^{1/3}\right)^{-1}\Big)\ \mathrm{MeV}. \qquad (16)$$

The -0.78 MeV energy term is the reduction in mass excess on transformation of n to p, and the other term is ΔE_c with oxygen as the ordinary nucleus and taking $\alpha = 2$. In this reaction beta decay is exothermic for A>1760 and is otherwise endothermic. For $\mathrm{A} < 1760$ the only decay channel for ${}^{16}\mathrm{O}\,{}^{\mathrm{A}}\mathrm{n}$ requires double beta decay and alpha emission in a single coordinated process,

$$^{16}\mathrm{O}\,{}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O}\,{}^{\mathrm{A-4}}\mathrm{n} + {}^{4}\mathrm{He} + (0.38/5.18)\,\mathrm{MeV}. \qquad (17)$$

The first energy value corresponds to the small A region and the second to the large A region. The energy term $4D - \Delta(^{4}\mathrm{He})$ requires $D > 0.61$ for the reaction to be exothermic and is more restrictive than the $D > 0.39$ requirement for exothermic beta decay. the choice $D = 0.70$ previously made satisfies both requirements.

6. Lifetime and Size Effects

As shown in reaction (17) neutron isotopes decay by a succession of β, β, and α decays. Because the probability of β decay of a neutron is independent of the size of the isotope to which it belongs, the overall rate of decay is proportional to the size of the isotope. As isotope size A tends to increase by repetitions of reaction (5) the decay rate increases in proportion to A while the rate of reaction (5) stays nearly constant.

Reaction (5) adds neutrons to isotope ${}^{\mathrm{A}}\mathrm{n}$ at a nearly steady rate independent of A, but the rate of removal of neutrons by reaction (17) increases in proportion to A. If reactions (5)

and (17) were the only operative reactions polyneutrons would cease growing at the vallue of A for which the rates of neutron addition and removal became equal. This is the maximum equilibrium size that can be achieved by any combination of reactions (in oxygen), because all possible additional reactions result in a reduction of polyneutron size or capture of an entire polyneutron. Chain reaction requires that the rate of growth via reaction (5) exceed the sum of the rates of shrinkage and elimination due to the additional reactions.

In consequence we can anticipate that changes in the physical environment of the ^{18}O nuclei that support polyneutron growth in oxygen gas cn shrink the equilibrium sizes of polyneutrons in a chain reaction, or in extreme cases can abort the reaction if the rate of growth falls below the combined rates of shrinkage. Beginning with oxygen gas some additions including ^{1}H do not interact strongly with polyneutrons and have essentially no influence on chain reactions. The reaction observed in the oxygen-hydrogen vapor over a light-water electrolyte is the same as would be expected for oxygen alone.

The situation is different for a mixture of oxygen and nitrogen. Nitrogen acts to shrink polyneutron size in the reaction

$$^{14}\mathrm{N} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{15}\mathrm{N} + {}^{\mathrm{A-1}}\mathrm{n} + (3.46/4.66)\,\mathrm{MeV}. \tag{18}$$

As the nitrogen/oxygen ratio increases the equilibrium size of chain-reaction polyneutrons must decrease. The decrease in equilibrium size can in turn affect the rate of multiplication via reaction ( ). The multiplication reaction (6) is rewritten here with the energy term shown explicitly.

$$^{18}\mathrm{O} + {}^{\mathrm{A}}\mathrm{n} \longrightarrow {}^{16}\mathrm{O} + {}^{\mathrm{B}}\mathrm{n} + {}^{\mathrm{A-B+2}}\mathrm{n} \tag{19}$$

$$+ \left(3.96 + \Delta({}^{\mathrm{A}}\mathrm{n}) - \Delta({}^{\mathrm{B}}\mathrm{n}) - \Delta({}^{\mathrm{A-B+2}}\mathrm{n})\right)\ \mathrm{MeV} \tag{20}$$

where $\Delta({}^{\mathrm{A}}\mathrm{n}$ is given by equation (13). The magnitude of the energy term depends on the sizes of B and of $\mathrm{A}-\mathrm{B}+2$. The reaction is exothermic only when both of these quantities are ≥ 22, giving a net energy release of 0.16 MeV. [The reaction appears to be exothermic when both quantities are less than 22, but this is an artifact of the straight-line approximation to $\Delta({}^{\mathrm{A}}\mathrm{n})$. Considering the physically correct upward concave curve for $\Delta({}^{\mathrm{A}}\mathrm{n})$ throughout its range the reaction is endothermic.] As a result no polyneutron smaller than ^{42}n for which the multiplication reaction is $^{18}\mathrm{O} + {}^{42}\mathrm{n} \longrightarrow {}^{16}\mathrm{O} + {}^{22}\mathrm{n} + {}^{22}\mathrm{n}$ can participate in the chain reaction. If the concentration of nitrogen is large enough to bring the equilibrium polyneutron size below 42 neutrons, chain reaction is impossible and will be aborted if a free polyneutron is introduced into the system.

On such introduction a single polyneutron will grow in interaction with ^{18}O via reaction (5) and will shrink by $\beta\beta\alpha$ decay and by interaction with ^{14}N via reaction ( ), reaching an equilibrium size having fewer than 42 neutrons. Until the polyneutron is captured via reaction ( ) or otherwise it will continue to undergo $\beta\beta\alpha$ reactions which will generate a small shower

of alphas before the capture reaction aborts the reaction.

[do the alpha energies, the intermittent reaction since some steps are charged, etc.]

Acknowledgment

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