

POLYNEUTRONS AS AGENTS FOR COLD NUCLEAR REACTIONS

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New nuclear reactions are described where polyneutrons exchange neutron pairs with charged nuclides, liberating substantial energy with only minor production of neutrons and tritium. It is postulated that polyneutrons are bound in a totally paired collective phase analogous to the Bardeen-Cooper-Schrieffer superconducting phase, that massive precursor hydrogen nuclides are bound in the same collective phase, and that polyneutrons are generated from precursor hydrogen by reaction with neutrons. The concentration and disposition of precursor hydrogen, of lithium, and of neutron-moderating and neutron-absorbing materials in the reactor environment emerge as key variables in cold nuclear reaction processes.

INTRODUCTION

Fleischmann and Pons¹ reported cold nuclear reactions in electrolytically deuterated palladium, based on observations of net energy output from their electrochemical cells far in excess of anything that could be attributed to chemical processes. Following their initial report, many attempts have been made to duplicate or extend their work. A comprehensive review by Storms² of the experimental situation has been published. A number of calorimetric experiments have confirmed energy generation at levels attributable only to nuclear processes.^a Other experiments have detected tritium^b or neutrons^c significantly exceeding background, but far below the amounts expected from fusion of deuterium. Bush et al.³ have detected ⁴He in amounts more nearly comparable with what would be expected from deuterium fusion.

If one accepts that nuclear reactions are responsible for the excess energy, one sees that the limited production of neutrons and tritium indicates that deuterium fusion cannot account for it. A new nuclear reaction path is required. Because electrostatic forces prevent the close approach of charged nu-

clei at ordinary temperatures, one of each pair of reacting entities must be neutral. Because so few neutrons are observed, the neutral entity cannot be a neutron. I hypothesize that it can be a polyneutron.

Many conditions must be satisfied for polyneutrons to be able to serve as agents for nuclear reaction. Polyneutrons ^An must be bound for mass numbers $A \geq 6$. They must be generated from precursor ^AH nuclides by interaction with neutrons in the reactions $n + {}^A\text{H} \rightarrow {}^A n + {}^1\text{H}$. Precursor ^AH nuclides must be stable and must be present in some heavy water samples. Polyneutron reactions must be able to account for the various results of cold nuclear reaction experiments.

In the following sections, it is shown that these conditions are plausibly satisfied.

STRUCTURAL PHASES OF NUCLEAR MATTER

In all known nuclides, the structural phase of the constituent nuclear matter is well described by an independent-particle shell model. Protons occupy spin-orbital levels beginning with the lowest energy level and continuing through progressively higher energy levels until the last proton is accommodated. Neutrons independently occupy the same spin-orbital levels beginning with the lowest energy level and continuing through progressively higher levels until the last neutron is accommodated. Only in the neighborhood of the last protons and neutrons are there departures from strict independent-particle level filling. In these energy regions, there are generally admixtures of nearby spin-orbitals that have the effect of reducing the Coulomb energy by distorting the nuclear shape and by introducing short-range order that tends to keep protons farther apart in the nucleus. In neutron-rich nuclei, there may be pairing of neutrons of opposite spins and momenta with the effect of increasing the nuclear binding strength by the Bardeen-Cooper-Schrieffer (BCS) mechanism.⁴ A schematic representation of the occupation numbers of energy levels for a slightly neutron-rich nuclide is shown in Fig. 1.

The independent-particle phase of nuclear matter, quantified in the shell model, has been generally successful in accounting for the binding energies and other properties of nuclides near the valley of stability beginning with neutron number $N \approx 0.50A$ for small A and extending to $N \approx 0.62A$ for the largest known A . Extrapolation to $N \approx A$ suggests that polyneutrons ^An are not bound for any A . Experimentally, this expectation is supported for ²n, ³n, and ⁴n where

^aSee Table I of Ref. 2, which cites 23 reports of energy generation.

^bSee Table II of Ref. 2, which cites 13 reports of tritium generation.

^cSee Table III of Ref. 2, which cites 36 reports of neutron generation.

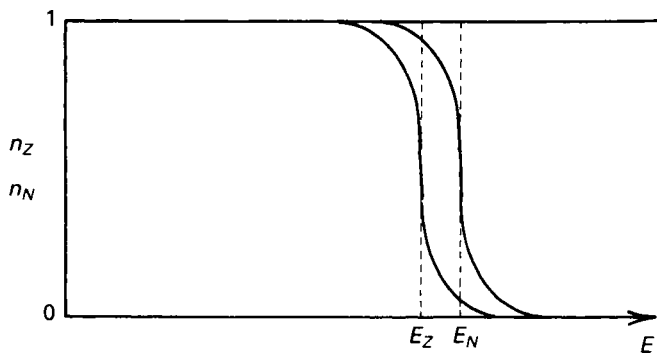


Fig. 1. Energy level occupation numbers in the independent particle phase (schematic). Z protons and N neutrons fill energy levels up to E_Z and E_N , respectively, with occupation numbers $n_Z = n_N = 1$ except near the highest energy levels where adjustments in occupation number allow reduction of Coulomb energy, or reduction of nuclear interaction energy by pairing of excess neutrons.

extensive searches for bound neutron configurations have given negative results.⁵ If bound polynucleons are to exist in nature, as they must if they are to serve as agents for cold nuclear reactions, they must be more massive and must be organized in some other structural phase.

As a candidate, consider the collective phase in which protons and neutrons are jointly paired throughout all energy levels, maximizing the BCS binding energy. This state is totally symmetric in the interchange of isospin coordinates between pairs of nucleons and thus has isotropic spin $T = A/2$. Pairs of time-reversed spin orbitals are empty or are occupied by pairs of nucleons—never by a single unpaired nucleon. Because of the rigidity of the pairing wave function, there is little opportunity for a reduction of Coulomb energy by an admixture of higher levels. A schematic representation of the occupation numbers of energy levels for a collective-phase nuclide is shown in Fig. 2.

There are few guidelines to the properties of the collective-pair phase except for those imposed by the experimental evidence against binding of polynucleons with $A \leq 4$ and by the hypothesized binding of more massive polynucleons to serve as agents for cold nuclear reactions.

The collective phase can be viewed as a condensation of

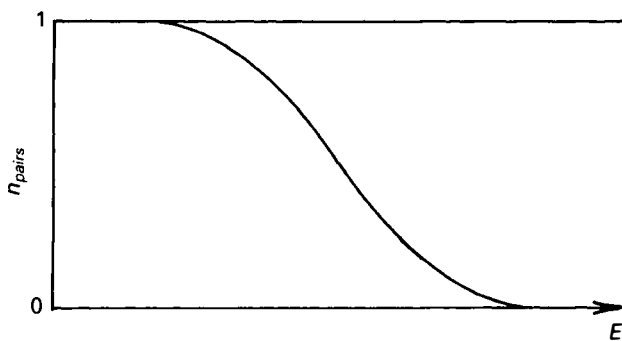


Fig. 2. Energy level occupation numbers in the collective-pair phase (schematic). The wave function is totally symmetric in the interchange of isotopic spin coordinates. Pairs of spin orbitals are empty or are occupied by pairs of nucleons—never by a single unpaired nucleon.

1S_0 pairs. Isolated 1S_0 neutron pairs are quasi-bound resonances⁵ with energy $E_2 \approx 0.1$ MeV. When P pairs are condensed into the collective phase, the nuclear portion of the condensation energy can be approximated by a liquid drop model represented by a volumetric term $-E_v(P - 1)$ and a surface term $+E_s(P - 1)^{2/3}$ where the use of $(P - 1)$ instead of P ensures that there is no contribution from a single pair. Because E_2 is so small compared with E_v , I neglect it in this illustrative analysis. Then, for even A , the resulting expression for the mass excess is

$$\Delta(A) = -\alpha(A - 2) + \beta(A - 2)^{2/3} + 8.0714N + 7.2890Z + CZ(Z - 1)A^{-1/3} \text{ MeV} . \quad (1)$$

Here, $-\alpha(A - 2) + \beta(A - 2)^{2/3}$ is the nuclear pair interaction portion written in terms of $(A - 2)$ instead of $(P - 1)$. The sum $+8.0714N + 7.2890Z$ is the mass excess of the constituent neutrons and protons. The $+CZ(Z - 1)A^{-1/3}$ term is the Coulomb energy of the constituent protons in a droplet with radius proportional to $A^{1/3}$.

To obtain illustrative estimates of the parameters in Eq. (1), I assume that $^A n$ is unbound for $A < 6$ but bound for $A \geq 6$. This sets $1.26\alpha < \beta < 1.59\alpha$. I assume that ^6H is more strongly bound than $^3\text{H} + 3n$, a necessary condition for its stability. This requires that the volumetric term for the collective phase be comparable with the volumetric term for the independent-particle phase. Stability of collective-phase precursor ^4H also requires that the beta decay $^4\text{H}(\text{collective}) \rightarrow ^4\text{He}(\text{collective})$ be energetically forbidden for the smallest bound ^4H nuclides. This in turn requires a larger Coulomb energy for the collective phase than for the independent-particle phase for which the decay $^3\text{H} \rightarrow ^3\text{He}$ is marginally exothermic. A larger Coulomb energy is reasonable because of Bose condensation correlations between pairs and because of the rigidity of the collective phase wave function, which inhibits Coulomb-reducing adjustments of proton configuration. For illustrative purposes, I assume $C = 0.75$ for the collective phase (compared with $C = 0.55$ for the independent-particle phase as determined from ^3H decay). A provisional formula for the mass excess for collective-phase nuclides that satisfies these various requirements is

$$\Delta(A) = -16(A - 2) + 21(A - 2)^{2/3} + 8.0714N + 7.2890Z + 0.75Z(Z - 1)A^{-1/3} \text{ MeV} . \quad (2)$$

NUCLEAR ENERGY LEVELS AND STABILITIES

The binding energy of a nuclide with mass number A in its minimum energy configuration for isotopic spin T is the sum of two parts, a strictly nuclear part $E(A, T)$ and a Coulomb part $C(A, T)Z(Z - 1)$. The Coulomb part is always positive and tends to prevent binding. The nuclear part can be negative, and when numerically greater than the Coulomb part, it causes binding.

Consider first only the nuclear part of the binding energy $E(A, T)$. The most strongly bound nuclei in the independent-particle phase correspond to $N = Z = A/2$ (or to $A/2 \pm 1/2$ for odd- A nuclei). The nuclear part of the binding energy becomes numerically smaller in nuclides for which the numbers of neutrons and protons are unequal. An illustrative example for $A = 6$ is shown in Fig. 3. The nuclear binding energies $E(6, T)$ for $T = 0$ and $T = 1$ are taken from experiment. The energy for $T = 2$ is estimated, and the extrapolation to $T = 3$ is unbound. Because the nuclear interaction is invariant under isotopic spin rotation, the binding energies are identical for the members of each isospin multiplet.

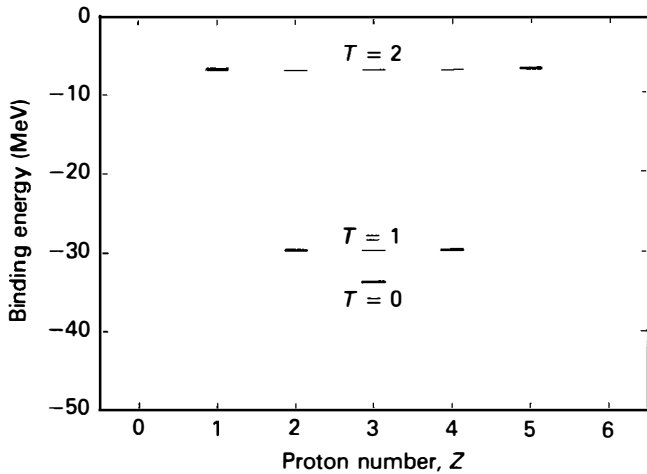


Fig. 3. Isospin multiplets for bound $A = 6$ nuclides in the independent-particle phase, showing isospin dependence of the nuclear portion of the binding energy. Ground-state nuclides are indicated by heavy bars. The binding energies correspond to the lower edges of the bars.

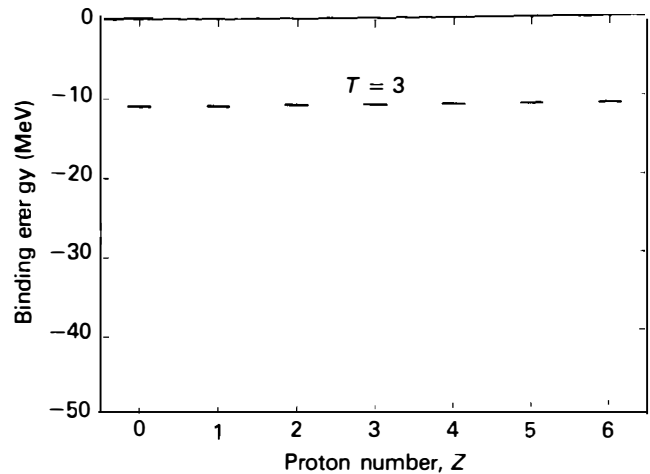


Fig. 4. Isospin multiplet for the $A = 6$ nuclides in the collective-pair phase.

Turning now to the collective phase, still considering only the nuclear portion of the binding energy, the isospin symmetry of the collective phase corresponds to $T = A/2$ independent of N or Z . All nuclides are bound equally strongly. Any departure from complete pairing corresponds to an excitation of the collective-pair phase and carries with it a finite excitation energy. An illustrative example for $A = 6$ is shown in Fig. 4. The binding energy for the $T = 3$ ground state is calculated from Eq. (2).

In their ground states, nuclides organize themselves into whichever phase is more strongly bound. For $A = 6$, referring to Figs. 3 and 4, nuclei with $Z = 0, 1, 5,$ and 6 will be in the collective phase, and nuclei with $Z = 2, 3,$ and 4 will be in the independent-particle phase. The resulting ground states are as sketched in Fig. 5.

To examine the stabilities of the various $A = 6$ nuclei, it is necessary to compare their mass excess values including the effects of the unequal neutron and proton masses and of the Coulomb energy. Ground-state and selected excited state energy levels are shown for the ${}^6n, {}^6\text{H},$ and ${}^6\text{He}$ nuclides in Fig. 6. The excited states shown are the minimum-energy states for the indicated phases and values of isospin T .

The collective hydrogen nuclide ${}^6\text{H}$ is stable. No strong, electromagnetic, or weak decay channel is available, as summarized in the caption of Fig. 6. The Coulomb energy plays an essential role in stabilizing collective hydrogen against beta decay to collective helium. If Z increases from 1 to 2, the constituent mass term in Eq. (2) changes by -0.7824 MeV, and the Coulomb portion of the binding energy increases from zero to $+1.5A^{-1/3}$ MeV. For $A = 6$, the overall change would be $+0.0431$ MeV, indicating that ${}^6\text{H}$ is stable. As A increases, the value of the Coulomb term decreases. Hence, there is a limited range of A for which ${}^A\text{H}$ is stable. With the parameters illustratively postulated in Eq. (2), this range includes only $A = 6$.

The parameters in Eq. (2) were estimated for nuclei with even A , and a question remains concerning the mass excess for nuclei with odd A . The binding energy of the collective phase is entirely due to the collective interaction of nucleon pairs. In the BCS model of fermion-pair condensation, a bro-

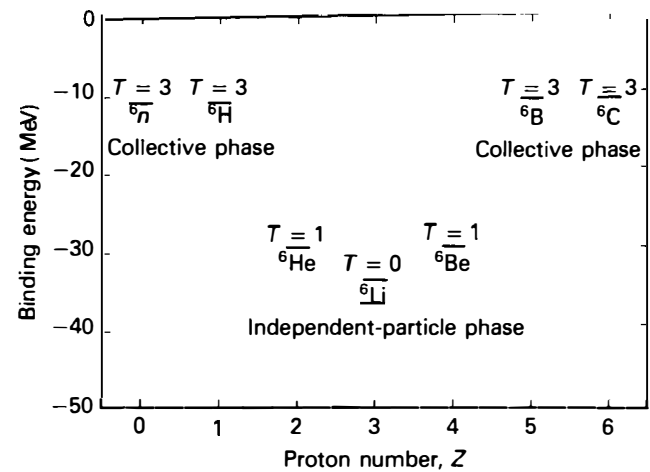


Fig. 5. Nuclear binding energies and isospins for the ground states of $A = 6$ nuclides from Figs. 3 and 4.

ken pair, consisting of two unpaired fermions in a confined state orthogonal to the ground state, is antibound. A single unpaired nucleon confined to the nuclear volume is also expected to be antibound. Hence, I assume that collective-phase nuclides with $A = 2P + 1$ are unstable against expulsion of the odd nucleon and that only those nuclides with even A are bound.

The valley of stability for collective-phase nuclides is very different from that for independent-particle nuclides. With the parameters of Eq. (2), stability shifts from nuclides with charge Z to nuclides with charge $Z + 1$ at $A = (1.5Z/0.7824)^3$, giving the following ranges of stability for the first few elements:

Element	Range of A Values for Collective-Phase Stability
Hydrogen	6
Helium	8 to 56
Lithium	58 to 190
Beryllium	192 to 450

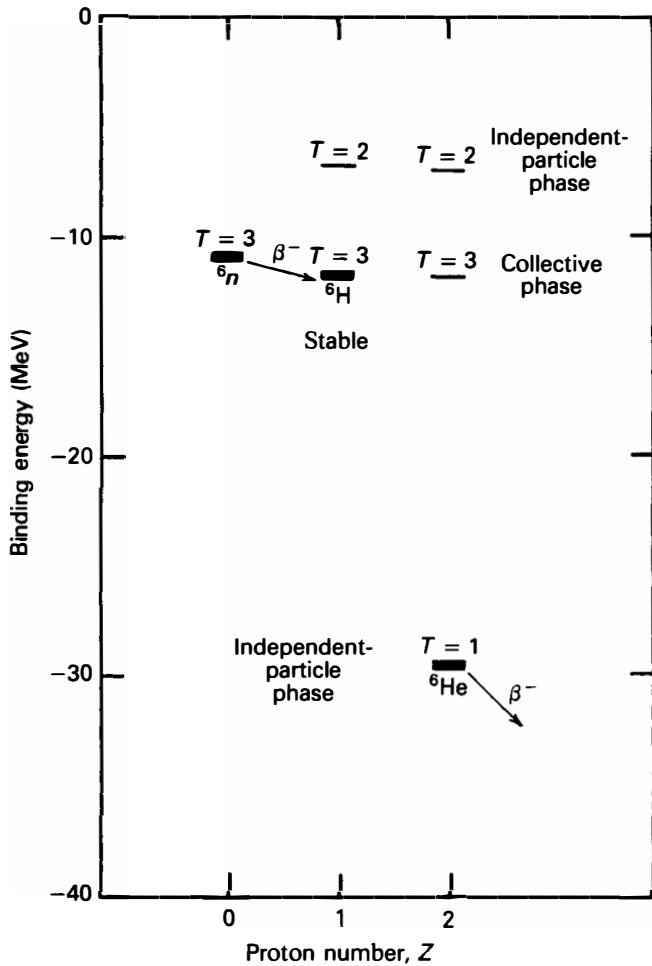
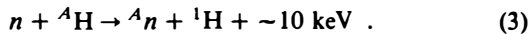


Fig. 6. Mass excesses for selected ground states and excited states of $A = 6$ nuclides. The collective-phase hydrogen isotope ${}^6\text{H}$ is stable because the breakup reaction ${}^6\text{H} \rightarrow {}^3\text{H} + 3n$ is endothermic, all electromagnetic transitions are endothermic, the beta decays ${}^6\text{H} \rightarrow {}^6\text{He}$ ($T = 3$) and ${}^6\text{H} \rightarrow {}^6\text{He}$ ($T = 2$) are endothermic, and the beta decay ${}^6\text{H} \rightarrow {}^6\text{He}$ ($T = 1$) is prohibited by the $\Delta T = 0, \pm 1$ selection rule.

The electrostatic energy of collective-phase nuclides is very small, and the mass excess falls without limit as sketched in Fig. 7.

POLYNEUTRON REACTIONS

Deuterium is an ingredient in all cold nuclear reaction experiments. I assume that stable ${}^4\text{H}$ is present as an impurity and that neutrons are available to initiate the formation of polyneutrons in the reaction



This reaction is estimated to be slightly exothermic with energy release of $\sim 10 \text{ keV}$ as indicated. The argument runs as follows. A neutron is more massive than a proton. Hence, if constrained to exactly the same wave function as the proton in ${}^A\text{H}$, a neutron will have slightly smaller kinetic energy. Equilibration of the ${}^A n$ wave function will further reduce the energy. In consequence, ${}^A n$ is slightly more strongly bound

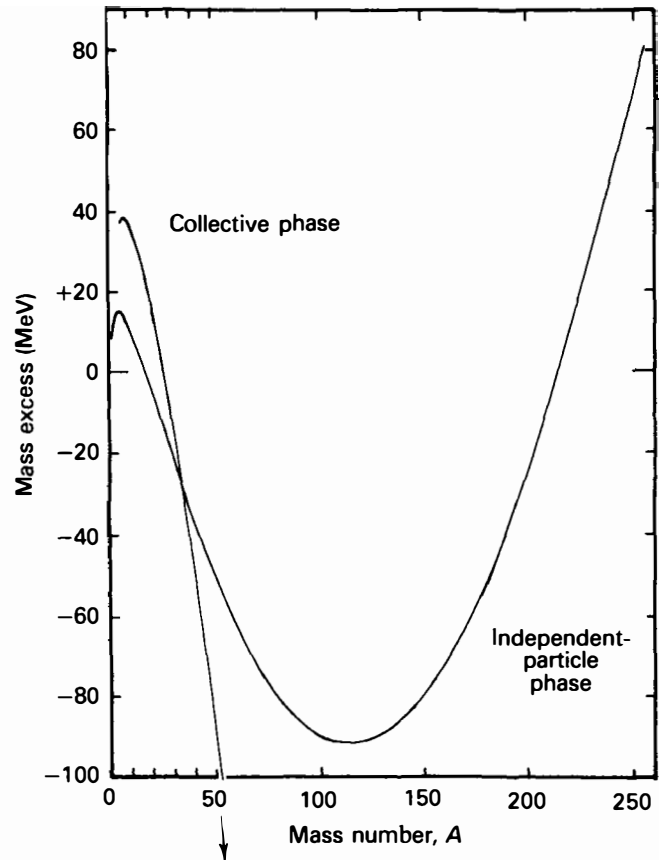


Fig. 7. Mass excesses for beta-stable nuclides in the collective and independent-particle phases. The curves correspond to the respective liquid-drop mass formulas. The Coulomb energies of collective phase nuclides are very small, and the mass excess declines without limit as A increases.

than ${}^4\text{H}$ even when the nuclear interaction potential is exactly the same for both, with the result that the reaction is exothermic.

Reaction (3) is the key initiating reaction for cold nuclear reactions, generating polyneutrons for various subsequent reactions. Since neutrons are neutral and the reaction is exothermic, the reaction cross section is inversely proportional to the neutron momentum. For thermal neutrons, the cross section can be very large. Polyneutrons also are neutral, and their cross sections for reactions with other nuclides are inversely proportional to polyneutron momentum.

In electrolytic cold nuclear reaction experiments, hydrogen, lithium, oxygen, and sometimes sulfur and other elements are present in the electrolyte; palladium and platinum are usually present as electrode materials; and various elements such as boron, silicon, aluminum, copper, and others are present as constituents of glass or metal reaction vessel materials. All of these are potential reactants with polyneutrons. Such reactions and their experimental implications can be explored in a self-consistent analysis based on plausible estimates of the relevant physical parameters. Specifically,

1. The mass excess values for collective phase nuclides are approximated by Eq. (2).
2. Only exothermic nuclear reactions that conserve isotopic spin are considered.

3. Reactions are considered to be of the form $A(B, X)Y$ with two reactants A and B and with two products X and Y . Reaction rates are assumed to be much smaller for reactions with three or more products.

4. Reactions with two charged reactants or two charged products are not considered, as their rates are very much reduced by the Coulomb barrier.

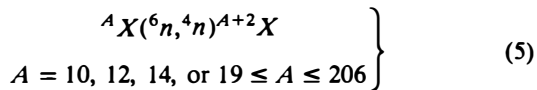
5. Recall that collective-phase nuclides have even A , so that nucleons must be transferred to or from them in pairs. The reaction rate is assumed to decrease as the number of pairs increases, and for simplicity, only those reactions involving transfer of a single pair are considered.

As a convention of notation, nuclides written within the parentheses of $A(B, X)Y$ are collective phase, and those outside are independent-particle phase. In addition, wherever they appear, ${}^A n$ is collective phase for $A \geq 4$, and ${}^A \text{H}$ is collective phase for $A \geq 6$.

With the mass excess values from Eq. (2), as assumed for illustrative purposes in this analysis, ${}^6\text{H}$ is the sole stable collective-phase hydrogen nuclide, and reaction (3) particularizes to



The polynutron products from this reaction can participate in subsequent reactions. As an example, in interaction with almost any nuclide, 6n can lose a pair of neutrons and shrink to 4n , which is unstable and promptly decays to four neutrons:

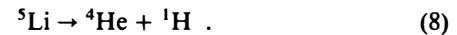
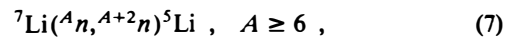


In most cold nuclear reaction experiments, reaction (4) proceeds when stray neutrons from the laboratory environment interact with ${}^6\text{H}$ present at low concentration in ordinary hydrogen compounds or deuterated hydrogen compounds in the experimental apparatus. Because ${}^6\text{H}$ tends to be concentrated in the production of deuterium, the concentration of ${}^6\text{H}$ is expected to be higher in deuterated compounds. Reaction (5) then proceeds by reaction of the resulting 6n with nuclides such as silicon, carbon, sulfur, platinum, palladium, copper, sodium, iron, or any of many others in the experimental apparatus, producing 4n , which disintegrates to four neutrons via reaction (6). Some of these neutrons can react with ${}^1\text{H}$ to form ${}^2\text{H}$ or can be lost in other ways. Some can react with ${}^6\text{H}$ nuclides to produce second-generation 6n via reaction (4).

If the concentration of ${}^6\text{H}$ is low, the likelihood of second-generation 6n production is small, and it is not possible to sustain a chain reaction. In this circumstance, neutrons are generated primarily in bursts of four, one burst for each stray neutron that interacts with ${}^6\text{H}$ somewhere in the apparatus. Occasionally, there will be an aggregate burst of seven when one of the neutrons from a primary burst generates a secondary burst, and exceptionally, there will be an aggregate burst of ten when a neutron from a secondary burst generates a tertiary burst, and so on. In experiments where the time resolution of neutron detection is poor, the microburst nature of neutron generation cannot be resolved, and neutrons from reactions (4), (5), and (6) reveal themselves only through an average level of neutron emission that is somewhat elevated over background.

If the concentration of ${}^6\text{H}$ is sufficiently high and if appropriate concentrations and dispositions are achieved for other reactive nuclides and for neutron and polynutron absorbing and moderating materials within and surrounding the experimental equipment, reactions (4), (5), and (6) will support a chain reaction that generates supplies of both neutrons and polyneutrons. On average, more than one neutron from a given burst of four will participate in reaction (4) and produce a next-generation burst. The number of bursts in successive generations will grow exponentially until sufficient ${}^6\text{H}$ is consumed that its concentration drops below the critical level. The time required for completing the chain reaction is extremely short, on the order of a small fraction of a second.

In other reactions, polyneutrons can gain pairs of neutrons and grow in size. In interaction with lithium, for example, a polynutron of any size $A \geq 6$ can gain a pair of neutrons from ${}^7\text{Li}$ while ${}^7\text{Li}$ is reduced to unstable ${}^5\text{Li}$, which promptly decomposes to ${}^4\text{He}$ and a proton:



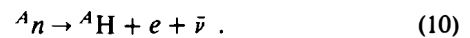
No matter what the value of A , from $A = 6$ on up, reaction (7) will increase it to $A + 2$, and by repeated reaction in a sufficiently large volume of ${}^7\text{Li}$, enormous values of A can be achieved. At the same time, reaction (8) can produce substantial quantities of helium and hydrogen.

Polyneutrons can grow but they cannot shrink in interaction with ${}^7\text{Li}$ because the reactions ${}^7\text{Li}({}^A n, {}^{A-2}n){}^9\text{Li}$ are endothermic for all A . Moreover, after reaching $A = 22$, polyneutrons cannot shrink in interaction with any independent-particle-phase nuclide. Beyond $A = 20$, polynutron growth must continue, in the ${}^7\text{Li}$ if that system is sufficiently large or otherwise outside that system at the expense of other nuclides, until it is stopped by conversion of ${}^A n$ to a charged nuclide.

The growth of large polyneutrons can be terminated only by a reaction that produces a charged collective-phase nuclide instead of a new polynutron. It can be that instead of a pair of neutrons, a neutron and a proton can be transferred as in

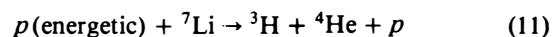


It also can be that beta decay of one of the neutrons in ${}^A n$ can convert it to ${}^A \text{H}$,



In each of these reactions, the collective-phase ${}^{A+2}\text{H}$ or ${}^A \text{H}$ product can no longer participate in cold nuclear reactions because of its electrostatic charge. Reactions (9) and (10) are both very slow, and the average polynutron size achieved before one of them can terminate growth is expected to be extremely large.

Polynutron growth transmutes the nuclides from which pairs of neutrons are taken and produces substantial nuclear energy, but it produces no neutrons and no tritium. A limited amount of tritium can be produced in ${}^7\text{Li}$ breakup reactions such as



driven by energetic reaction products, in this instance the proton from reaction (8), but the amount of ${}^3\text{H}$ is small compared with what would be expected if the energy released in polynutron growth had instead been released in deuterium fusion.

The near-absence of neutrons and the limited production of tritium, in relation to the production of energy, are characteristic of cold nuclear reactions. This suggests that most of the energy is derived from polynutron growth. Even with individual polynutron growth to $A \approx 10^9$, a considerable supply of polyneutrons is required to account for the magnitude of the energy generated. A corresponding supply of neutrons is required to trigger their production in reaction (4). Here, the chain reaction inherent in reactions (4), (5), and (6) plays an essential role. Reaction can be triggered by stray neutrons, but the chain reaction must continue on its own to produce the required supply of neutrons.

INTERPRETATION OF COLD NUCLEAR REACTION EXPERIMENTS

Reactions (4) through (8) can account for much of what is observed in electrolytic cold nuclear reaction experiments. In most of these, the anode and cathode are small, and the major portion of the nuclear energy is generated from the growth of polyneutrons in the electrolyte and its container. Although hydrogen nuclides ^1H and ^2H and lithium nuclide ^6Li are present in the electrolyte, they cannot react exothermally with polyneutrons.

The significance of deuterium in the electrolyte is limited to its roles as a relatively concentrated source of collective phase ^4H precursor for 4n and as a moderator and reflector for neutral nuclides.

Precursor ^6H is essential to the nuclear processes under consideration. The concentration of ^6H in some D_2O samples must be close to that required for criticality in typical electrolytic experiments since otherwise no chain reaction could be achieved and no substantial excess energy could be released. Because of its large mass, ^6H is expected to be concentrated along with deuterium during the production of D_2O . However, the concentration can never rise above the critical level where a chain reaction could occur through the coupled reactions (4), (5), and (6). If criticality is ever exceeded during production, packaging, shipment, or storage of D_2O , chain reaction promptly ensues, and the ^6H concentration is driven back down to the level of criticality.

As one relevant configuration, consider a group of D_2O samples in glass bottles that have been packed together for storage and shipping. Neutrons can react with ^6H in the D_2O to make polyneutrons, and polyneutrons can react with nuclides in the glass to make neutrons. The extended geometry of the mass of bottles provides moderating and reflecting power for both neutrons and polyneutrons, holding most of them within the system and favoring reactivity. No bottle of D_2O can retain a concentration of ^6H exceeding the critical concentration level for such a system.

It seems unlikely that the ^6H concentration in nature would have just the right value to approach, yet not to exceed, the critical level during concentration and packaging along with D_2O . It seems more likely that the concentration is higher in nature and that some ^6H is lost in chain reactions during the production and packaging processes. The concentration of the remaining ^6H cannot exceed the level for criticality in the last chain reaction in the history of the D_2O but would likely be close to the level required for criticality in cold nuclear reaction experiments. Only a modest increase of reactivity would be required in these experiments to achieve criticality again.

To the extent that ^6H is consumed in chain reactions

during heavy water production, as suggested to account for a near-critical concentration of ^6H in some heavy water samples, there must be an accounting for the neutrons and nuclear energy that are expected as by-products. The neutrons that are liberated when ^6H is consumed could have been overlooked if the natural abundance of ^6H is low. But, the energy generated from polynutron growth, estimated to be on the order of 10^9 MeV per polynutron, could be relatively large, and if present, would likely have been observed. Hence, it must be that polyneutrons are not able to grow in the deuterium production environment.

Assuming that the materials in the typical D_2O production environment are composed primarily of elements that exclude lithium and that are lighter than zirconium, only the rare oxygen isotope ^{18}O (0.2% abundance) is capable of initiating polynutron growth. About 10^{-3} of the 6n polyneutrons are expected to find an ^{18}O nuclide and to participate in the reaction $^{18}\text{O}(^6n, ^8n)^{16}\text{O}$ generating 8n polyneutrons, while all the others react with nuclides in the production environment to produce neutrons. The 8n polyneutrons can grow to ^{10}n in reactions with ^{18}O (0.2%), ^{36}S (0.02%), ^{48}Ca (0.2%), or ^{64}Ni (0.9%) to the extent that these nuclides are present in the reaction environment. Overall, perhaps 10^{-3} to 10^{-2} of the 8n grow to ^{10}n , while the rest react with other nuclides in the environment and shrink back to 6n . In the end, perhaps 10^{-9} proportion of polyneutrons reach the size beyond which unlimited growth becomes more probable than shrinkage. As a result, no significant excess energy is expected during the production of deuterium.

The situation must be quite different in cold nuclear reaction experiments, where large quantities of energy have been observed. Beyond establishing conditions that support a nuclear chain reaction and the production of polyneutrons, it is essential also to establish conditions that favor polynutron growth.

Consider first the factors that can improve reactivity and can in combination achieve a chain reaction in electrochemical experiments. I assume that the ^6H concentration in the D_2O employed is within a small factor of the critical concentration for the experimental configuration.

The ^6H concentration can be increased by dissociation of D_2O and loss of deuterium preferentially to loss of ^6H from an open system, followed by addition of fresh ^6H along with makeup D_2O . It is probable that the ^6H concentration can be increased several-fold in this way. Chain reaction requires that neutrons from reaction (6) not be lost to the system before they can react with ^6H to generate polyneutrons in reaction (1). Neutron management can be improved by enlarging the volume of electrolyte, so that the ^6H target size for effective neutron reaction is increased. For small systems, neutron management can be further improved by surrounding the electrolytic cell with water or other materials to act as neutron moderators and reflectors. It is important that neutron-absorbing materials not be present in the moderation and reflection volume. Chain reaction also requires that nuclides AX be present so that reaction (5) can perform its role.

It is important to keep in mind that chain reaction promptly follows criticality. If a chain reaction is to be observed in any experiment, reactivity must be increased after all measuring equipment is in place and the experiment is in operation, or else the action will already have taken place and will have been missed. Dissociation of D_2O and replenishment of lost electrolyte with makeup D_2O (containing ^6H impurity) is perhaps the simplest way to achieve an increase of reactivity during the course of an experiment.

Having achieved criticality and a chain reaction, the production of energy requires that an additional condition be met. Nuclides must be present with which small polyneutrons can react and grow. Here, ${}^7\text{Li}$ plays a unique role, being the only nuclide (other than the rare ${}^{18}\text{O}$) that supports polyneutron growth but not polyneutron shrinkage. (Some heavy elements scattered from zirconium to uranium can support growth of small polyneutrons, but they also support shrinkage and are not as effective as ${}^7\text{Li}$ in producing net growth.) Polyneutron growth and energy generation can be achieved by adding sufficient ${}^7\text{Li}$ to a sufficiently large volume of electrolyte that an appreciable proportion of polyneutrons will react several times successively with ${}^7\text{Li}$, thereby achieving the size required for continued growth in any environment. Note, however, that generation of energy implies loss of reactivity since polyneutrons that pass the threshold for unlimited growth are no longer able to participate in a chain reaction. If the lithium concentration is too large in relation to the concentration of ${}^A X$, the reaction will be quenched.

The foregoing discussion relates to experiments where the volume of palladium is small and where chain reactions (4), (5), and (6) occur primarily in the electrolyte. If, however, the volume of palladium is sufficiently large, with linear dimensions exceeding neutron and polyneutron mean free paths, chain reaction is possible in the palladium-hydrogen system alone where reactions (4), (5), and (6) particularize to



and



For reactions (4) and (5), each having a neutral reactant and a neutral product, there is no Coulomb barrier for merging of reactants or for separation of products, and the reaction cross sections can be extremely large. The neutron and polyneutron mean free paths can be correspondingly short. Given sufficient concentration of ${}^6\text{H}$ in the palladium via the electrodeposition process, palladium linear dimensions of a fraction of a centimetre may be sufficient to contain the chain reaction. Under these circumstances, a level of intermittent chain reaction can be maintained by the influx of ${}^6\text{H}$ from electrolysis, and the excess energy characteristic of cold nuclear reactions can be generated by growth of polyneutrons that escape to the electrolyte where they can interact with ${}^7\text{Li}$.

Although the situation is extremely complex when all factors are taken into consideration, overall, it appears that the general features of cold nuclear reactions in electrolytic cells can be explained in this way.

IMPLICATIONS

The evidence from cold nuclear reaction experiments points to a new branch of nuclear physics. Bound polyneutrons are postulated as mediators of cold nuclear reactions. Stable massive hydrogen is postulated as a polyneutron precursor. Stability of these nuclides implies a collective-pair structural phase of nuclear matter. The model of polyneutrons as participants in chain reactions that multiply their numbers, and as agents for transmutation and energy production as they grow by accretion of neutron pairs removed from ordinary nuclides, appears capable of accounting for the experimental results. It suggests that the cold nuclear reaction discovery of Fleischmann and Pons may have opened the way to rich new fields of nuclear science and technology.

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