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NUCLEAR FUSION CHAIN REACTION APPLICATIONS IN PHYSICS AND ASTROPHYSICS

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ABSTRACT

Nuclear fusion chain reactions have been proposed for supernovae and controlled fusion reactors. The concept of fusion chain reactions will be traced with emphasis on possible applications in physics and astrophysics. Reaction kinetics calculations of D-T and D-³He fusion-ing plasmas reveal the presence of suprathermal particles as the end products of the reactions. These suprathermal end products can be active chain centers for the propagation of energy releasing fusion chain reactions with fuels having $Z \geq 3$. A ⁶LiD fueled fusion reactor has a calculated Lawson number, $n\tau$, lower by a factor of three compared to a pure deuterium fueled fusion reactor. The first ⁶LiD fueled fusion reactor will be sub-critical with the electrons sustained at MeV temperatures by electron cyclotron heating. If net power producers using ⁶LiD fuel are eventually feasible they would be large in size, well reflected, and have a high beta ($\beta = 8\pi m k T / B^2$) in order to minimize synchrotron radiation losses. Closed magnetic configurations would also be required to ensure the propagation of fusion chain reactions. Higher powered d.c. accelerators would be essential to exploit this field of controlled fusion reactors, although a scientific feasibility experiment may be executed with existing accelerators (~ 2 mA, 4 MeV H_2^+). Present day astrophysical calculations appear to be inadequate to account for the rapid nuclear processes in astrophysical explosions inasmuch as such calculations neglect the presence of suprathermal chain centers and multiplying chain reactions. The 55 day light decay of Type I supernovae may possibly be explained by the production of ⁷Be (53.61 d) in chain reaction burning of neon and oxygen followed by ⁷Li burning in the residual star. Evaluation of these new prospects will require more accurate data on and broader coverage of the pertinent nuclear reaction cross sections for fuels Li - S and n, p, d, t, ³He, and α particles as suprathermal (E up to 20 MeV) chain centers.

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PREFACE

No present controlled fusion experiment is within a factor of 1000 of the temperature, density, and confinement time product, $Tn\tau > 10^{22}$ K cm⁻³ sec, condition required for a scientific demonstration for fusion analogous to that obtained in 1942 by Fermi for the fission process. I shall present some ideas on a relatively new, bold and expensive approach to a scientific feasibility experiment for controlled fusion. The major ingredient of this approach is the concept of charged particle nuclear fusion chain reactions at MeV energies for fuels like ⁶LiD and catalysts or suprathreshold chain centers like p, d, t, ³He, and α which permit the more rapid burning of ⁶LiD to alpha particles than the direct reaction does. One of the chief requirements for evaluating the concept of nuclear fusion chain reactions in controlled fusion research is the accurate, wide-ranging determination of absolute nuclear reaction cross sections as well as those for nuclear elastic and inelastic processes.

A fitting corollary to these ideas is the concept of nuclear fusion chain reactions in the field of astrophysics, such as the gigantic explosions of supernovae. Here again there is a real need for accurate nuclear data which could lead to the evaluation of new and pregnant ideas on nuclear fusion chain reactions involving fuels like C, N, O, Ne, etc. Such processes might explain the production of the light elements, Li, Be and B, which is apparently an unresolved puzzle in astrophysical systems.

1. INTRODUCTION

Nuclear fusion chain reactions are very analogous to chemical chain reactions. In contradistinction to fission chain reactions which give a multiplication of neutrons in one reaction step, the nuclear fusion and chemical chain reactions generally produce a multiplication of catalysts or suprathreshold chain centers in two or more reaction steps with an overall net energy release in the complete chain sequence. These suprathreshold particles speed up the reaction rate by by-passing the direct thermal (or thermonuclear) reaction. Thermal or thermonuclear reactions between two fuel nuclei will generate additional chain centers and thus can lead to an increased possibility of exponentially growing chain reactions. The complete process should probably be referred to as a chain-thermal or chain-thermonuclear reaction.

The first chemical chain reactions were recorded by Max Bodenstein, a German chemist, who observed that a single initiation reaction in molecular hydrogen and chlorine gas mixtures stimulated a sequence of chain reactions which propagated through the chemical fuel several tens of thousands of times[1]. His proposed chemical chain reaction processes were later correctly identified as involving free atoms of H and Cl as the active chain centers by Nernst (Fig. 1). The propagation chain involves a free chlorine atom reacting with H₂ to produce HCl and a free hydrogen atom which then can react with a chlorine molecule to produce both a net energy release and the regeneration of a new free chlorine atom, which could keep the chain reaction going. Chain breaking reactions include wall or plasma recombination processes and will tend to stop the chain. On the other hand, chain branching reactions, such as the dissociation of HCl, H₂ or Cl₂ molecules by photon, electron, or atom collision processes, will continue or even proliferate the

chains. In general, the active chain centers are slightly suprathermal in energy since they carry energy provided by the center of mass of the energetic colliding species as well as the energy released in the reaction. The presence of suprathermal chain centers and multiplying chain reactions is extremely important in the explanation of rapid combustion or explosive processes.

Practically all chemical combustion or explosion processes depend on chain or chain-thermal reaction steps. In the case of nuclear fusion chain reactions, we find analogous examples of the initiation steps, propagation chains, and both chain breaking and chain branching steps of chemical chain reactions, as well as breeding reactions which can produce exotic nuclear fuels like tritium or ^3He as highly active chain centers.

At high plasma temperatures, where one expects endothermic and inverse reactions to occur as well as increased radiation losses, the important property of a negative temperature coefficient for the control of the burning or operating temperature of the chemical or nuclear system becomes of importance. The nuclear operating temperature is quite distinct from the kindling or ignition temperature for the nuclear fire. It was apparently first discussed for the thermonuclear case by Huss[2] and later by Ohta, et al[3] and others. By proper control of fuel feed, ash loss, and confinement configuration one can maintain a stable burning temperature. The reacting system is thermally unstable at, or just above, the ignition temperature and flashes over to the "burning temperature" of the system. As ash build-up occurs this burning temperature decreases in general to a somewhat lower operating temperature though still above the ignition temperature if burning continues. If, on the other hand, the ashes include suprathermal particles which can operate as active chain centers to speed up the reaction, the system will be again thermally unstable and a somewhat higher, secondary burning temperature will be established.

The concept of "temperature" is ill defined in both chemical and nuclear combustion processes: the chain centers are suprathermal, i.e., somewhat hotter than the electrons or fuel atoms or nuclei. This has been shown in calculations at the Culham and Lawrence Livermore Laboratories for $\text{d}\cdot\text{t}$ and $\text{d}\cdot^3\text{He}$ nuclear fusing systems in which the protons and alpha particles are calculated to be at least ten times hotter than the electrons.

Nuclear fusion chain reactions were apparently first proposed by Ulrich Jetter, a German engineer, back in 1950[4]. He chose ^6LiD as the basic nuclear fusion fuel and selected neutrons and tritons as the active chain centers. The propagation cycle which he proposed utilized the two most reactive light element fusion reactions ($\text{d}\cdot\text{t}$ and $\text{n}\cdot^6\text{Li}$) and would burn ^6LiD to alpha particles much faster than the direct reaction $^6\text{Li} + \text{D} \rightarrow 2\alpha + 22.4 \text{ MeV}$. In addition, he suggested thermal or thermonuclear chain branching reactions involving the $\text{d}\cdot\text{d}_t$ and $\text{d}\cdot\text{d}_n$ processes. He also proposed neutron branching reactions involving the fast neutron dissociation of the deuteron or ^9Be , or the fission of uranium. These branched reactions give a multiplication of the number of active neutron and triton chain centers, and thus can speed up the reaction many-fold.

It is of historical interest to note that, shortly after the discovery of the neutron by James Chadwick, Leo Szilard proposed a chain

reaction probably involving the ${}^9\text{Be}(n,2n)2\alpha$ - 1.7 MeV neutron multiplying reaction, but apparently Szilard could not find any way to keep the neutrons hot to maintain the chain reaction.

In 1961 Richard Post of Lawrence Livermore Laboratory proposed a nuclear fusion chain reaction involving only charged particles[5]—such a process might permit the magnetic containment of the energetic reaction products in controlled fusion reactors. Figure 3 illustrates the essential elements of his scheme. Since Post was at that time interested in open-ended, leaky magnetic mirror confinement systems using $\text{D}\cdot{}^3\text{He}$ fuel with added ${}^6\text{Li}$, he visualized re-injecting the ${}^3\text{He}$ end product from the $\text{p}\cdot{}^6\text{Li}$ reaction back into the fusion reactor to fuse with deuteron fuel ions and thus regenerate the 14 MeV protons to continue the cycle. Breeding (or chain branching) reactions of the type $\text{d}(\text{d},\text{n}){}^3\text{He} + 3.3$ MeV and $\text{d}(\text{d},\text{p})\text{t} + 4.0$ MeV would generate both of the energy-rich t and ${}^3\text{He}$ in such a ${}^6\text{Li}\cdot\text{D}$ fueled fusion reactor. However, Post limited his considerations to leaky or open-ended magnetic mirror confinement configurations and presumed very efficient reinjection of the t and ${}^3\text{He}$.

In 1963, completely unaware of these various nuclear fusion chain reaction prospects, I discovered a whole plethora of charged particle fusion chain reactions[6]. However, I could find no way at that time to overcome the stopping power losses of the energetic chain centers on the colder electrons in order to maintain a meaningful burning temperature for ${}^6\text{Li}$ or ${}^6\text{LiD}$ fueled plasmas[7]. More recently, the prospects for overcoming the stopping power losses have brightened as the result of the development of electron cyclotron heating techniques which could lead to a sub-critical fusion chain reactor. In addition, the principle of closing the ends of a leaky magnetic mirror has been experimentally demonstrated. Thus, it may be possible in the near future to develop controlled, but sub-critical, fusion chain reactors using ${}^6\text{Li}$ or ${}^6\text{LiD}$ fuels and in which some of the "ashes" behave as active chain centers at MeV energies. Net fusion power producers, if they ever become feasible, would involve major engineering developments and efficient microwave reflecting walls as well as high β plasmas. Ignition of such devices would require powerful d.c. accelerators while the understanding and design of such reactors will require more accurate charged-particle nuclear cross sections covering a wide range of energies up to about 20 MeV. More than 50 reactions are involved among the various light isotopes up to at least beryllium.

In late 1963, I discovered the first of many nuclear fusion chain reactions which involve medium heavy element fuels like C, N, O, and Ne reacting with active chain centers such as energetic n , p , d , t , ${}^3\text{He}$, and α particles[8]. It appears that these latter nuclear chain reactions can occur only in super-dense media like pre-supernovae stars where the degenerate electron gas has a grossly reduced stopping power for the fast ions.

My presentation today deals with prospective applications of nuclear fusion chain reactions in physics and astrophysics. In the physics case of controlled fusion reactors, the basic reactions are primarily of the charged particle type inasmuch as neutrons do not appear to be conservable in a magnetically confined plasma. The escaping

neutrons can be used for energy or tritium multiplication in an external Na or Li blanket. In the astrophysics case of exploding dense stars, neutrons will play a very important role as one of the active chain centers in the fast nuclear processes taking place in these very high temperature systems. These latter nuclear fusion chain reactions will supplement the thermal or thermonuclear reactions originally proposed by Hoyle and Fowler for supernovae explosions[9].

2. NUCLEAR FUSION CHAIN REACTION PROSPECTS IN PHYSICS

It is too early to claim that charged particle nuclear fusion chain reactions may play a decisive role in controlled fusion reactors, but the prospects are much brighter now than in 1961 when Post first suggested charged particle fusion chain reactions. Closed magnetic confinement devices would be required such as stoppered magnetic mirrors (closed by large internal plasma currents), bumpy tori (which are multiple magnetic mirrors connected toroidally), or tori of the Tokamak or stellarator varieties. Magnetic bremsstrahlung at the high electron temperatures would have to be grossly reduced by utilizing large reactor sizes, by operating with plasmas having a high plasma beta ($\beta = 8mkT/B^2$), and by providing efficiently reflected microwave and/or infrared radiation. The magnetic bremsstrahlung or synchrotron radiation power is reduced proportional to $(1-R)$ and $(1-\beta)$, respectively. $R > 0.99$ may be expected for clean metallic walls in the infrared and microwave region and $\beta > 0.5$ has been actually obtained in a number of plasma experiments.

Figure 4 illustrates some of the major developments which have occurred in CTR magnetic mirror research. A mini breakthrough in energetic ion trapping in magnetic mirrors has been marginally attained at Culham on the PHOENIX II device and more definitively established at Lawrence Livermore Laboratory on the Baseball II device. At Livermore large scale trapping (30 fold increase over the Lorentz or $v \times B$ trapping by dissociation of excited hydrogen atoms) has been observed for the injected neutrals by the already trapped plasma. A very important process called exponential build-up of the proton density over the charge exchange losses has been conclusively demonstrated at Livermore although it eventually dies out at a density approaching 10^{10} cm^{-3} [10]. The Fermi fission feasibility experiment of 1942 demonstrated an exponential growth process for the build-up of neutrons in a fission experiment. The plasma exponential process for trapping of protons under a more optimum choice of injection energy would permit the large scale exponential build-up of the plasma into the density range of real fusion interest[11]. In various magnetic mirror devices, such as the original Soviet OGRA and the American DCX facilities, the ion "temperature" and confinement times were of thermonuclear interest, but the density was orders of magnitude too low. Now, a realistic exponential scaling law has been demonstrated at Culham and especially at Livermore somewhat analogous to the critical exponential test of Fermi for fission. If instabilities do not limit the build-up process a large scale exponential test for fusion may be demonstrated with multi-MeV injection[11].

The scaling law for the density $\times$ confinement time product, $n\tau$, for scatter-dominated losses of energetic ions in magnetic mirror machines indicates that the crucial $n\tau$ number increases as the $3/2$ power of the

energy of the injected ions[12]. Thus, at 1 MeV injection energy for the ions, $n\tau$ is a factor of 1000 times more favorable than at 10 keV injection energy. The electrons must also be raised to very high energy in order to reduce their stopping power effects—however, this has been satisfactorily accomplished at Oak Ridge by resonance and upper off-resonance electron cyclotron heating of the electrons to MeV energies in devices such as the ELMO magnetic mirror facility[13].

The possibility of the large scale exponential build-up of plasmas to high densities at MeV energies and for long confinement times was outlined by me in 1970 and 1971[11] and involved injection of 2 mA of 4 MeV H_2^+ ions into a simple magnetic mirror. Closure of the magnetic mirror by the self-current of the trapped protons would require a 10-20 mA, 4 MeV H_2^+ beam to produce a sufficiently large circulating ion current to reverse the magnetic field on the axis—a small scale version of the proton E-layer of the late N. C. Christofilos of Livermore.

The experimental prospect for closing a magnetic mirror by a large internal current of relativistic electrons—the so-called E-layer—has been studied at Livermore and eventually was successfully demonstrated in 1971 and 1972 at Cornell University[14]. Such closed magnetic mirror devices might be termed "orthogonal Tokamaks" since the plasma current is at right angles to the applied magnetic field whereas in the Tokamak device the plasma current is parallel to the magnetic guide field.

Reaction kinetics calculations of fusing plasmas fueled with D-T and D- 3He have been carried out at Culham and Livermore by means of Fokker-Planck equations which include the slowing down and energy diffusion of the charged reaction products, p and α , in the reacting plasma[15,16]. These calculations revealed mean ion energies greater than 1 MeV for both the protons and the alpha particles even without supplemental microwave heating of the electrons. However, the calculations omitted radiation losses so that electron cyclotron heating would probably be required in any small scale laboratory device to offset the synchrotron losses and maintain the protons and alphas at MeV energies.

Nuclear fusion chain reactions require such suprathermal or MeV particle energies to propagate the fusion chain reactions in fuels like 6Li or 6LiD . Since even in leaky magnetic mirrors the fusion "ashes" can have multi-MeV energies, the overall prospect for viable nuclear fusion chain reactions in closed magnetic configurations looks extremely favorable. Initially such systems would be sub-critical because of the synchrotron losses, but large systems may prove to have a net power.

Figure 5 shows the calculated energy distribution function for a 3 MeV proton slowing down in a mirror confined plasma having $T_e \sim 30$ keV. Figure 6 illustrates Livermore calculations on the particle velocity distribution functions for different ion and electron species in a fusing D-T plasma confined in a magnetic mirror having a mirror ratio $R (= B_{max}/B_0)$ of 3 and 10, respectively[16]. For the $R = 10$ case the alpha products slow down and diffuse to an average energy of 1.2 MeV whereas the D and T fuel ions move from their injected energy of 100 keV to a mean energy slightly higher than 100 keV. In contrast, the electrons are essentially cold, being injected initially into the plasma at

the same velocity as the fuel ions. The electrons eventually attain an electron temperature of only about 17 keV. Despite the expected strong stopping power of the electrons for the 100 keV deuterons and tritons, the average energy of the latter increases slightly, primarily as a result of collisional heating by the initially 3.5 MeV alphas.

Figure 7 illustrates that alpha heating of the deuterons would be even more pronounced if one included nuclear elastic scattering effects. Here, the nuclear elastic collisional heating rate of deuterons by alpha particles is based on the excellent paper by Devaney and Stein of Los Alamos Scientific Laboratory for some light element nuclear elastic scattering collisions[17]. More elastic and inelastic collision cross sections are needed for the elements Li through at least neon.

Most astrophysical and physics calculations of nuclear reaction processes generally assume all particles (fuel, electrons, and reaction products) have the same temperature, i.e., that local thermodynamic equilibrium (LTE) prevails. Spectroscopic and other diagnostic studies of dynamic plasma systems in the laboratory reveal markedly different "temperatures" for each specie. A good example of a physical system having a gross departure from temperature equilibrium is the fast breeder reactor in which the neutrons will have a so-called "temperature" of order 3×10^9 °K whereas the fuel, sodium heat exchanger, and associated structures will be at about 1000°K. The energetic, magnetically confined, long carbon arc plasma at Oak Ridge revealed ions at 5×10^6 °K whereas the electrons were at only about 4×10^4 °K[18]. The Burnout series of experiments at Oak Ridge revealed kilo-electron volt ions immersed in electrons at only a few eV temperature[19]. The DCX experiments at ORNL had a kinetic "temperature" for the ions in excess of 3×10^9 °K whereas its electrons were at 10^7 °K or less[20]. Similar non-LTE results have been observed in numerous plasma experiments in the CTR world community.

A nuclear fusing plasma will probably have a fuel mix at moderate fuel ion and electron temperatures ($\sim 10^9$ °K), but the fusion reaction products which enter the system at multi-MeV energies, may well have an ion "temperature" of order 10^{10} °K or more. This is beautifully illustrated by the reaction kinetics calculations at the Culham and Lawrence Livermore Laboratories where the α product from the d-t reaction has a mean energy of about 1.2 MeV, whereas protons from the d- 3 He reaction have a mean energy of ~ 5 MeV[15,16]. Thus, these very energetic charged particles from the fusion reactions may react very favorably with added nuclear fuels such as 6 Li or 6 LiD to initiate nuclear fusion chain reactions. Subsequent generations of active chain centers can, in principle, maintain the criticality condition or reproduction factor, k, under appropriate conditions of fuel feed, ash exhaust, and controlled electron temperature. Whether such reactions can proceed in moderate density, magnetically confined plasmas having large radiation losses remains for future experiments to determine. It is quite possible that the first nuclear fusion reactors will be sub-critical fusion chain reactors in which the electrons are sustained at MeV temperatures by electron cyclotron heating (ECH). Such sub-critical fusion reactors may also be of significant value as pilot plant fusion reactors having greater application for nuclear reaction kinetic analyses than the most

complicated electronic computer—although the diagnostic readouts will be difficult to evaluate.

Figure 8 illustrates a possible multiplying fusion chain reaction proposed by Watson of the Culham Laboratory[21]. Here, a single triton reacting with ${}^7\text{Li}$ can generate as many as 2 neutrons which can then react further in a lithium blanket to breed tritons in excess. The new tritons must eventually be reintroduced into the reacting plasma to replace the burn-up of the original tritons in the plasma. Blow and Watson have calculated that a $\text{T} - {}^7\text{Li} - {}^{238}\text{U}$ system can produce a very large energy multiplication—about 100 MeV per fusion event or as much as 200 MeV per fusion event if Pu breeding is taken into account[21]. Such a complex system would, like the fission reactor, be energy rich rather than neutron rich; however, there are major complications in such a system (fission products, reinjection problems, tritium inventory, sustainment, etc.).

As mentioned earlier, the process of nuclear fusion chain reactions involves both chain and thermal (or thermonuclear) reactions and thus should more precisely be called a chain-thermal or chain-thermonuclear reaction. Figure 9 shows several thermonuclear reactions which give chain branching in a ${}^6\text{LiD}$ fueled plasma, i.e., the reactions are breeding reactions for t and ${}^3\text{He}$ as well as for energetic protons and alphas. The energetic protons, ${}^3\text{He}$, t , and alpha particles, will all end up in the reaction mix as suprathermal ions capable of further reactions with deuterons or ${}^6\text{Li}$ fuel nuclei. In the case of pure deuterium fueled plasmas the reaction can be catalyzed by the t and ${}^3\text{He}$ ashes for only one more generation. In the case of ${}^6\text{Li}$ or ${}^6\text{LiD}$ fuel, many further reaction generations may be expected—the reactions can be auto-catalytic, i.e., lead automatically to the next reaction. The use of ${}^6\text{LiD}$ fuel will permit true auto-catalytic reactions to occur so long as new fuel is added and cold ashes removed.

Even some of the very energetic alphas and protons can regenerate new fast deuterons from ${}^6\text{Li}$ dissociation. Figure 10 shows the nuclear mass-energy level diagram for ${}^6\text{Li}$ [22]. The low-lying 2.2 MeV state is extremely important for converting very fast alphas or protons to colder ashes plus a fast deuteron when the excited 2.2 MeV state decays to $\text{d} + \alpha$. The 9 MeV alphas originating from the ${}^6\text{Li}({}^3\text{He}, \alpha){}^6\text{Li} \rightarrow \text{p} + \alpha + 16.9 \text{ MeV}$ and 11 MeV alphas from ${}^6\text{Li}(\text{d}, \alpha)\alpha + 22.4 \text{ MeV}$ probably have a large cross section for excitation of this state. The ${}^6\text{Li}(\text{p}, \text{p}'){}^6\text{Li}^* - 2.2 \text{ MeV}$ reaction has a fairly flat σ from 10 MeV down to almost 3 MeV proton energy as shown in Fig. 11[6]. Figure 11 illustrates the importance of the reactions (1) and (14) to Jetter's proposed chain reaction cycle.

Note the five important $\text{d} \cdot {}^6\text{Li}$ reactions, (6), (7), (8), and also (12) for which there are two reaction branches possible. The reactivity product, $\sigma v Q_+$, where Q_+ is the energy release in charged particles, is about four times larger for $\text{d} \cdot {}^6\text{Li}$ than for the two $\text{d} \cdot \text{d}$ reaction channels. This fact leads to a value of τ of about $1.8 \times 10^{15} \text{ sec/cm}^3$ for a proposed $\text{d} \cdot {}^6\text{Li}$ fueled fusion reactor as compared to a value of 6×10^{15} needed for the $\text{d} \cdot \text{d}$ system[23]. The five $\text{d} \cdot {}^6\text{Li}$ reactions have the additional advantage that they can initiate nuclear fusion chain reactions whereas the $\text{d} \cdot \text{d}$ breeding cycle, in which the tritium and ${}^3\text{He}$

can react only in one second generation reaction, will revert back to a pure thermal or thermonuclear cycle after the second generation.

Reactions (9) and (10) illustrate the importance of converting very energetic particles to reactive deuterons. The analogous ${}^6\text{Li}(\alpha, \alpha') {}^6\text{Li}^* \rightarrow d + \alpha - 1.5 \text{ MeV}$ has a σv of almost $2 \times 10^{-15} \text{ cm}^3/\text{sec}$ at 31 MeV but needs to be measured accurately down to about 3 MeV. In fact all of these reaction rate parameters, σv , are poorly known despite the seeming authority of this prepared figure. There are many lacunae in the data, many cross sections have been measured only once; also, differential cross sections are frequently measured for only one angle and gross uncertainties have been introduced in converting the differential cross sections to absolute cross sections.

Figure 12 illustrates a multiplying chain for suprathermal alpha particles with ${}^6\text{Li}$ nuclei. Here, one fast alpha reacts with the first ${}^6\text{Li}$ nucleus to produce a fast deuteron ($\sim 0.5 \text{ MeV}$ not including the center of mass energy contribution) which can then react with a second ${}^6\text{Li}$ fuel nucleus to give two fast alpha particles each with an energy above 11 MeV; thus, this two step reaction has a theoretical multiplication factor of 2.

Figure 13 illustrates five charged particle propagation chain reactions with ${}^6\text{Li}$ or ${}^6\text{LiD}$ fuel. In the first case, ${}^3\text{He}$ is produced by the reaction of fast protons with ${}^6\text{Li}$ and then reacts with d to regenerate a 14 MeV proton which can continue to propagate the chain cycle. In the second reaction cycle the fast ${}^3\text{He}$ can react with a ${}^6\text{Li}$ fuel nucleus to regenerate a fast proton as well as two energetic alphas. The energy spectrum of the alphas in this second reaction cycle extends up to about 9 MeV. It should be noted that the maximum multiplication factor in the first reaction cycle of Fig. 13 is unity so that any chain center losses would have to be replenished via $d-d$ or $d-{}^6\text{Li}$ chain branching thermonuclear reactions (Fig. 9).

To illustrate how a very simple reaction such as ${}^6\text{Li}(p, {}^3\text{He})\alpha + 4.0 \text{ MeV}$ has widely varying cross section measurements, consider Fig. 14 which is taken from Crocker, Blow and Watson of the Culham and Harwell Laboratories[24]. More recent data of Spinka, Johnston, Hooton, et al[25] is shown. This $p-{}^6\text{Li}$ reaction could be an excellent standard for the much more difficult 5 channel $d-{}^6\text{Li}$ reactions as well as others involving ${}^6\text{Li}$, but it needs to be measured accurately from 100 keV to at least 15 or 20 MeV.

It appears that considerably more nuclear cross section measurements—both theoretical and experimental—are required to evaluate more thoroughly the ultimate prospects of nuclear fusion chain reactions in controlled fusion applications.

3. NUCLEAR FUSION CHAIN REACTION PROSPECTS IN ASTROPHYSICS

Nuclear fusion chain reactions in astrophysical systems do not appear to have received the degree of study they probably merit. Present day astrophysical calculations, especially for rapid phenomena such as occur in supernovae, presume local thermodynamic equilibrium (LTE) among all species and determine $\langle \sigma v \rangle$ vs. T for a large class of

possible reactions. This type of LTE calculation omits or severely reduces the prospect for certain high energy reactions for which σv may be unusually large. This is especially true in the case of endothermic reactions having a high energy threshold. I first proposed the possibility of nuclear fusion chain reactions involving such fuels and suprathermal chain centers in 1964 in an ORNL Status and Progress Report[8]. The ORNL report stated briefly, "Other light isotopes also possess chain-reacting capabilities, at least in principle. It is quite possible that the various light-element thermonuclear chain reactions can occur only in optically thick media, such as are found in astrophysical systems, and possibly may contribute to the generation of novas and supernovas. In such cases, neutrons would play a more important role than in laboratory plasmas." Since that time a fuller development of the prospect for nuclear fusion chain reactions in astrophysical systems has evolved and is outlined here.

Figure 15 depicts the production of suprathermal chain centers by thermonuclear reactions among the fuels C, N, O, and Ne. Each reaction gives rise to a light product, n, p, or α , which will carry away the bulk of the reaction Q from center of mass considerations. Thus for a nitrogen burning system the neutron enters the reaction mix at 9 MeV or more, the proton at 15 MeV or more, and the α particle at 15 MeV or more depending on the Q and the incremental amount of energy available in the center of mass of the colliding nuclei. In fast reacting systems such as supernovae, these energetic particles will be suprathermal chain centers as they slow down on the colder electrons and on the nuclear fuel materials via Coulomb and nuclear elastic and inelastic collision processes.

In very dense systems such as supernovae, the plasma is usually treated as a degenerate electron gas (see Fermi and Teller[26] and Gryzinski[27]) and the stopping power of the cold electrons is very greatly reduced. This effect can be illustrated by Fig. 16 which gives the Coulomb logarithm, $\ln \Lambda_{ie}$, for a 1 MeV proton slowing down in a non-degenerate plasma of varying electron density and $T_e \sim 10^9$ °K. Note that at supernovae densities the stopping power, which is proportional to the Coulomb logarithm, $\ln \Lambda_{ie}$, approaches zero asymptotically whereas the stopping power for the faster electrons on the protons as measured by $\ln \Lambda_{ei}$ is significantly larger. The net effect of this is to permit the energetic proton to remain suprathermal much longer than in more ordinary lower density plasmas such as those having densities near that of air, water, or the sun's core. In fact, the slowing down time becomes independent of density whereas the nuclear reaction time continues to decrease as the density increases. Thus, in very dense systems such as pre-supernovae stars, the suprathermal fusion reaction products will slow down primarily on the fuel nuclei keeping the nuclear or ion "temperature" somewhat higher than that of the electrons. The neutrons are of course uncharged and do not suffer Coulomb slowing down collisions. A local severe fluctuation in the nuclear reaction rate can produce a strong compressional shock wave in a dense star which may shift the electrons from non-degenerate to degenerate and the explosion may then propagate through a large fraction of the whole system.

Figure 17 illustrates multiplying chain reactions in nitrogen fuel. The chains are now more complex than those involving ${}^6\text{Li}$ or ${}^7\text{Li}$

but show that in principle these multiplying chain reactions may supplement the ordinary thermonuclear burning of nitrogen. The overall process in cycle A utilizes two initially fast alpha particles and converts one nitrogen nucleus by (α, p) and (α, n) reactions up to neon whereas a second nitrogen nucleus is reduced to alpha particles by (p, α) and (n, α) reactions. There is a net energy release of 7.93 MeV and a multiplication factor of two since four energetic alphas are produced in the complete chain cycle.

Figure 18 shows several propagation chains which are possible in nitrogen fuel. Here, the theoretical reproduction factor is unity. The loss of a suprathermal chain center either due to too much slowing down or by a nonproductive neutron capture reaction will terminate or break such propagation chains. In this case new neutron, proton, or alpha chain centers must be produced by thermonuclear reactions between two nitrogen fuel nuclei as depicted earlier in Fig. 15. It should be noted that nitrogen is probably not a major constituent in pre-supernovae stars.

Fusion chain reaction possibilities have been discovered for fuel elements at least up to silicon. The most abundant elements in pre-supernovae stars were thought to be C, O, and Ne[9]. One of the most interesting cases is that of chain reaction burning of an oxygen and a neon nucleus as shown in Fig. 19. Here, in the closed chain, four alpha particles can burn neon up to ^{32}S and produce protons and neutrons which subsequently can burn an oxygen nucleus down to alpha particles by (p, α) and (n, α) reactions with a very large energy release. It is of interest to note that the elements up to sulphur are quite prominent in the spectra of old supernovae such as the Crab Nebula. In young supernovae the expansion velocities are much too high to render valid interpretation of the spectroscopic data to ascertain the most prominent elements. It appears that helium, oxygen, carbon, and possibly iron and other metals are now being identified[28] in the 1937 Type I supernova, IC-4128, which had a well defined 55 ± 1 day half life for its light decay[29]. In 1950 Lyle Borst suggested this light decay of 55 days was due to ^7Be radioactivity[30] which has a half life of 53.61 days[31]. He proposed the very endothermic $\alpha(\alpha, n)^7\text{Be} - 19.0$ MeV reaction to produce the ^7Be in a contracting star. Gryzinski[27] suggested ^7Be production by the $\alpha(^3\text{He}, \gamma)^7\text{Be}$ reaction and postulated that ionization of the L electron shell would extend the half life of 53.61 days by about 4%, thus making for almost a perfect fit of the long light decay curve after the initial burst of the Type I supernovae.

Figure 19 shows that ^7Be can be produced in chain reaction cycles involving Ne and O fusion reactions (also C, Mg or Si and O chain reaction burning can generate ^7Be). The ^7Be residue would be especially prominent if the alpha particles slow down too fast so that they can not produce sufficient neutrons via the $^{29}\text{Si}(\alpha, n)^{32}\text{S}$ reaction to destroy the ^7Be . For example, early expansion of the supernovae star would increase the stopping power of the alphas by the electrons because the Coulomb logarithm increases significantly as the density of the star decreases (Fig. 16). There are, of course, many other chain reaction combinations that can produce ^7Be ; e.g., ^{16}O and ^{24}Mg , ^{16}O and ^{28}Si , etc.

The residual ^7Be would decay to ^7Li with a half life of about 55 days for doubly ionized Be in the core of the star where low energy

proton reactions may then occur much more rapidly in the core remnant. For example, the ${}^7\text{Li}$ can be consumed by the highly exothermic reaction ${}^7\text{Li} + p \rightarrow {}^8\text{Be}^* \rightarrow 2\alpha + 17.3 \text{ MeV}$. Thus, a much smaller amount of ${}^7\text{Be}$ would be required in the residual core than the figure of 0.007 of the supernovae mass postulated by Borst[30] to explain the 55 day afterglow of supernovae of Type I.

Figure 20 shows a possible nuclear fusion chain reaction involving two neon nuclei which are burned up and down respectively to α 's and ${}^{32}\text{S}$. In this case one also sees a multiplication of alpha chain centers and a net energy release for the closed cycle.

The various fusion chain reactions with C, N, O, and Ne suggest more direct ways of producing significant abundances of Li, Be, and B whose presence in the heavens is still apparently an astrophysical puzzle. Even a short chain length for the fusion chain reactions would ensure the production of relatively large quantities of these elements.

Figure 21 illustrates a nuclear fusion chain cycle for a hypothetical pure oxygen star. This cycle has a very highly endothermic step requiring a center of mass energy in excess of 8.12 MeV. Thus, oxygen-rich, as well as carbon-rich, stars do not appear to be nearly as favorable a nuclear environment for the production of multiplying chain reactions as do mixtures of oxygen and neon or carbon and neon. It appears that stars rich in carbon, oxygen, and neon or other medium heavy elements are most likely to permit nuclear fusion chain reactions to occur if there is a strong compression of the stellar material and the conditions for the compressional shock wave persist.

4. SUMMARY

Nuclear fusion chain reactions may have a potential impact on controlled fusion reactors and may give a more complete explanation of supernovae processes; however, much more basic research in science and technology will have to be done to elucidate the true role of fusion chain reactions. Of especial importance in this broad ranging research endeavor will be the accurate measurement of many nuclear cross sections involving both neutrons and charged particles as projectiles and fuels at least up to sulphur.

I hope I have stimulated in some small way the nuclear data community to the prospect for new and challenging research needs in the area of light element cross sections for controlled fusion and astrophysical applications. In closing, I paraphrase Louis Rosen, Director of the Los Alamos Meson Physics Facility who said at the National Particle Accelerator Conference in Chicago in 1971, "One barrier to the pursuit of this idea of fusion chain reactions in controlled fusion reactors is the grossly incomplete knowledge of reaction cross sections for light nuclei at low energies"[32]. The same kind of statement might also be made with regard to astrophysical explosions.

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FIGURE CAPTIONS

- Fig. 1. Chemical chain reactions in hydrogen-chlorine gas with free atoms of H and Cl as chain centers.
- Fig. 2. The first proposed nuclear fusion chain reaction.
- Fig. 3. The first proposed charge particle nuclear fusion chain reaction for controlled fusion applications[5].
- Fig. 4. Major developments in controlled fusion research on magnetic mirror systems. E = Experimental; T = Theoretical.
- Fig. 5. Fokker-Planck calculations of energy distribution function for 3 MeV protons injected into a 2/1 magnetic mirror with $T_e \sim 30$ keV. E_{+e} = average energy of escaping protons, E_{+t} = average energy of trapped protons. Obtained by Mozelle Rankin in 1964 at ORNL.
- Fig. 6. Fokker-Planck calculations of particle velocity distribution functions in magnetic mirrors for d-t reactions[18]. Abscissa scale for electrons to be multiplied by 6×10^9 and for ions by 6×10^8 cm/sec.
- Fig. 7. Energy gain and loss rates for alpha particles via Coulomb collisions and nuclear elastic collisions with deuterons and electrons.
- Fig. 8. Neutron multiplying fusion reactions with ${}^7\text{Li}$ fuel and tritons in a hot plasma and triton or neutron multiplying reactions in the blanket[21].
- Fig. 9. Thermonuclear reactions in ${}^6\text{LiD}$ fueled plasmas leading to branched chains.
- Fig. 10. Nuclear mass-energy level diagram of ${}^6\text{Li}$ showing the important 2.18 MeV state which dissociates into energetic d and alpha particles [22].
- Fig. 11. Various reaction rate parameters, σv , for several important light element reactions as a function of projectile energy. Data only approximate in most cases.
- Fig. 12. Fusion chain reaction initiated by fast alphas on ${}^6\text{Li}$ fuel nuclei. The ${}^6\text{Li}^*$ excited state emits a 0.5 MeV deuteron.
- Fig. 13. Several charged particle fusion chain reactions involving ${}^6\text{Li}$ or ${}^6\text{LiD}$ fuel.
- Fig. 14. Various measurements of the cross section of the ${}^6\text{Li}(p, {}^3\text{He})\alpha + 4.0$ MeV reaction as a function of energy [24,25].
- Fig. 15. Thermonuclear reactions among C, N, O, or Ne nuclear fuels indicating energy of the light reaction product (center of mass energy of the reacting nuclei would increase E).

- Fig. 16. Coulomb logarithm for 1 MeV proton slowing down on 100 keV electron gas at various densities ($2n \Lambda_{ie}$) and for 100 keV electron slowing down on 1 MeV protons ($2n \Lambda_{ei}$).
- Fig. 17. Multiplying nuclear fusion chain reactions in nitrogen.
- Fig. 18. Propagation nuclear fusion chain reactions in nitrogen.
- Fig. 19. Nuclear fusion chain reaction burning of oxygen and neon nuclei.
- Fig. 20. Nuclear fusion chain reaction in neon fuel.
- Fig. 21. Nuclear fusion chain reaction in oxygen fuel. Note highly endothermic reaction requiring at least 8.12 MeV energy in center of mass system, thus preventing early explosion of pure oxygen systems. The theoretical multiplication factor is 1.333 for the complete cycle or an average of 1.04 per generation. $\bar{E}_{\max}$ is the maximum propagation energy assuming negligible energy feed to degenerate electrons and complete consumption of fuel.

CHEMICAL CHAIN REACTION STEPS

Fig. 1

THE FIRST PROPOSED FUSION CHAIN REACTION*

Fuel: ${}^6\text{LiD}$; Chain Centers: n and t

*Ulrich Jetter, Physik. Blätter 6, 199 (1950).

FIRST PROPOSED CHARGED PARTICLE FUSION CHAIN REACTION*

PROPAGATION CHAIN

BRANCHING CHAINS

RE-INJECTION OF ${}^3\text{He}$ AND t -DECAY PRODUCT (${}^3\text{He}$)
INTO LEAKY MAGNETIC MIRROR

*R. F. POST, *NUCLEAR FUSION SUPPLEMENT*,
PART 1 (1962) 119.

MAJOR DEVELOPMENTS IN CTR MIRROR RESEARCH

I. Plasma Trapping and Incipient Exponential Build-Up of Density
(Culham, Livermore)	E
II. Scaling Laws for Scatter-Dominated Mirrors ($n\tau \propto E^{\frac{3}{2}}$)
(Livermore, Culham, Oak Ridge)	T
III. Hot Electron Plasmas by ECH ($T_e \gtrsim 1$ MeV)
(Oak Ridge)	E
IV. Exponential Build-Up of Density at MeV Energies with ECH
(Oak Ridge)	T
V. Closed Magnetic Mirror
(Livermore, Cornell)	E
VI. MeV Energies for Fusion Reaction Products
(Culham, Livermore)	T
VII. Fusion Chain Reactions (${}^6\text{Li}$ or ${}^6\text{LiD}$ Fuel)
(Oak Ridge)	T

Distribution Function for Protons in DCX Plasma for 6-MeV H_2^+ Injection.

A. H. FUTCH, JR., *et al.*, UCRL-73226 PREPRINT (1971)

FOR $R=10$: $\bar{E}_D \sim 110$ keV, $\bar{E}_T \sim 120$ keV, $\bar{E}_e \sim 17$ keV, $\bar{E}_\alpha \sim 1180$ keV

INJECTION ENERGY: $E_D = E_T = 100$ keV; $E_e \approx 25$ eV

Fig. 6

Fig. 7

MULTIPLYING FUSION CHAIN REACTION POSSIBILITIES WITH ${}^7\text{Li}^*$

*C.J.H. Watson, Appendix III, EUR-CEA-FC-628-AG (1971).

Fig. 8

ORNL-DWG 71-7336

BREEDING REACTIONS (THERMAL REACTIONS GIVING CHAIN BRANCHING)

Fig. 9

① $t(d, n) \alpha + 17.6 \text{ Mev}$	⑧ ${}^6\text{Li}(d, \alpha) \alpha + 22.4 \text{ Mev}$
② ${}^3\text{He}(d, p) \alpha + 18.4 \text{ Mev}$	⑨ ${}^6\text{Li}(d, d_1') d + \alpha - 1.5 \text{ Mev}$
③ $d(d, p) t + 4.0 \text{ Mev}$
$+ d(d, n) {}^3\text{He} + 3.3 \text{ Mev}$	⑩ ${}^6\text{Li}(n, n') d + \alpha - 1.5 \text{ Mev}$
④ ${}^6\text{Li}(p, {}^3\text{He}) \alpha + 4.0 \text{ Mev}$	⑪ ${}^6\text{Li}(p, p') d + \alpha - 1.5 \text{ Mev}$
⑤ ${}^6\text{Li}({}^3\text{He}, \alpha) p + \alpha + 16.9 \text{ Mev}$	⑫ ${}^6\text{Li}(d, n) {}^{17}\text{Be} + 3.4 \text{ Mev}$
⑥ ${}^6\text{Li}(d, p) {}^7\text{Li} + 5.0 \text{ Mev}$	⑬ ${}^6\text{Li}(d, n) {}^3\text{He} + \alpha + 1.8 \text{ Mev}$
⑦ ${}^6\text{Li}(d, t) p + \alpha + 2.6 \text{ Mev}$	⑭ $t(p, n) {}^3\text{He} - 0.8 \text{ Mev}$
	⑮ ${}^6\text{Li}(n, t) \alpha + 4.8 \text{ Mev}$

Fig. 11

Fig. 12

CHARGED PARTICLE FUSION CHAIN REACTIONS

Fig. 14

THERMONUCLEAR REACTIONS LEADING TO CHAIN BRANCHING

plus numerous isotope mixtures such as $^{12}\text{C} + ^{14}\text{N}$, etc.

Fig. 15

Fig. 16

Possible Multiplying Nuclear Fusion Chain Reaction Sequences in Burning Nitrogen in Supernovae.

Fig. 17

PROPAGATION FUSION CHAIN REACTIONS IN NITROGEN

Fig. 18

Possible Fusion Chain Reaction Sequence in Burning

Neon and Oxygen Nuclei in Supernovae

$$k = \sqrt[9]{1.25} = 1.03; \bar{E}_{\text{max}} = 5.91 \text{ MeV}$$

Delayed Reaction (^7Be Residue)

Fig. 19

POSSIBLE FUSION CHAIN SEQUENCE IN BURNING NEON

$$k = \sqrt[8]{1.5} = 1.05; \bar{E}_{\text{max}} = 2.35 \text{ MeV}$$

$$\text{or } \begin{cases} 2^{20}\text{Ne} + 3\alpha \rightarrow ^{32}\text{S} + 5\alpha + 7.06 \text{ MeV} \\ k = \sqrt[8]{1.667} = 1.07; \bar{E}_{\text{max}} = 2.35 \text{ MeV} \end{cases}$$

Fig. 20

POSSIBLE FUSION CHAIN SEQUENCE IN BURNING OXYGEN

$$k = \sqrt[8]{1.333} = 1.04; \bar{E}_{\text{max}} = 4.82 \text{ MeV}$$

Fig. 21