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ORAL VERSION

NUCLEAR FUSION CHAIN REACTION APPLICATIONS IN PHYSICS AND ASTROPHYSICS*

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Unlike the nuclear fission chain reaction in which only one chain center particle — the neutron — is multiplied, the chemical and nuclear fusion chain reactions propagate by means of two or more species of active or suprathermal chain centers. In the nuclear fusion case one expects a proliferation of energetic neutrons, protons, and other light particles from the thermonuclear reactions. If the conditions are right these energetic reaction products or chain centers may have an opportunity to react themselves with fuel nuclei before they completely slow down and diffuse in energy enough to thermalize with the background fuel ions and electrons. In addition, hard nuclear elastic collisions will promote fuel ions into the non-thermal region where again high energy reactions can occur. If there is a multiplication of the number of such active chain centers in the reaction cycles and the cycles are also exothermic, a true nuclear fusion chain reaction exists.

First, let us consider the area of controlled fusion. There have been several major developments in recent years involving magnetic mirror confinement devices as shown on the first slide.

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The first major development is the experimental achievement at Culham and Livermore of an exponential build-up of the hot ion density over the charge exchange losses when injecting 1-10 keV excited hydrogen atoms into open magnetic configurations. Eventually, the exponentiation of the plasma density stops due to a depletion of the number of excited atoms and the ion density is limited to about 10^{10}.

The second major development is the Fokker-Planck calculation of the pertinent scaling laws for magnetic mirror systems. The $n\tau$ product, which must exceed 10^{14} sec/cm^3 for a scientific feasibility experiment, increases as the 3/2 power of the injection energy of the ions. Thus, at 1 MeV injection energy, the attainable $n\tau$ is a factor of 1000 greater than that for 10 keV injection.

To prevent the MeV ions from slowing down too much on the cold electron background it is necessary to also heat the confined electrons to MeV temperatures. Such MeV electron temperatures have been produced experimentally at Oak Ridge by electron cyclotron heating using microwaves at or above the gyro-frequency of the electrons in the magnetic field. This inviting prospect of keeping the electrons hot led me to propose in 1971 a scientific feasibility experiment using only 2 mA of 4 MeV H_2^+ injected into a magnetic mirror. This should permit a large scale exponential buildup of the plasma density by several orders of magnitude to give an $n\tau$ product of 5×10^{14} at about 1 MeV plasma temperature. G. I. Budker of the Soviet Union was apparently the first to suggest MeV molecular ion injection into magnetic mirrors in 1954, but he did not foresee the exponential build-up process which was first outlined in 1955 by the U.S. scientists, Lauer and Hiskes.

A significant loss of plasma will still occur at high density as a result of Coulomb and nuclear scattering of MeV ions into the mirror loss cones.

Therefore some means of reducing this loss must be found if mirrors are to lead to a realistic fusion reactor design. The late Nick Christofilos at Livermore proposed a relativistic electron current ring configuration called an E-layer to obtain closure of the magnetic mirror by the internal electron current. In the past two years Fleischmann and co-workers at Cornell University have successfully demonstrated the principle of the E-layer. In 1971 I proposed injecting 10-20 mA of 4 MeV H_2^+ into a magnetic mirror to produce a reversed magnetic field configuration which I called an ion I-layer.

British and American scientists have made extensive Fokker-Planck calculations of D·T and D·^{3}He reacting systems by following the slowing down, energy dispersion and loss of ions in open magnetic mirrors. They found that the fusion reaction products, p and α, ended up with an average energy above 1 MeV. If the various fusion reaction products retain such high energies, then cold ^{6}Li or ^{6}LiD fuel could be introduced to permit nuclear fusion chain reactions to occur with such suprathermal ions. This would release nuclear fusion energy by non-thermal processes. This might also permit one to turn off the injection accelerator although the reaction would still be sub-critical since electron-cyclotron heating would be required in small systems.

Slide 2 shows the results of Fokker-Planck reaction kinetics calculations made by Futch at Lawrence Livermore Laboratory for a D·^{3}He fusioning plasma for two mirror situations. The three fusion reactions are shown in the lower left. In the plot are given the average energies of the fuel, reaction products, and electrons plotted against their respective densities. Injection currents for the fuel and the reaction products are shown at the top. Data is given for two magnetic mirror ratios, the higher one simulating the approach to a closed mirror.

Note that the mean energy of the proton, p', from the d·^{3}He reaction stays above 4 MeV. These high energy protons ensure the strong possibility of initiating nuclear fusion chain reactions if cold fuel were to be added.

Slide 3 shows the 7 channels of thermonuclear reactions expected for a ^{6}Li·D fueled fusioning plasma. Not included are the eight exothermic ^{6}Li·^{6}Li reactions. The energy-rich tritium and ^{3}He would be produced rapidly in a high temperature plasma and would lead to second generation, or autocatalytic, reactions in a closed magnetic configuration. The energetic protons and alpha particles can also lead to second generation reactions. In fact, the D·^{6}Li system is so much more reactive than a pure D·D system that the calculated Lawson criterion is a factor of three more favorable for D·^{6}Li than for D·D.

Slide 4 shows several charged-particle fusion chain reactions in ^{6}Li or ^{6}LiD fuel. If the reaction products stay sufficiently suprathermal, these chain reactions would continue indefinitely provided new fuel were added and the colder ashes were removed. In the first chain, proposed by Post of Livermore, the proton and ^{3}He alternate as chain centers. Any chain center losses will have to be replenished 1) by multiplicative type reactions such as the three particle producing reaction shown on the fourth line for ^{3}He + ^{6}Li, or 2) by thermonuclear or chain branching reactions among the d and ^{6}Li fuel nuclei as shown on the previous slide, or 3) by nuclear elastic collisions promoting fuel ions from thermal to suprathermal ions.

Many of the cross sections for evaluating these processes are very poorly known. Accurate measurements of the absolute reaction cross sections as well as the elastic and inelastic cross sections are badly needed. Slide 5 illustrates this fact with the most recent data of Hooton and Ivanovich of Harwell being about a factor of three <u>higher</u> near 1 MeV proton energy than previous measurements for the $p \cdot {}^{6}Li$ reaction. If these recent higher measurements prove to be valid the possibility of charged particle nuclear fusion chain reactions is very significantly enhanced.

I want to emphasize that we do not know at this period of time what the final fuel will be in an operating fusion reactor. Although d·t is the favored thermonuclear fuel, it may be that nuclear fusion chain reactions will play an important role. This is particularly true should the present calculations of MeV average energies for the reaction products hold up in a real system. To evaluate the prospects of alternate fusion fuels it will be necessary to obtain new or improved nuclear data on the various light element reactions.

Let us turn now to astrophysical explosions such as the gigantic supernovae outbursts. We find that the astrophysicists believe these occur in stars having central densities of order 10^{8} gm/cm^{3} and having a temperature approaching 1 MeV or 10^{10}°K during the explosion. The model dependent studies that have been made of various fuel systems such as C, O, Ne, Mg, etc., generally assume that the initially multi-MeV fusion reaction products – the neutrons, protons and alphas – come into immediate local thermodynamic equilibrium with the fuel and the electrons. A $\overline{\sigma v}$ is used for each reaction possibility at the given temperature. Actually it takes a finite time for the neutrons, protons and alphas to slow down and thermalize and thus we should expect significant numbers of non-thermal reactions to occur. For example, in very dense systems the electrons will play a minor role in the stopping power of the energetic protons and alphas and most of the reaction energy will reside in the fuel ions and reaction products. Fermi and Teller and later Gryzinski considered the dense medium case by treating the electron plasma as a degenerate gas and found a grossly reduced stopping power for energetic ions.

Slide 6 illustrates the dependence of $\ln \Lambda_{ie}$ for energetic ions slowing down in a plasma of varying electron density and at an electron temperature of 100 keV. At supernovae densities of 10^8 gms/cm^3 the stopping power calculated from this expression for $\ln \Lambda_{ie}$ compares very favorably with the degenerate electron gas model. In the high density limit the stopping power becomes independent of electron density. In contrast, the nuclear reaction rate continues to increase as the density increases. Thus, at very high densities we should expect the fusion energy to go primarily by nuclear elastic and Coulomb collisions to the fuel ions and not to the electrons. Thus, the average energy of fuel ions and chain centers will be much higher than permitted by the current model of complete equipartition of the energy among fuel and the electrons.

The basic thermonuclear reactions for pairs of C, N, O, and Ne nuclei are shown in Slide 7. The light fusion reaction products, n, p, and α, carry away the bulk of the energy as indicated. In a pure neon reacting system they come in at an energy of 5.8, 12.1, and 12.3 MeV or more depending on the contribution from the center of mass motion. As these energetic chain centers slow down principally by hard nuclear elastic collisions on the fuel nuclei, they will trigger both thermonuclear and non-thermal nuclear reactions among the fuel nuclei thus proliferating the number of such energetic chain centers. The energetic neutrons, protons and alphas can also directly initiate non-thermal reactions such as shown in the next slide (slide 8) for a neon-oxygen system. The neon nucleus may burn up to ^{32}S by (α,p) and (α,n) reactions while the oxygen nucleus will burn preferentially down to alpha particles by (n,α) and (p,α) reactions. Thus, four alpha particles can burn oxygen and neon to sulphur and to five alpha particles by a circuitous route but producing the same result as the direct thermonuclear reaction: $^{20}Ne + ^{16}O$ giving $^{32}S + \alpha + 11.81$ MeV. However, the Coulomb barrier is greatly reduced for this cycle of reactions. Such fusion chains can be written down for many element pairs such as Mg and O, etc., at least through Fe and O. This nuclear fusion chain reaction feature, supplemented by the direct thermonuclear reactions, can lead to an exponentially growing explosion as long as the nuclear matter remains in a sufficiently compressed or electron degenerate state such as a strong local nuclear explosion shock wave might trigger in a dense star.

As the supernova explosion expands, one would expect rather significant residues of lithium, boron, and beryllium left behind. This prospect offers a new explanation for the presence of these elements in the universe, instead of non-thermal reactions involving spallation of C, O, Ne. The production of radioactive ^{7}Be is of especial interest since it has a decay period approximately the same as that for the decay of the light emitted by supernovae of Type I, namely 55 days. In fact, Gryzinski postulated that the 53.6 day decay of ^{7}Be would be extended by about 4% if the L electrons of the Be were ionized, thus reducing the orbital electron capture proability. This would give almost perfect agreement with the observed light decay of 55 days.

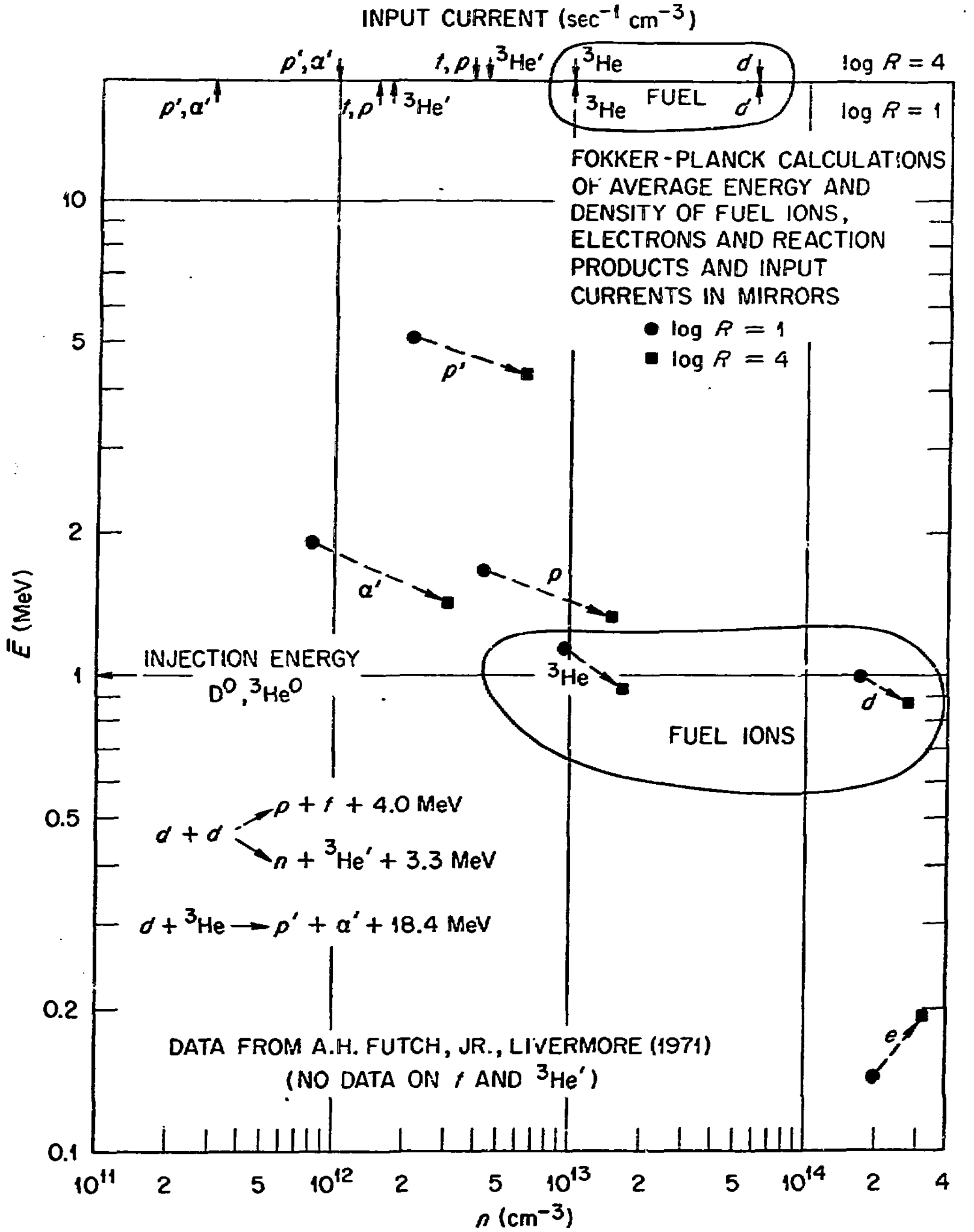
SUMMARY

The role of nuclear fusion chain reactions in controlled thermonuclear systems or in supernovae is not well defined as yet. It does, however, represent a new and potentially important type of nuclear burn mechanism and hence may be deserving of further study. A major need appears to be that of obtaining accurate nuclear elastic, inelastic and reaction cross sections such as only nuclear physicists can provide.

ORNL-DWG 72-12305

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 ($T_e \geqslant 1$ 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}Li or ^{6}LiD Fuel) (Oak Ridge)	T


INPUT CURRENT (sec⁻¹ cm⁻³)
p′, α′
t, p
³He′
³He
d
FUEL
log R = 4
log R = 1
FOKKER-PLANCK CALCULATIONS OF AVERAGE ENERGY AND DENSITY OF FUEL IONS, ELECTRONS AND REACTION PRODUCTS AND INPUT CURRENTS IN MIRRORS
log R = 1
log R = 4
p′
α′
p
INJECTION ENERGY D⁰, ³He⁰
³He
d
FUEL IONS
d + d → p + t + 4.0 MeV
d + d → n + ³He′ + 3.3 MeV
d + ³He → p′ + α′ + 18.4 MeV
DATA FROM A.H. FUTCH, JR., LIVERMORE (1971)
(NO DATA ON t AND ³He′)
e
Ē (MeV)
n (cm⁻³)
10
5
2
1
0.5
0.2
0.1
10¹¹
2
5
10¹²
2
5
10¹³
2
5
10¹⁴
2
4

ORNL-DWG 71-7336

BREEDING REACTIONS (THERMAL REACTIONS GIVING CHAIN BRANCHING)

$$d + d \rightarrow n + {}^{3}He + 3.3\ MeV$$

$$d + d \rightarrow p + t + 4.0\ MeV$$

$$d + {}^{6}Li \rightarrow 2\alpha + 22.4\ MeV$$

$$d + {}^{6}Li \rightarrow p + {}^{7}Li + 5.0\ MeV$$

$$d + {}^{6}Li \rightarrow p + t + \alpha + 2.6\ MeV$$

$$d + {}^{6}Li \rightarrow n + {}^{7}Be + 3.4\ MeV$$

$$d + {}^{6}Li \rightarrow n + {}^{3}He + \alpha + 1.8\ MeV$$

ORNL-DWG 72-13436

CHARGED PARTICLE FUSION CHAIN REACTIONS

$$\left\{\begin{array}{l} p + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + \alpha + 4.0\ \mathrm{MeV} \\ {}^{3}\mathrm{He} + d \rightarrow p + \alpha + 18.4\ \mathrm{MeV} \end{array}\right.$$

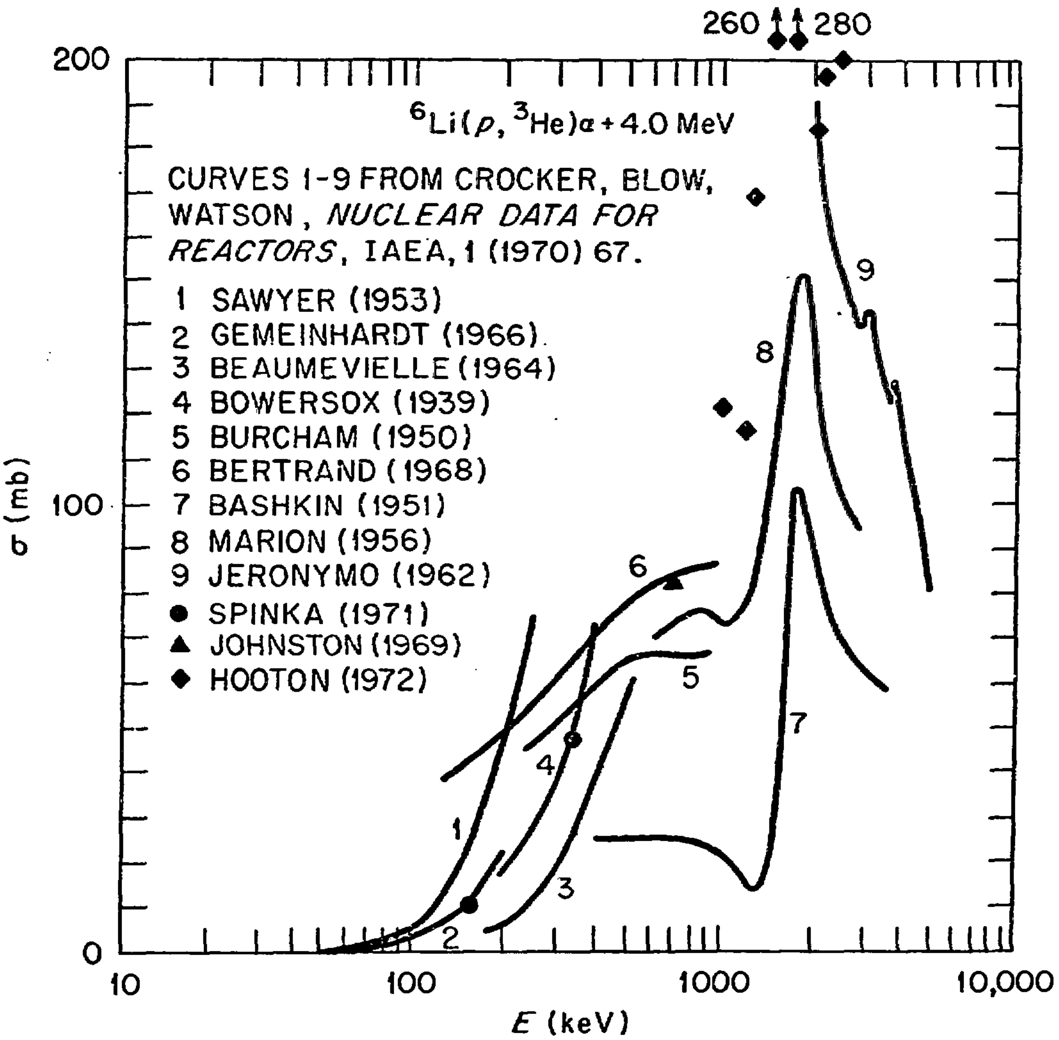
$$\left\{\begin{array}{l} p + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + \alpha + 4.0\ \mathrm{MeV} \\ {}^{3}\mathrm{He} + {}^{6}\mathrm{Li} \rightarrow p + 2\alpha + 16.9\ \mathrm{MeV} \end{array}\right.$$

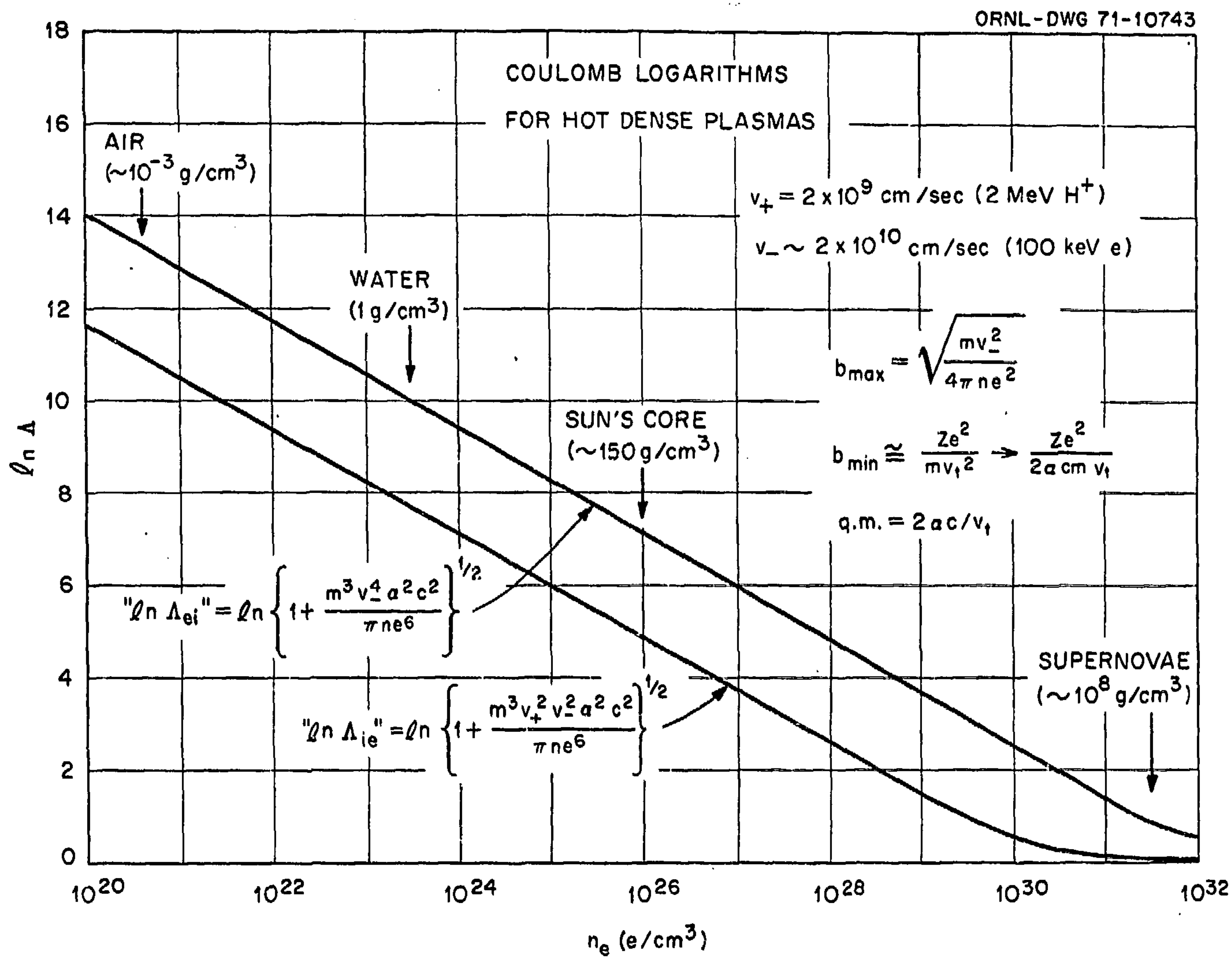
$$\left\{\begin{array}{l} p + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + \alpha + 4.0\ \mathrm{MeV} \\ \alpha + {}^{6}\mathrm{Li} \rightarrow p + {}^{9}\mathrm{Be} - 2.1\ \mathrm{MeV} \end{array}\right.$$

$$\left\{\begin{array}{l} d + {}^{6}\mathrm{Li} \rightarrow t + p + \alpha + 2.6\ \mathrm{MeV} \\ t + {}^{6}\mathrm{Li} \rightarrow d + {}^{7}\mathrm{Li} + 1.0\ \mathrm{MeV} \end{array}\right.$$

$$\left\{\begin{array}{l} d + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + n + \alpha + 1.8\ \mathrm{MeV} \\ {}^{3}\mathrm{He} + {}^{6}\mathrm{Li} \rightarrow d + {}^{7}\mathrm{Be} + 0.1\ \mathrm{MeV} \end{array}\right.$$

ORNL-DWG 72-13437R




ORNL-DWG 71-10743
COULOMB LOGARITHMS
FOR HOT DENSE PLASMAS
AIR
(~10^-3 g/cm^3)
WATER
(1 g/cm^3)
SUN'S CORE
(~150 g/cm^3)
SUPERNOVAE
(~10^8 g/cm^3)
$v_+ = 2 \times 10^9$ cm/sec (2 MeV H^+)
$v_- \sim 2 \times 10^{10}$ cm/sec (100 keV e)
$b_{max} = \sqrt{\frac{mv_-^2}{4\pi ne^2}}$
$b_{min} \cong \frac{Ze^2}{mv_t^2} \rightarrow \frac{Ze^2}{2\alpha cm v_t}$
q.m. $= 2\alpha c/v_t$
"$\ell n\, \Lambda_{ei}$" $= \ell n \left\{1 + \frac{m^3 v_-^4 \alpha^2 c^2}{\pi ne^6}\right\}^{1/2}$
"$\ell n\, \Lambda_{ie}$" $= \ell n \left\{1 + \frac{m^3 v_+^2 v_-^2 \alpha^2 c^2}{\pi ne^6}\right\}^{1/2}$
$\ell n\, \Lambda$
n_e (e/cm^3)

Slide 6

ORNL DWG. 71-10204

THERMONUCLEAR REACTIONS LEADING TO CHAIN BRANCHING

$$^{12}C + {}^{12}C \rightarrow \begin{cases} p + {}^{23}Na + 2.2\ \text{MeV} & E_p > 2.1\ \text{MeV} \\ \alpha + {}^{20}Ne + 4.6\ \text{MeV} & E_\alpha > 3.6\ \text{MeV} \end{cases}$$

$$^{14}N + {}^{14}N \rightarrow \begin{cases} n + {}^{27}Si + 9.1\ \text{MeV} & E_n > 8.8\ \text{MeV} \\ p + {}^{27}Al + 15.6\ \text{MeV} & E_p > 15.0\ \text{MeV} \\ \alpha + {}^{24}Mg + 17.3\ \text{MeV} & E_\alpha > 14.8\ \text{MeV} \end{cases}$$

$$^{16}O + {}^{16}O \rightarrow \begin{cases} n + {}^{31}S + 1.6\ \text{MeV} & E_n > 1.5\ \text{MeV} \\ p + {}^{31}P + 7.7\ \text{MeV} & E_p > 7.5\ \text{MeV} \\ \alpha + {}^{28}Si + 9.7\ \text{MeV} & E_\alpha > 8.5\ \text{MeV} \end{cases}$$

$$^{20}Ne + {}^{20}Ne \rightarrow \begin{cases} n + {}^{39}Ca + 6.0\ \text{MeV} & E_n > 5.8\ \text{MeV} \\ p + {}^{39}K + 12.4\ \text{MeV} & E_p > 12.1\ \text{MeV} \\ \alpha + {}^{36}Ar + 13.7\ \text{MeV} & E_\alpha > 12.3\ \text{MeV} \end{cases}$$

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

ORNL-DWG 71-11829

Possible Fusion Chain Reaction Sequence in Burning

Neon and Oxygen Nuclei in Supernovae

$^{20}Ne(\alpha,p)^{23}Na - 2.38$ MeV

$^{23}Na(\alpha,p)^{26}Mg + 1.84$ MeV

$^{26}Mg(\alpha,n)^{29}Si + 0.02$ MeV

$^{29}Si(\alpha,n)^{32}S - 1.53$ MeV

$^{16}O(n,\alpha)^{13}C - 2.20$ MeV

$^{13}C(p,\alpha)^{10}B - 4.08$ MeV

$^{10}B(p,\alpha)^{7}Be + 1.15$ MeV

$^{7}Be(n,\alpha)\alpha + 18.99$ MeV

$$^{20}Ne + {}^{16}O + 4\alpha \rightarrow {}^{32}S + 5\alpha + 11.81 \text{ MeV}$$

$$k = \sqrt[8]{1.25} = 1.03; \; \bar{E}_{max} = 5.91 \text{ MeV}$$

Delayed Reaction (^{7}Be Residue)

$^{7}Be + e \rightarrow {}^{7}Li + 0.86$ MeV (53.6 days)

$^{7}Li(p,\gamma)^{8}Be \rightarrow 2\alpha + 17.34$ MeV