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Importance of Limiting the Proton Energy in Optimizing the $p + {}^{11}B \rightarrow {}^{4}He + {}^{4}He + {}^{4}He$ Fusion Reaction

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ABSTRACT

The $p + {}^{11}B \rightarrow {}^{4}He + {}^{4}He + {}^{4}He$ fusion reaction is attractive because it limits the productions of neutrons that have implications for minimizing maintenance and materials degradation from radiation induced damage. This reaction is optimized by limiting the proton energy to < 1 MeV. The energy limitation minimizes the production of secondary reaction products that can scavenge protons and contaminate the fusion plasma. It is also important to utilize purified boron that is enriched in ${}^{11}B$, and contains minimal amounts of other elemental contaminants.

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Introduction

Current fusion baseline technologies utilize the D +T reaction [1]. This reaction has a number of disadvantages from a nuclear interaction perspective

$$D + T \rightarrow {}^{4}He + n \ (14.1 \text{ MeV}) \quad (1)$$

For example, the production of 14.1 MeV neutrons presents engineering issues related to sustainable materials and longevity of components [1]. These issues have led to searches for alternative fusion reactions. One of the reactions of current interest is the ${}^{11}B$ + p reaction that produces no neutron radiation [2-5]

$$p + {}^{11}B \rightarrow {}^{4}He + {}^{4}He + {}^{4}He \quad (2)$$

Table 1 provides an overview of the advantages of the ${}^{11}B$ + p fusion reaction in comparison to the D + T process. Currently, there has been significantly more work on the D + T process particularly in the critical engineering development area [1]. However, open issues remain for both fusion reactions [1-5]. A selected comparison of the D + T and ${}^{11}B$ + p fusion reactions is summarized in Table 1.

Table 1: Selected Comparison of D + T and $p + {}^{11}B$ Fusion Reactions

$D + T \rightarrow {}^{4}He + n$	$p + {}^{11}B \rightarrow {}^{4}He + {}^{4}He + {}^{4}He$
High energy neutrons damage the fusion reaction chamber and associated components	Limited neutron radiation is produced
Significant quantities of tritium must be stored and that presents a radiological concern	Fuel is not radioactive
Currently, world tritium inventories are not sufficient to fuel D + T fusion reactors	The fuel is abundant and non-toxic
Limited reaction channels are available to complicate the reaction	Numerous reaction channels open as the proton energy increases. Limiting the proton energy is important
Light systems inherently limit other elemental contaminants	Elemental contaminants require control
Isotopic issues are limited	Isotopic issues must be considered
ITER prototype is under construction	No significant construction comparable to ITER
Neutron radiation produces numerous activation products that create a radiological hazard	Limited neutron radiation is produced

Nuclear Physics Considerations

The proton energy determines the nuclear reactions that can occur in the ${}^{11}B$ + p fusion reaction. Higher proton energies create reaction products other than the desired Eq. 2 result. Since natural boron consists of ${}^{10}B$ (≈20%) and ${}^{11}B$ (≈80%), each of these isotopes must be considered if natural boron is used in the fusion reaction. Based on subsequent discussion, it would be

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beneficial to use highly enriched ^{11}B in the fusion reaction. In addition, elemental contaminants must be minimized to ensure an optimized fusion reaction.

^{11}B

The p + ^{11}B reaction channel represents a binary system within ^{12}C. As noted in Table 2, it lies 15.957 MeV above the ^{12}C ground state. At the p + ^{11}B energy threshold, all reaction channels at lower excitation energy can be populated including the three alpha system. Although $^{4}He + {}^{4}He + {}^{4}He$ is the desired reaction channel, the $^{4}He + {}^{8}Be$ channel can also be populated. Since ^{8}Be rapidly decays into two alpha particles, this channel presents no specific issues to the fusion reaction. ^{8}Be reactions with protons are addressed in subsequent discussion. However, as the proton energy increases, other reaction channels are accessible and have the potential to perturb and contaminate the fusion plasma. Therefore, a successful p + ^{11}B fusion reaction must limit the proton energy.

Based on numerical simulations, Ref. 4 suggests that incident proton energies should be in the range of 200 – 700 keV. Ref. 3 notes that the fusion reaction should occur at about 300 keV, while Ref. 5 investigates proton energies up to 225 keV. However, the optimum energy will likely depend on the operating configuration that has yet to be determined. Controlling the proton energy is essential to enhance the p + ^{11}B fusion reaction. For the purpose of this paper, minimizing the production of reaction products for proton energies less than 1 MeV is the main consideration. This is a reasonable first step based upon current modeling and preliminary experimental efforts.

It is essential to limit the proton energy to preclude these reaction channels from perturbing the desired fusion reaction. Exceeding a proton energy of 2.765 MeV (18.722 MeV – 15.957 MeV), opens the n + ^{11}C channel, and the ^{11}C nucleus can interact with the incident protons to produce the reaction products noted in Table 3.

Given the importance of the proton energy in the p + ^{11}B fusion reaction, this paper does not comprehensively investigate the reaction products produced as the proton energy increases. Considering initial testing suggests proton energies below 1 MeV are optimum [3-5], this paper investigates the various possible reaction products generated by this energy.

Table 2: Reaction Thresholds and Nuclear Systems Associated with p + ^{11}B Fusion^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
^{12}C	0.000
$^{4}He + {}^{4}He + {}^{4}He$	7.275
$^{4}He + {}^{8}Be$	7.367
^{12}B	13.369
p + ^{11}B	15.957
^{12}N	17.338
n + ^{11}C	18.722
$^{2}H + {}^{10}B$	25.186
$^{3}He + {}^{9}Be$	26.280
$^{3}H + {}^{9}B$	27.366
$^{6}Li + {}^{6}Li$	28.174
^{a}Derived from Ref. 6.	

If proton energies were to exceed 2.765 MeV, the ^{11}C and its associated reaction products must be considered in the evaluation of the p + ^{11}B fusion reaction. These reaction products are summarized in Table 3.

Table 3: Reaction Thresholds and Nuclear Systems Associated with the p + ^{11}C Channel^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
^{12}N	0.000
p + ^{11}C	0.601
$^{4}He + {}^{8}B$	8.008
$^{3}He + {}^{9}Be$	10.010
$^{2}H + {}^{10}C$	11.496
^{a}Derived from Ref. 6.	

As the incident protons energy increases, additional systems noted in Table 3 can be produced. The production of these species (e.g., ^{8}B, ^{4}He, ^{3}He, ^{9}Be, ^{3}H, and ^{10}C). can interact with protons intended to produce the p + ^{11}B fusion reaction and create a variety of interaction products that could contaminate the plasma and limit the fusion power output. The net result is a loss of proton efficiency and plasma contamination that must be considered in the engineering design. If these secondary reaction structures are produced, their subsequent products and interaction cross sections must be considered to optimize the p + ^{11}B fusion reaction.

^{10}B

If natural boron is utilized the p + ^{10}B reaction products must be considered. These are summarized in Table 4.

Table 4: Reaction Thresholds and Nuclear Systems Associated with the p + ^{10}B Reaction^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
^{11}C	0.000
^{11}B	-1.982
$^{4}He + {}^{7}Be$	7.544
p + ^{10}B	8.689
$^{3}He + {}^{8}Be$	9.223
n + ^{10}C	13.120
$^{2}H + {}^{9}B$	14.902
^{a}Derived from Ref. 7.	

The $^{4}He + {}^{7}Be$ channel lies below the p + ^{10}B channel and will be produced when ^{10}B interacts with protons. Above 550 keV proton energy, the $^{3}He + {}^{8}Be$ channel opens. Given the 1 MeV energy limitation considered in this paper, proton induced reactions on ^{4}He, ^{7}Be, ^{3}He, and ^{8}Be must be considered. These reactions are summarized in Tables 5 – 8.

Reaction thresholds and nuclear systems associated with the p + ^{7}Be channel are provided in Table 5. Below 1 MeV, there are no reaction products that are generated by proton interactions.

Table 5: Reaction Thresholds and Nuclear Systems Associated with the p + ^{7}Be Channel^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
^{8}B	0.000
p + ^{7}Be	0.138
^{3}He + ^{5}Li	3.690
^{2}H + ^{6}Be	8.589
^{a}Derived from Ref. 8.	

In a similar manner, reaction thresholds and nuclear systems associated with the p + ^{4}He channel are provided in Table 6. Given the 1 MeV proton consideration, no additional reaction products associated with p + ^{4}He are of concern.

Table 6: Reaction Thresholds and Nuclear Systems Associated with the p + ^{4}He Channel^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
^{5}Li	0.00
p + ^{4}He	-1.690
^{2}H + ^{3}He	16.66
2p + ^{3}H	18.12
^{a}Derived from Ref. 9.	

Reaction thresholds and nuclear systems associated with the p + ^{3}He channel are provided in Table 7. For the 1 MeV proton restriction, no additional nuclides associated with p + ^{3}He are a consideration.

Table 7: Reaction Thresholds and Nuclear Systems Associated with the p + ^{3}He Channel^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
p + ^{3}He	0.00
^{2}H + 2p	5.494
n + 3p	7.718
^{a}Derived from Ref. 10.	

Table 8 provides the reaction thresholds and nuclear systems associated with the p + ^{8}Be channel. Given the 1 MeV proton energy restriction, no reaction channels are open. Accordingly, no additional nuclear systems need be considered if the proton energy is limited to 1 MeV.

Table 8: Reaction Thresholds and Nuclear Systems Associated with the p + ^{8}Be Channel^{a}

Reaction Channel / Nuclide	Threshold Energy (MeV)
^{9}B	0.000
p + ^{8}Be	-0.185
^{4}He + ^{5}Li	1.689
^{2}H + ^{7}Be	16.490
^{3}He + ^{6}Li	16.602
p + ^{8}Be	18.577
^{3}H + ^{6}Be	20.909
^{a}Derived from Ref. 11.	

Boron Contaminants

There will be other elemental species that exist in the boron targets. It is essential that the highest purity of ^{11}B be utilized in the process. Although ^{11}B comprises about 80% of natural boron, the ^{10}B system can introduce additional reaction products and contamination into the plasma. In addition, even highly purified laboratory grade boron contains a variety of contaminants including hundreds of ppm of iron, copper, and platinum as well as lower levels of other elements [12]. These systems also have the potential to scavenge protons and their associated proton reaction products would contaminate the plasma. The proton interactions of these elements must be considered in the final engineering design of a p + ^{11}B fusion power system.

Conclusions

The p + ^{11}B → ^{4}He + ^{4}He + ^{4}He fusion reaction is an attractive alternative to D+T fusion. One of its attractive features is the minimization of the production of neutrons that have implications for minimizing maintenance and materials degradation from radiation induced damage. The p + ^{11}B reaction is optimized by limiting the proton energy below 1 MeV. This limitation minimizes the production of secondary reaction products that can scavenge protons and contaminate the fusion plasma. It is also important to utilize purified boron that is enriched in ^{11}B, and contains minimal amounts of other elemental contaminants.

The final optimized engineering design may require higher proton energies. If this occurs, the various reaction channels noted in this paper could become an important consideration.

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