

On fusion chain reactions in ^{11}B targets for laser driven aneutronic fusion

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The work presented in this letter suggests that it is possible to enhance the yield in laser driven aneutronic fusion devices by fusion chain reactions. This mechanism will be described using the example of aneutronic fusion between an incoming high-energy proton beam and a ^{11}B target. Such fusion reactions create alphas that can again fuse with a ^{11}B particle in a dense solid state target. An improved target design will be shown that enhances the recycling of fast alpha particles that are created from fusion reactions. It will also be argued that such alpha recycling may have already been observed in experiments, although it was attributed to another, more complex physical mechanism.

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I. Introduction

Different schemes for obtaining fusion reactions have been proposed but in recent years, concepts for aneutronic fusion reactors emerged [1-4]. One particular novelty, laser driven fusion devices with solid targets, consisting of boron, which can react with incoming proton beams, have been studied [5, 6]. In Refs. [6] and [7] an unexpected high yield of around 10^9 alpha particles was observed and explained by the occurrence of so-called avalanche proton boron reactions. The basis for these avalanche reactions was believed to be inelastic collisions between alpha particles and protons. It was argued that the alphas, which were produced during the fusion processes, transferred kinetic energy to protons through multiple inelastic collisions. These protons were accelerated up to about 660 keV, which falls into the energy range for the maximum fusion cross section between proton and boron. However, we argue that due to the isotropy of particle ejection after a fusion event and directional nature of an incoming proton beam as it was used in the aforementioned papers such a process is highly unlikely. There is also another paper by M. Shmatov that also argues against the proposed mechanism of avalanche reactions [9]. Thus, in this work a much

simpler mechanism is proposed that can explain the extraordinary yields of alpha particles observed by the cited authors. It will be argued that in a densely packed solid state fusion target, it is much more likely that some of the produced ^4He particles will directly fuse with some of the neighbouring ^{11}B atoms in the lattice. Such a fusion chain reaction, on the other hand, is able to produce again protons with a kinetic energy (around 730 keV) that matches the energy at the maximum reaction cross section for proton-boron fusion reactions (about 620 keV) very well. These thoughts will be outlined in the next section of this paper.

II. Physical basics

As a starting point the most important experimental parameters from [6] are recapitulated: The authors used the Prague Asterix Laser System (PALS), which is able to accelerate up to 10^{14} protons to fusion relevant kinetic energies [8]. The researchers used different versions of hydrogen enriched silicon targets that were doped with boron. For this work the target with a 100 nm boron thickness D and a concentration of $10^{26} / \text{m}^3$ ($10^{20} / \text{cm}^3$) are used as an example. A schematic graph of the target

setup with an incoming high energy proton beam is shown in the following Fig. 1:

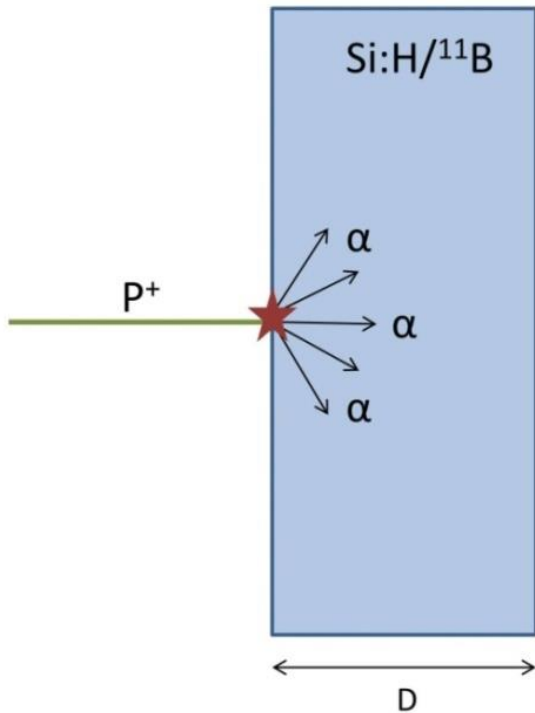


Figure 1: Schematic spread of alpha particles created through aneutronic proton boron fusion events.

It can be seen from Fig. 1 that half of the fusion products that are created at or near the surface of the target, will be ejected from the target backwards into the direction of the incoming proton beam. This loss will be accounted for in the subsequent calculations. First, we will have a look at the number of fusion events F that is normalised to one m^3 :

$$F = n_p n_B (\sigma D) \tag{1}$$

Where n_p and n_B are the proton and boron number density, σ is the (energy dependent) fusion cross section and D is the thickness of the boron target (100 nm for the PALS experiment). It has to be noted that D as well as the densities are taken to be constant in this case. In general an expanding gas or plasma plume may form at the point of proton impact that causes D to increase and the density n_B to go down locally, which is neglected in this work. It has also to be

emphasized that the number of fusion reactions that are obtained by using Eq. (1) are normalised to $/m^3$. Hence, the actual number of fusion reaction that occurs in a thin layer will be considerably less. The same normalisation to $/m^3$ is applied to the proton and boron densities as well. In order to explain the aforementioned enhanced alpha yields, it is sufficient to compare only the ratios of incoming protons to created ^4He particles and secondary protons, respectively. For simplicity we will only look at the maximum value of the fusion cross section and assume that the incoming proton beam has exactly this kinetic energy, i.e. it is monoenergetic. The values used in this paper are listed in the following Table 1:

Reaction	σ_{\max} [mbarn]	$E_{\text{kin}} @ \sigma_{\max}$ [MeV]
$^{11}\text{B} + \text{p} \rightarrow 3\alpha (2.89 \text{ MeV})$	800	0.62
$\alpha + ^{11}\text{B} \rightarrow ^{14}\text{C} (52.2 \text{ keV}) + \text{p} (731 \text{ keV})$	100	3-6
$\alpha + ^{11}\text{B} \rightarrow ^{15}\text{N} (1.2 \text{ MeV}) + \gamma (9.87 \text{ MeV})$	100	3-6

Table 1: Fusion reactions used in this paper, their maximum cross section and kinetic energy at the maximum cross section, taken from the EXFOR data base [12].

The proton bunch created by the PALS laser is about 80 μm in diameter and 200 μm in length [8], which yields a volume of 10^{-12} m^3 and, thus, a proton number density of $10^{26} /\text{m}^3$. Inserting these values into Eq. (1) gives 8×10^{16} fusion reactions per m^3 , which produce 2.4×10^{17} alpha particles per m^3 . Each helium nucleus produced has a 50 % chance of creating a ^{14}C nucleus and a proton with ca. 730 keV or a ^{15}N nucleus and a gamma ray when fusing with a ^{11}B atom. Each of those reactions is depicted in more detail in the following Fig. 2, which also illustrates that the kinetic energy of the proton produced matches the kinetic energy at the peak cross section for proton boron fusion and can, thus, be 'recycled' for further fusion reactions.

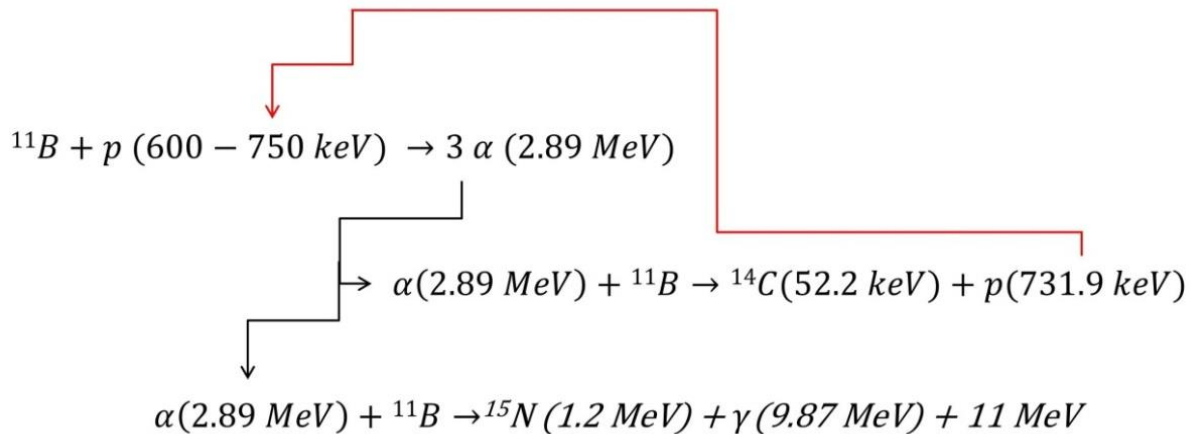


Figure 2: Fusion chain reaction through the creation of a 731.9 keV proton, which is fed into a second fusion cycle in the ¹¹B target material.

5 However, as mentioned before, half of the alphas
 6 will be lost due to the fraction of particles ejected
 7 away from the target after fusion events occur.
 8 Thus, 6×10^{16} alphas will be able to fuse again in
 9 the target, although with a lower cross section of
 10 only 100 mbarns. The possibility to do this quite
 11 efficiently is due to the fact that boron-11 has a
 12 rhombohedral unit cell with a lattice constant of
 13 506 pm, which is far smaller than the range of an
 14 alpha particle in a boron layer (about 9 μm for 2.9
 15 MeV ⁴He nuclei [10]). Hence, the produced alphas
 16 can cross several atomic layers before they are
 17 stopped. Taking the ejection losses and the fact
 18 into account that the PALS experiment used
 19 natural boron, which contains only 80 % of ¹¹B by
 20 multiplying Eq. (1) with a factor of 0.5 and 0.8,
 21 respectively, one obtains 4.8×10^7 protons/ m^3 in
 22 the second fusion cycle and 0.4×10^{-7} J in
 23 dissipated energy from the ¹⁴C nuclei as well as
 24 8.4 mJ from the created ¹⁵N nuclei and gamma
 25 rays. Since those secondary protons are
 26 produced within the material and have
 27 considerably less kinetic energy than the alphas
 28 (see Table 1), they will stay within the target layer.
 29 Thus, when recalculating the amount of fusion
 30 reactions per m^3 the factor of 0.5 for the escaping
 31 particles can be dropped with 0.04 fusion
 32 reactions / $\text{m}^3 \times 3 \sim 0.1$ alphas / m^3 . This about 8
 33 orders of magnitude lower than the number of
 34 alphas created in the first cycle. Hence, this
 35 process will die out quite soon. However, if the
 36 number of initial reactions is sufficiently high
 37 (about 10^9 or higher) the contribution from
 38 additional secondary alphas will be about an
 39 order of magnitude. These numbers are obtained
 40 by looking at the values normalised to / m^3 . Since
 41 each reaction number, particle density, etc. is

42 related to this volume, it is sufficient to examine
 43 the ratio of the fusion reaction number in each
 44 cycle in order to get an understanding of the
 45 fractional contributions of the suggested chain
 46 reactions. This is well within the possibilities of
 47 existing experiments and can explain the
 48 unexpected higher yield for ⁴He nuclei that was
 49 reported in the aforementioned works.

51 III. Optimised target design

52 In order to maximise the number of fusion
 53 reactions in the target and, thus, the fusion
 54 energy output one can use a different target
 55 design. Such a design has to be made in a way
 56 that lets as few alpha particles as possible
 57 escape. It should also be made out of pure ¹¹B in
 58 order efficiently induce boron-proton fusion
 59 reactions. Furthermore, it has to be much larger
 60 than the range of protons in boron in order to
 61 capture as many positive charge carriers as
 62 possible in fusion reactions. For calculating the
 63 proton range in boron, the equation by Burrell
 64 [13] gives a good estimation:

$$65 R(E) = \frac{a}{2b} \times \ln[1 + 2bE^{1.78}] \left(\frac{g}{\text{cm}^2} \right) \quad (2)$$

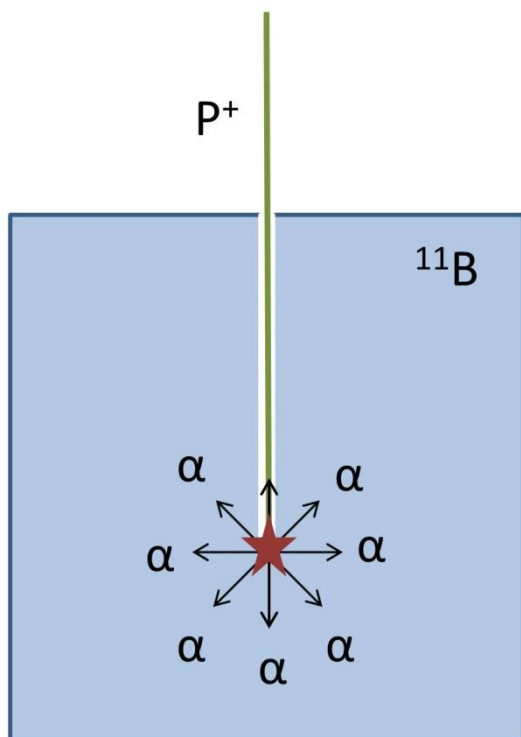
$$66 a = 1.53 \times 10^{-3} + 2.33 \times 10^{-4} \sqrt{A} \quad (3)$$

$$67 b = 1.6 \times 10^{-6} + 10^{-6} \sqrt{Z}, \quad (4)$$

68 where E is the energy of the incoming protons, A
 69 is the mass number and Z is the atomic number.
 70 Eq. (2) is accurate to about 5 % for $Z < 20$.

71 However, it has to be noted that strictly speaking
 72 this is only for proton bunches with a power law
 73 energy distribution but for a simple estimation
 74 about the characteristic thickness of an optimised
 75 target this is assumed to be sufficient. Inserting
 76 protons with a kinetic energy of 731 keV, this
 77 equation yields a range of about 13 μm . This is
 78 far more than the interatomic distance in the
 79 boron target but very in the order of a target
 80 distance D of 1 μm , which was used in the former
 81 case and will also be used here to calculate the
 82 fusion reactions per m^3 . The same value for D is
 83 applied since it allows a more direct comparison
 84 between the two target types, although, of course
 85 the optimised target can be much thicker than is
 86 1 micron.

87 One possible design, which fulfils these
 88 requirements, is a bloc of ^{11}B with a thin, vertical
 89 aperture through which the incoming proton
 90 beam can enter the material. A schematic of this
 91 target setup is depicted in the following Fig. 3:



92
 93 **Figure 3:** optimised target design for a maximum alpha
 94 recycling yield within the boron target.

95 It is evident that a proton beam that enters the
 96 target vertically will produce nearly no losses in
 97 alpha particles resulting from the fusion reactions
 98 within the target material. Since the mass density
 99 of boron is 2460 kg/m^3 [14] and the mass of a
 100 single boron atom is $1.8 \times 10^{-26} \text{ kg}$ [15], a pure ^{11}B
 101 target has a particle density of $1.4 \times 10^{29} /\text{m}$.


102 Inserting this into Eq. (1) and letting the proton
 103 density be the same as before, one obtains $1.1 \times$
 104 10^{20} fusion reactions per m^3 with 3.3×10^{20} ^4He
 105 nuclei created in the process. Taking again a
 106 range of 9 μm for the alphas in a boron target,
 107 the second fusion cycle yields 3×10^{15} fusion
 108 reactions between the alphas and the boron. The
 109 created ^{14}C atoms will therefore dissipate about
 110 25 J into the target while the ^{15}N nuclei and
 111 gamma particles will deposit up to 2.6 kJ into the
 112 boron bloc. This is a considerable gain in fusion
 113 energy when one takes into account that the
 114 PALS laser is able to deliver energies up to 600 J
 115 per shot. These numbers would indicate that a
 116 gain of at least a factor 4 is possible with such an
 117 optimised boron target. A third fusion cycle
 118 within such a target would start with about 10^{15}
 119 secondary protons and yield 4.5×10^{11} alpha
 120 particles. This is a notable amount. However, it is
 121 about 4 orders of magnitude smaller than the
 122 amount of alphas created in the first cycle.
 123 Hence, the energy output from this cycle will only
 124 contribute some mJ.

125

126 IV. Conclusions

127 This letter presented the possibility of fusion
 128 chain reactions between laser-accelerated
 129 protons and a solid boron target. It was argued
 130 that the energy output for such configuration can
 131 already be positive if a solid boron target is used
 132 in such a manner that ^4He nuclei, which are
 133 created through fusion reactions between the
 134 high energy protons and the ^{11}B atoms undergo
 135 additional fusion chain reactions in the densely
 136 packed boron lattice. It was also argued that the
 137 protons that are created through these
 138 secondary reactions can also be 'recycled' and
 139 add to subsequent aneutronic p-B fusion
 140 reactions. The energy output is expected to be
 141 considerable with a theoretical limit of a factor 4
 142 when it is compared to the already existing PALS
 143 laser system even if the whole laser energy is
 144 deployed for proton acceleration, which is usually
 145 not the case. It was also shown by Brenner et al.
 146 that a laser-to-proton conversion efficiency for
 147 laser proton acceleration of about 15 % was
 148 experimentally achieved [11]. Thus, the energy
 149 gain in such a case is already very close to break
 150 even, even when the laser to proton energy
 151 conversion efficiency is taken into account. It is
 152 reasonable to assume that the advances in laser
 153 technology and laser particle acceleration will
 154 only further improve those results in the near
 155 future.

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