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 ^{4}He 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} /m³ (10^{20} /cm³) 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:

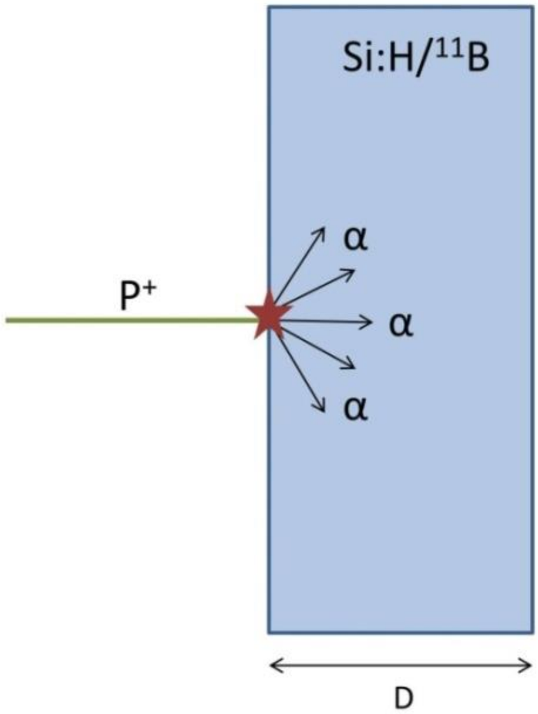

Figure 1: Schematic spread of alpha particles created through aneutronic proton boron fusion events.

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 m³:

$$F = n_p n_B \langle \sigma D \rangle \quad (1)$$

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 /m³. Hence, the actual number of fusion reaction that occurs in a thin layer will be considerably less. The same normalisation to /m³ 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 ^{4}He 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_{kin} @ σ_{max} [MeV]
^{11}B+p→3α(2.89 MeV)	800	0.62
α+^{11}B→^{14}C (52.2 keV) + p (731 keV)	100	3-6
α+^{11}B→^{15}N (1.2MeV) + γ(9.87 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} m³ and, thus, a proton number density of 10^{26} /m³. Inserting these values into Eq. (1) gives 8 x 10^{16} fusion reactions per m³, which produce 2.4 x 10^{17} alpha particles per m³. 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.

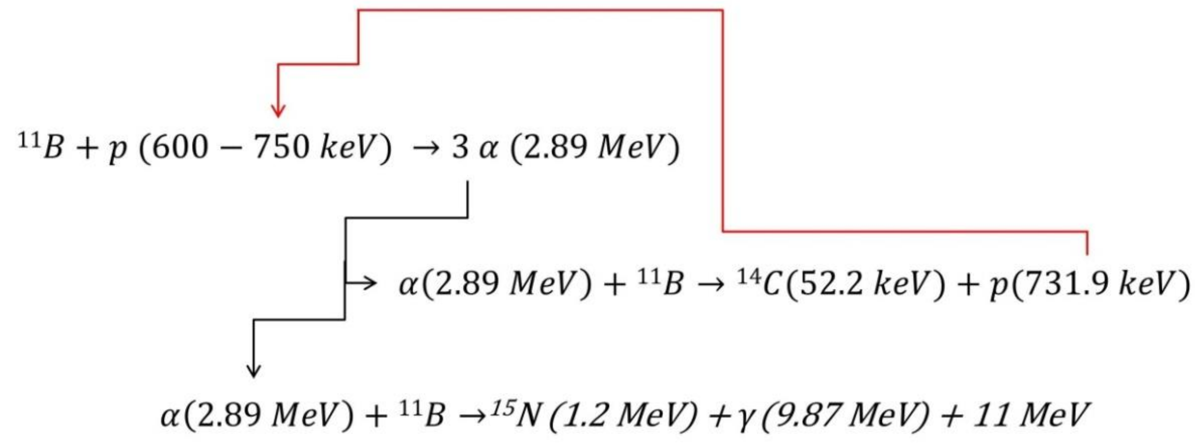

Figure 2: Fusion chain reaction through the creation of a 731.9 keV proton, which is fed into a second fusion cycle in the ^{11}B target material.

However, as mentioned before, half of the alphas will be lost due to the fraction of particles ejected away from the target after fusion events occur. Thus, 6 x 10^{16} alphas will be able to fuse again in the target, although with a lower cross section of only 100 mbarns. The possibility to do this quite efficiently is due to the fact that boron-11 has a rhombohedral unit cell with a lattice constant of 506 pm, which is far smaller than the range of an alpha particle in a boron layer (about 9 µm for 2.9 MeV ^4He nuclei [10]). Hence, the produced alphas can cross several atomic layers before they are stopped. Taking the ejection losses and the fact into account that the PALS experiment used natural boron, which contains only 80 % of ^{11}B by multiplying Eq. (1) with a factor of 0.5 and 0.8, respectively, one obtains 4.8 x 10^7 protons/m³ in the second fusion cycle and 0.4 x 10^{-7} J in dissipated energy from the ^{14}C nuclei as well as 8.4 mJ from the created ^{15}N nuclei and gamma rays. Since those secondary protons are produced within the material and have considerably less kinetic energy than the alphas (see Table 1), they will stay within the target layer. Thus, when recalculating the amount of fusion reactions per m³ the factor of 0.5 for the escaping particles can be dropped with 0.04 fusion reactions /m³ x 3 ~0.1 alphas /m³. This about 8 orders of magnitude lower than the number of alphas created in the first cycle. Hence, this process will die out quite soon. However, if the number of initial reactions is sufficiently high (about 10^9 or higher) the contribution from additional secondary alphas will be about an order of magnitude. These numbers are obtained by looking at the values normalised to /m³. Since each reaction number, particle density, etc. is related to this volume, it is sufficient to examine the ratio of the fusion reaction number in each cycle in order to get an understanding of the fractional contributions of the suggested chain reactions. This is well within the possibilities of existing experiments and can explain the unexpected higher yield for ^4He nuclei that was reported in the aforementioned works.

III. Optimised target design

In order to maximise the number of fusion reactions in the target and, thus, the fusion energy output one can use a different target design. Such a design has to be made in a way that lets as few alpha particles as possible escape. It should also be made out of pure ^{11}B in order efficiently induce boron-proton fusion reactions. Furthermore, it has to be much larger than the range of protons in boron in order to capture as many positive charge carriers as possible in fusion reactions. For calculating the proton range in boron, the equation by Burrel [13] gives a good estimation:

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

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

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

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

However, it has to be noted that strictly speaking this is only for proton bunches with a power law energy distribution but for a simple estimation about the characteristic thickness of an optimised target this is assumed to be sufficient. Inserting protons with a kinetic energy of 731 keV, this equation yields a range of about 13 µm. This is far more than the interatomic distance in the boron target but very in the order of a target distance D of 1 µm, which was used in the former case and will also be used here to calculate the fusion reactions per m³. The same value for D is applied since it allows a more direct comparison between the two target types, although, of course the optimised target can be much thicker than is 1 micron.

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

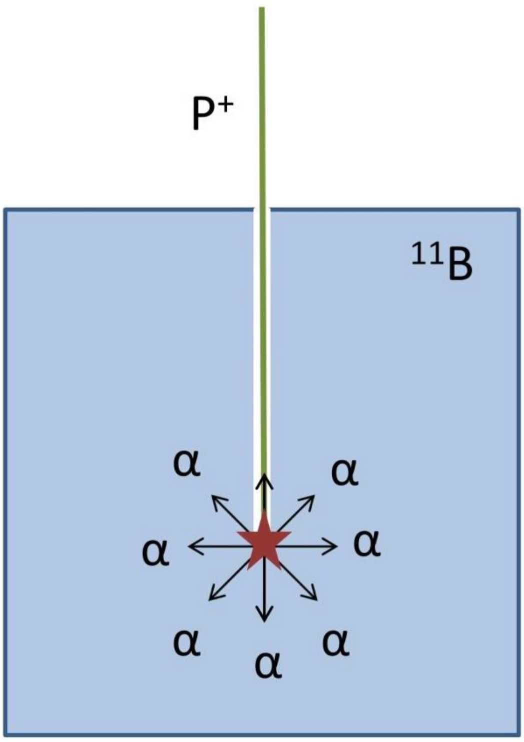

Figure 3: optimised target design for a maximum alpha recycling yield within the boron target.

It is evident that a proton beam that enters the target vertically will produce nearly no losses in alpha particles resulting from the fusion reactions within the target material. Since the mass density of boron is 2460 kg/m³ [14] and the mass of a single boron atom is 1.8×10^{-26} kg [15], a pure ^{11}B target has a particle density of 1.4×10^{29} /m. Inserting this into Eq. (1) and letting the proton density be the same as before, one obtains 1.1×10^{20} fusion reactions per m³ with 3.3×10^{20} ^{4}He nuclei created in the process. Taking again a range of 9 µm for the alphas in a boron target, the second fusion cycle yields 3×10^{15} fusion reactions between the alphas and the boron. The created ^{14}C atoms will therefore dissipate about 25 J into the target while the ^{15}N nuclei and gamma particles will deposit up to 2.6 kJ into the boron bloc. This is a considerable gain in fusion energy when one takes into account that the PALS laser is able to deliver energies up to 600 J per shot. These numbers would indicate that a gain of at least a factor 4 is possible with such an optimised boron target. A third fusion cycle within such a target would start with about 10^{15} secondary protons and yield 4.5×10^{11} alpha particles. This is a notable amount. However, it is about 4 orders of magnitude smaller than the amount of alphas created in the first cycle. Hence, the energy output from this cycle will only contribute some mJ.

IV. Conclusions

This letter presented the possibility of fusion chain reactions between laser-accelerated protons and a solid boron target. It was argued that the energy output for such configuration can already be positive if a solid boron target is used in such a manner that ^{4}He nuclei, which are created through fusion reactions between the high energy protons and the ^{11}B atoms undergo additional fusion chain reactions in the densely packed boron lattice. It was also argued that the protons that are created through these secondary reactions can also be ‘recycled’ and add to subsequent aneutronic p-B fusion reactions. The energy output is expected to be considerable with a theoretical limit of a factor 4 when it is compared to the already existing PALS laser system even if the whole laser energy is deployed for proton acceleration, which is usually not the case. It was also shown by Brenner et al. that a laser-to-proton conversion efficiency for laser proton acceleration of about 15 % was experimentally achieved [11]. Thus, the energy gain in such a case is already very close to break even, even when the laser to proton energy conversion efficiency is taken into account. It is reasonable to assume that the advances in laser technology and laser particle acceleration will only further improve those results in the near future.

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