

α particle space distribution from fusion reactions in Boron irradiated by mono-energetic protons

Riccardo De Angelis¹, Danilo Giulietti^{1,2,*}, Lucio Calcagnile³, Gianluca Quarta³, Pierluigi Andreoli¹, Mattia Cipriani¹, Fabrizio Consoli¹, G. Cristofari¹, Domenico Delle Side³, Giorgio Di Giorgio¹, Francesco Ingenito¹, and Lucio Maruccio³

¹ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Via E. Fermi 45, 00044 Frascati, Italy

²Physics Department of the University and INFN, Pisa, Italy

³CEDAD, Dipartimento di Matematica e Fisica "E. De Giorgi", Università del Salento – Lecce, Italy

Abstract. This work presents results regarding the $p + {}^{11}\text{B} \rightarrow 3\alpha + 8.7\text{ MeV}$ aneutronic fusion reaction. We obtained such results by directing a 0.675 MeV proton beam from a Tandetron accelerator to a solid Boron sample, varying the incidence angle. Three different detectors were used to reveal the alpha particles emitted during the experiments. The evidence obtained leads us to propose an innovative scheme to investigate the yield of the aneutronic reaction when the proton beam is directed against a ${}^{11}\text{B}$ laser induced plasma.

1 Introduction

The fusion reaction $p + {}^{11}\text{B} \rightarrow 3\alpha + 8.7\text{ MeV}$ has been considered in the past as a possible fuel for future fusion reactors. The advantages over more conventional approaches (such as (D, T) and $(D, {}^3\text{He})$) lie in materials availability, absence of high energy neutrons and easiness of conversion to electrical energy. The possibility to produce this reaction in a plasma has been considered both for magnetically confined [1] and laser produced plasmas [2, 3], the latter being favored by the presence of strong non thermal energetic ions in laser-plasma interactions. Although the optimum cross section for this reaction occurs at very high colliding energies between the nuclei, the free electrons changing the screening of nuclei may result in the increase of the reaction rate.

At ENEA we have been studying the possibility to trigger aneutronic reactions such as $p + {}^{11}\text{B} \rightarrow 3\alpha + 8.7\text{ MeV}$ in laser produced plasmas. Experiments were performed in various laser facilities [4–6]. With the ABC, laser focusing 100J on plastic targets doped with Boron, the number of α particles detected is very low and the response of detectors is often uncertain. In order to test the behavior of our detectors we conducted conventional experiments by accelerating mono-energetic protons against a Boron target. The experiments, performed using three different detectors (CR39, imaging plates and Passivated Implanted Planar Silicon (PIPS)), allowed to detect reaction alpha particles and to measure the relative energy spectrum. Moreover the measurements represent an interesting and fruitful calibration of CR39 plates for proton and α particle detection. A pilot experiment was also planned and its feasibility at CEDAD evaluated. It consists of the study of the

*e-mail: danilo.giulietti@unipi.it

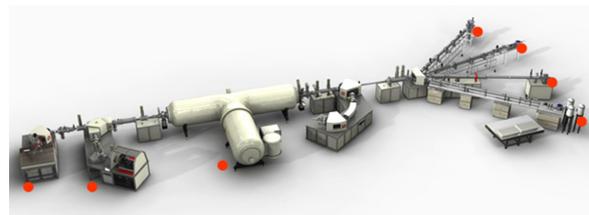


Figure 1. The 3 MV Tandetron accelerator at CEDAD – Brindisi, University of Salento.

($p + {}^{11}\text{B} \rightarrow 3\alpha$) reaction in a B plasma. The experimental set-up allowed to direct to a B plasma a 0.675 MeV proton beam. The plasma was produced by focusing on the B target the third harmonic (355nm) of a ns pulsed Nd:YAG laser, while the proton beam was focused on that plasma up to a 50 μm diameter.

2 Materials and methods

In Figure 1 a schematic view of the Tandetron accelerator used in the experiment is reported.

The $p + {}^{11}\text{B}$ reaction was first produced At CEDAD by a proton beam $\Phi \approx 1\text{ mm}$ impinging normally on a solid Boron target (thickness $\delta = 1.14\text{ mm}$). The particles emitted were measured by a PIPS detector located at the periphery of the vacuum chamber at 10° to the target normal as it is shown in 2. The PIPS detector has a 25 mm^2 active surface (3 mSr detection solid angle) with 15 keV energy resolution. In particular, we irradiated solid natural Boron with 0.675 MeV mono-energetic protons, detecting the α particles produced and the backscattered protons. For calibration purposes, the particles were also detected using

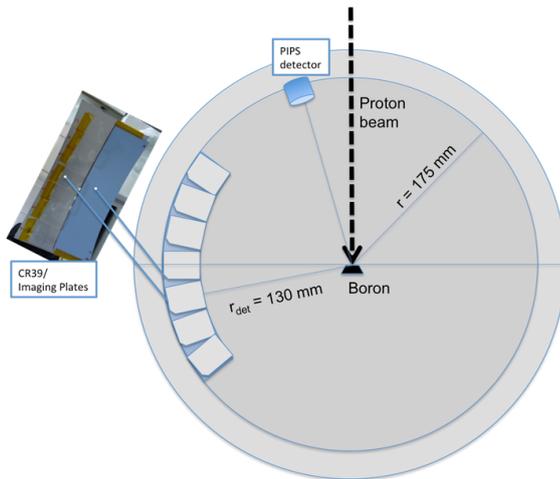


Figure 2. The vacuum chamber and the detector layout.

CR39 plates and imaging plates. Measurements were performed by irradiating the Boron sample at fixed impinging angle while varying the detection angle and afterward by keeping constant the angle between the proton beam and the detector view line and varying the proton beam incidence angle (i.e. by rotating the Boron sample).

The signal from the PIPS detector showed a clear evidence of the production of α particles with the expected energy spectrum, accompanied by backscattered protons. The energy of the incident proton was optimized to maximize the signal and the best value of $E_p = 675$ keV was found as expected.

The absence of artifacts was checked by substituting the natural B (80% ^{11}B + 20% ^{10}B) with pure ^{10}B or W targets. In Figure 3 we can see that no α particle are produced when the proton beam is directed to solid W target. It is worth noticing that energy measurements are reported in “channel”. This corresponds to the analog-to-digital conversion operated by the detection electronics. Nevertheless, each channel corresponds to an energy of 3.4 keV.

In order to eliminate the contribution of backscattered protons, all the detectors were covered with $7\ \mu\text{m}$ Al foils, which completely absorbed scattered protons. The spectra registered by the PIPS in the two cases (with and without the Al shield) is shown in Figure 4.

3 Results and Discussion

3.1 α yield Angular dependence

The angular dependence of the detected α particles was monitored and resulted consistent with the available literature. It is known indeed that the α particles yield has a weak dependence on the detection angle (θ). This dependence could be expressed in terms of a linear combination of the first 4 Legendre polynomials $P_n(\cos \theta)$ [7]. The coefficients of such expansion depend on the energy of the incident protons (E_p) and on the particular α particle emit-

ted in the reaction, i.e.

$$\text{yield} \propto 1 + \sum_{n=1}^4 a_n(E_p)P(\cos \theta). \quad (1)$$

Literature results show in particular that the two main contributions (namely α_0 and α_1) have a slightly different angular distribution [7]: α_1 is practically angle-independent, while α_0 weakly depends on θ .

In Figure 5 the dependence of the α energy spectrum on detection angle is reported. It is easy to see that the spectrum maximum displaces towards higher energies as the detection angle increases, whereas integrated α particle yield decreases. This is in good agreement with literature. In particular, we observe that the spectrum at the maximum is mainly the sum of the α_0 and α_1 contributions. Figure 5 can be interpreted as due to a contribution of the alpha particles at higher energies that remains practically constant, while the one of the lower energy alpha particles slightly decreases, leading to the observed displacement. We can see (Figure 6 left), in particular, that the maximum displacement is quite narrow, near 70 channels (i.e. less than 0.25 MeV). Moreover, integrating the plots of the Figure 5 we can ascertain that the yield remains always of the same order of magnitude (Figure 6 right).

3.2 CR39 and IP data

A set of CR39 track detectors and Imaging Plates (Fuji SR) was also deployed along the inner chamber wall. This allowed the calibration of the detectors’ responses and to estimate the dimensions of the tracks produced by the α particles. Following standard etching procedures [8] (7 h at 70°C in NaOH 6.25 molar), α particles were easily recognized as tracks with a 4 – 8 μm diameter. By irradiating the Boron target in normal incidence condition, we found ≈ 1000 particles/ mm^2 after a 900 s exposition of the B sample to continuous 2 nA proton beams. The CR39 analysis provided an angular pattern of alpha emission in accordance with PIPS results (Figure 7).

3.3 Protons on a Boron plasma

A preliminary attempt to produce the fusion reaction in a plasma was performed by sending the proton beam on a plasma pre-formed by focusing a 0.4J, 10ns, 10 Hz rep. rate Nd:Yag laser (3rd harmonic $\lambda = 355$ nm) on a Boron target. These measurements were conducted on a second chamber where the proton beam dimension was about $\Phi = 50\ \mu\text{m}$, see Figure 8. The α particle yield on the same solid target was preliminary tested and was within a factor 2 similar to that of the other chamber. The layout was such that the continuous proton beam was close to the target surface without touching it, so that no reaction occurs in such conditions. When the laser pulsed hit the target the plasma created interacts with the proton beam, allowing the occurrence of p-B reactions. Figure 9 shows one of the CR39 used in this setup. In these conditions, the average count was $\approx 50\alpha/\text{mm}^2$, with a 1 nA continuous proton beam for about 3000 laser pulses.

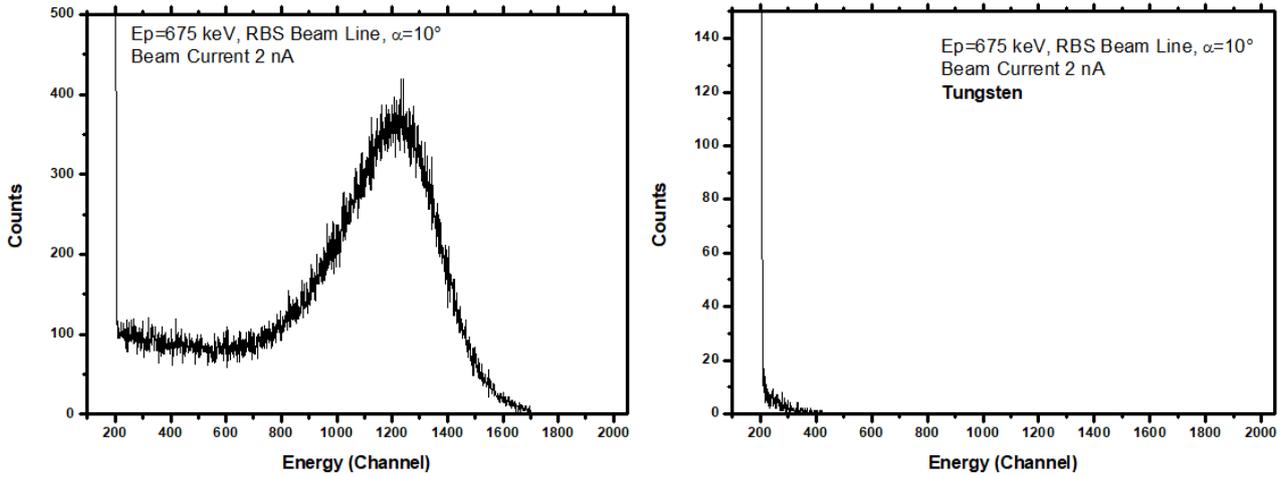


Figure 3. α particle yield when 0.675 MeV protons are directed on ^{11}B (left) and on W (right).

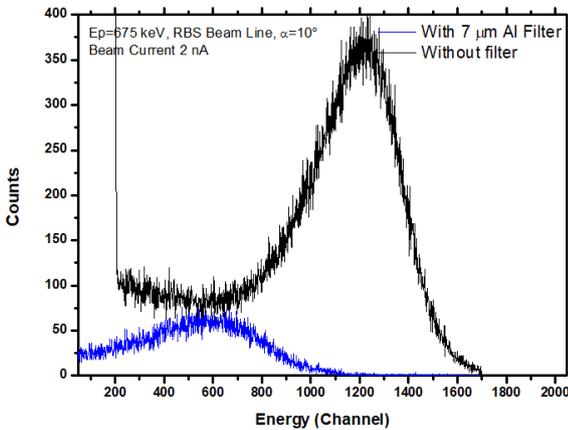


Figure 4. The spectrum of the α particle produced in the $p + ^{11}\text{B}$ fusion reaction as detected with and without a $7\ \mu\text{m}$ Al filter in front of the PIPS detector.

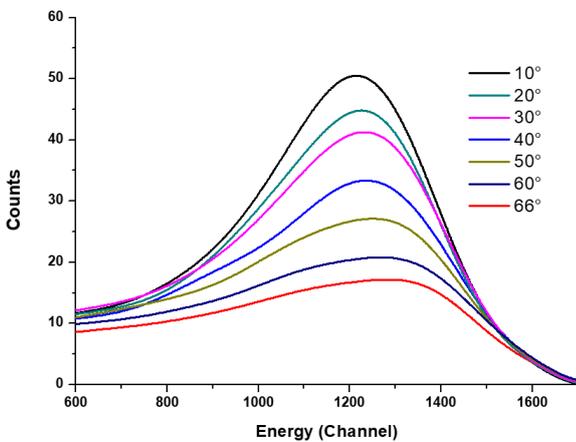


Figure 5. Dependence of the α energy spectrum on detection angle.

4 Discussion of the experimental results

We performed a first “back of the envelope” estimate of the number of alpha particles that should be produced in the interaction of the proton beam with both the ^{11}B sample in solid state and in the plasma state. In the first case, we direct a proton beam (2 nA current) for 900s onto a ^{11}B target, which corresponds to a total number of protons $N_p \approx 10^{13}$ sent to the Boron. Taking into account the penetration range of 700 keV protons in Boron ($L_{pB} \approx 10^{-4}$ cm), it is possible to estimate the number of fusion events (N_f)

$$N_f \approx n_B N_p \sigma_{pB} L_{pB} = 10^9 \text{ fusions} \quad (2)$$

Where $n_B \approx 10^{24} \text{ cm}^{-3}$ is the number of Boron atoms per volume unit; $\sigma_{pB} \approx 1$ barn is the cross section of the fusion process. Once estimated the number of fusion processes, the alpha produced is 3 times that number, i.e. $N_\alpha \approx 3N_f$. It is easy to get the number of alpha hitting on 1 mm^2 at a distance of 130 mm from the source, where the CR39 detector is located. We found: $N_\alpha/\text{mm}^2 \approx 1.5 \times 10^4/\text{mm}^2$, while the alpha detected by the CR39 were $N_\alpha/\text{mm}^2 \approx 10^3/\text{mm}^2$. Better agreement was obtained with the PIPS detector. In this case, the number of the alpha particle we estimate to reach the detector is near $2 \times 10^5/\text{mm}^2$, while the ones effectively counted are 1.6×10^5 . The disagreement of the CR39 measurements could be partly ascribed to the small differences observed in the angular distribution of the alphas. The CR39 plates were positioned at a larger detection angle than the PIPS, so they receive nearly half the number we computed. Consequently, we obtain $N_\alpha/\text{mm}^2 \approx 7 \times 10^3/\text{mm}^2$. Such estimates, indeed, neglect the fact that the alpha particles produced must in turn exit the Boron sample and the dependence of the cross section on energy (considering that protons lose energy as they penetrate the target).

In the second case, the estimate of the alpha particles produced when the proton beam interacts with the Boron plasma is much more complicated and the approximations even more rough. We can sketch the process as a well-defined proton beam that crosses a Boron plasma with

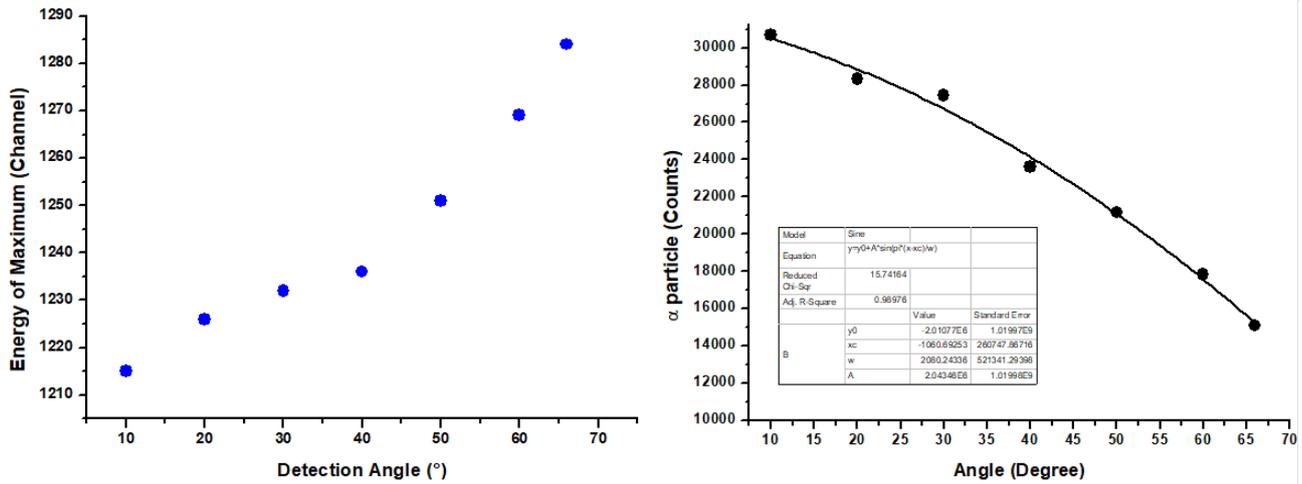


Figure 6. The maximum of the α particle spectrum (left) and the α reaction yield versus the detection angle (right).

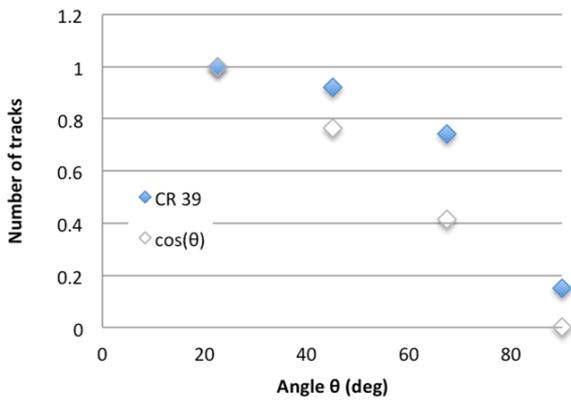


Figure 7. α particle yield versus detection angle, obtained by CR39 exposition.



Figure 9. The CR39 used in this setup. In these conditions the average count was $\approx 50\alpha/mm^2$, with a 1 nA continuous proton beam for about 3000 laser pulses.

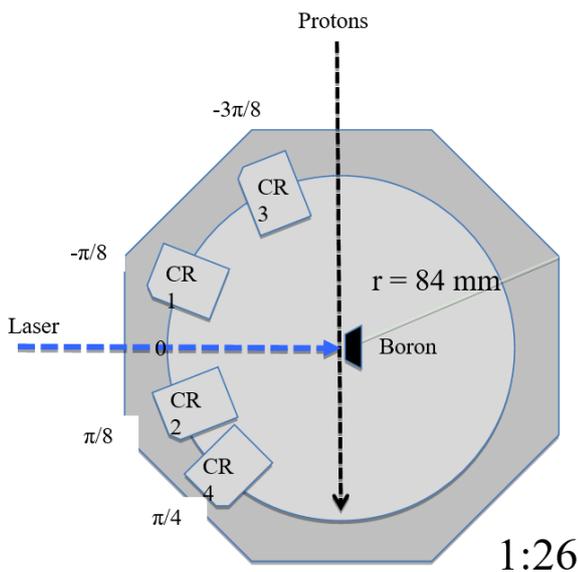


Figure 8. Experimental chamber during experiments with Boron laser induced plasma.

a density about the critical density for a $0.35\ \mu m$ radiation ($n_{Bplasma} \approx 10^{22} cm^{-3}$). The plasma extends for about $L_{Bplasma} \approx 1mm$, which corresponds to the sound velocity at plasma temperature at about $T \approx 100eV$ for the duration of the laser pulse near 10 ns, while the proton flux, corresponding to a 1 nA current, is $F_p \approx 6 \times 10^9$ protons/s

$$\frac{N_f}{shot} \approx n_{Bplasma} \sigma_{pB} L_{Bplasma} F_p \tau = 0.1 \frac{\text{fusions}}{\text{shot}} \quad (3)$$

Consequently, the number of the alpha particles impinging on $1mm^2$ at 84 mm from the alpha source after 3000 shots should be $N_\alpha/mm^2 \approx 10^{-2}\alpha/mm^2$. The number of alpha particle detected by CR39 is sensibly higher ($N_\alpha/mm^2 \approx 50\alpha/mm^2$). This extremely high yield probably cannot be attributed to an increased cross section for the fusion process in a plasma, but to some effects related to the particularly hasty set-up. There is therefore a need to repeat the experiment with a more accurate set-up. In fact in a plasma with an electron density $n_{Bplasma} \approx 10^{22} cm^{-3}$, at a temperature $T \approx 100eV$, the Debye length is $\lambda_D \approx 7.5\ \text{\AA}$,

about 10 times the Boron radius $r_B \approx 0.8 \text{ \AA}$. So the electron screening is less effective of the electron cloud of the atom and we expect the cross section for the fusion process is smaller in such a plasma. The situation could be opposed in a denser ($n_{Bplasma} \approx 10^{24} \text{ cm}^{-3}$) and cold plasma ($T \approx 10 \text{ eV}$) for which we have $\lambda_D \approx 0.23 \text{ \AA}$, as one might think to realize by focusing an X-ray backlight radiation on a solid ^{11}B target.

5 Conclusions

The results obtained for solid Boron give a number of α particles per incident proton N_α/N_p lower than expected, although estimates of the reabsorption of particles inside the solid were not yet taken into account. Conversely for the Boron plasma test, N_α/N_p was higher than expected showing a possible effect of stray protons inducing unwanted reactions on the solid Boron. Further experiments have been already planned to confirm the obtained results.

References

- [1] *TAE technologies, inc.*, <https://trialphaenergy.com>, accessed: 2017-09-30 and N.Rostoker, M.W. Binderbauer, H.J. Monkhorst, *Science* **278**, pp. 1419–1422 (1997)
- [2] D. Moreau, *Nuclear Fusion* **17**, 13 (1977)
- [3] V.S. Belyaev, A.P. Matafonov, V.I. Vinogradov, V.P. Krainov, V.S. Lisitsa, A.S. Roussetski, G.N. Ignatyev, V.P. Andrianov, *Phys. Rev. E* **72**, 026406 (2005)
- [4] A. Bonasera et al., in Proc. Int. Conf. Fission and Prop. Neut. Rich Nuclei, Sanibel Island, USA (2007)
- [5] C. Baccou, S. Depierreux, V. Yahia, C. Neuville, C. Goyon, R. De Angelis, F. Consoli, J. Ducret, G. Boutoux, J. Rafelski et al., *Laser and Particle Beams* **33**, 117–122 (2015)
- [6] D. Giulietti, P. Andreoli, D. Batani, A. Bonasera, G. Boutoux, F. Burgy, M. Cipriani, F. Consoli, G. Cristofari, R.D. Angelis et al., *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **402**, 373 (2017)
- [7] R.E. Segel, S.S. Hanna, R.G. Allas, *Phys. Rev.* **139**, B818 (1965)
- [8] F. Ingenito, submitted to the European Physical Journal Web Conferences