Calibration of CR-39 solid state track detectors with monoenergetic protons from 0.3 MeV to 2.5 MeV

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Abstract. The ^{2}H(d,p)^{3}H reaction is one of the most crucial reactions in the Big Bang nucleosynthesis (BBN). It is of particular interest to investigate this kind of reactions in plasma environments, generated by high intensity lasers, which are similar to real astrophysical conditions. We have experimentally investigated the ^{2}H(d,p)^{3}H reaction using laser-driven counter-streaming collisionless plasmas at the Shenguang-II laser facility. CR-39 track detectors are widely employed as the main diagnostics in such experiments and laser-driven ion acceleration. In this work, we performed calibration of CR-39 track detectors with monoenergetic protons from the tandem accelerator, and then presented their track diameters for proton energies ranging from 300 keV to 2.5 MeV and for etching times between 4 and 28 hours. In addition, we recommended the optimal etching time at the typical etching conditions, which will be very useful for the following massive data analysis from the CR-39 detectors.

1 Introduction

Nuclear fusions are the most crucial reactions in nuclear astrophysics because they are responsible not only for powering stars but also for the synthesis of the elements in the universe [1, 2]. The ^{2}H(d,p)^{3}H fusion reaction plays a key role not only in the design of future fusion power plants but also in the understanding of primordial abundances in Big Bang nucleosynthesis (BBN) models [3]. Therefore, this reaction has been studied using accelerators for many decades (see [4] and references therein). It is of particular interest to investigate this kind of reactions in plasma environments, generated by high intensity lasers, which are close to real astrophysical conditions. In recent years, with the rapid development of high-intensity laser technology, it is possible to produce this kind of plasma environment in the laboratories [5–9].

Recently we have performed experimental investigation of the ^{2}H(d,p)^{3}H reaction using laser-driven counter-streaming collisionless plasmas at the Shenguang-II laser facility at Shanghai Institute of Optics and Fine Mechanics of Chinese Academy of Sciences. In such a measurement, identification of reaction products and determination of their number have some difficulties, such as the electromagnetic pulse which can obstruct electronic devices. The CR-39 solid state track detectors [10, 11] are widely employed as the main diagnostics in the fusion reaction experiments [12] and ion acceleration by superintense lasers [13] because they are mostly sensitive to ions but are insensitive to the backgrounds such as electrons and photons. When charged particles collide with a sheet of CR-39 solid state track detectors, they generate the tracks observable with an optical microscope after an etching stage under controlled conditions. The detection efficiency of CR-39 was found to be nearly 100% for ion energies higher than 100 keV [14]. It was also demonstrated that the energy threshold could be around 20 keV [15–17]. We used CR-39 solid state track detectors to record the energy and number of the protons generated by the ^{2}H(d,p)^{3}H reaction. Proton identification requires the information on the track's diameters, depths and patterns which primarily depend on the proton energy, the etching parameters (solution temperature and concentration), and the etching time. However, the performance of CR-39 track detectors varies from batch to batch in the same factory [18]. Thus, one must calibrate the same batch of the CR-39 detectors with mono-energetic protons as that used in study of fusion reactions. To date the calibration of CR-39 solid state detectors with proton beam has several methods such as Rutherford backscattering method [19, 20], nuclear reaction method [21], laser accelerated proton (TNSA acceleration mechanism) combined with mass spectrometer [22], beam irradiation [17, 23].

In this work, we aim at calibration of CR-39 detectors with monoenergetic protons from 2×1.7 MV tandem accelerator, using a rotating target plate with CR-39 pieces pasted on it to receive the irradiation below required density.

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Table 1. Proton energy and the used CR-39 sheet number for each round in our calibrations.

Energy (MeV)	Number of CR-39
2.5	15
2.3	13
2.1	13
1.9	13
1.7	13
1.5	14
1.3	13
1.1	13
0.9	13
0.7	13
0.5	13
0.3	15

2 Experimental procedure

The proton beam was delivered by GIC4117 tandem accelerator at Beijing Normal University. In the experiment, proton beam intensity was about 20 pA during the calibration at different energies. A schematic layout of the experimental setup is shown in Fig. 1.

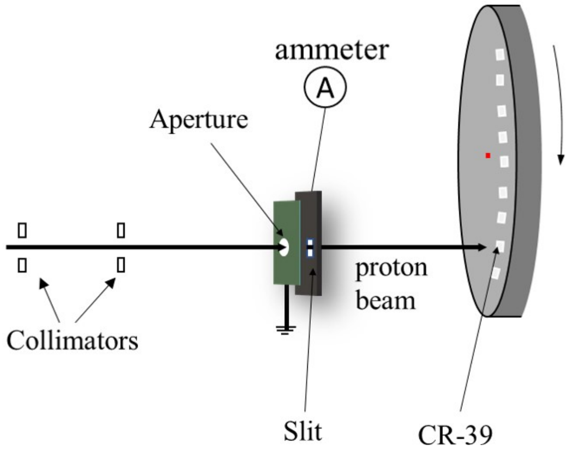

Figure 1. Schematic Layout of experimental setup.

In Fig. 1, two collimators are placed on the path where proton beam comes from. An aperture with the diameter of the 1 cm and a slit with the width of 0.439 mm are used to decrease the beam intensity. We connected the slit to an ammeter to get the beam intensity. CR-39 solid state track detector (Fukuvi Chemical Industry, Tokyo, Japan) sheets are pasted on a big rotating plate and arranged in a circle. For each CR-39 sheet, its geometrical dimension is 10 mm × 10 mm × 0.9 mm. The maximum speed of the rotating plate is 109 rpm.

In each measurement, the controllable target plate rotated for only one time, so the duration of irradiation on a CR-39 detector is the period of time that proton beam shots across one CR-39 sheet. This irradiating duration was measured by a He-Ne laser. The laser passed through the slit and received by an oscilloscope. The irradition time on each CR-39 piece is measured to be 12.5ms. It can be estimated that the amount of protons irradiated on one CR-39 solid state detector is $\sim 5{\times}10^4$. Table 1 lists out the proton energies, number of the used CR-39 pieces for each round.

The irradiated CR-39 sheets were chemially etched in the 6.5 mol/L of NaOH solution at the temperature of 70±0.1°C, and the volume of solution didn't change when we finished etching. The etched CR-39 sheets were processed in six steps: (1) Wash in 700 ml of deionized water for 5 minutes; (2) Wash in 500 ml of deionized water for 5 minutes and then wash for the second time; (3) Wash in 250 ml dilute nitric acid (10%) for 5 minutes;(4) Soak in 600 ml of deionized water for 5 minutes; (5) Soak in absolute ethanol (analytical purity) for 5 minutes; (6) Put it in a petri dish and then put them in a self-sealing bag.

The proton track diameters were measured by an automatic image analyzer provided by Beijing Institute of Radiology Medicine [25]. The optical images from microscope were acquired as analog pictures with CCD camera, then analog pictures were converted into digital ones by image acquisition card, and thus the track diameters were measured by image processing. In our experiment, the proton beam was focused on the CR-39 sheets at normal incidence. Therefore, the diameter of the track can be used as a reliable parameter for the calibration.

3 Results

Some sample tracks which were etched for 4 hours are shown in Fig. 2. In Fig. 3, we plot the proton track diameter versus proton energy etched for different times (4 h, 8 h, 12 h, 16 h, 20 h, 24 h, 28 h) at 70°C in the 6.5 mol/L of NaOH. Two preliminary conclusions can be drawn from Fig. 3: (1) Long time etching will make the track of low-energy protons shallow and difficult to measure accurately, hence the etching duration of the CR-39 detectors should not be too long; (2) The longer time of etching, the higher energy of the peak will move to for the curves of track diameter vs proton energy. Under the present etching conditions described herein, the tracks diameter of 0.3 MeV protons was the largest for 4 hours of etching. With the etching time increasing to 28 hours, the proton energy for the maximum value of track diameter changes to 1.1 MeV.

4 Summary and conclusion

In summary, we have carried out the proton calibration for CR-39 solid state track detectors which have been used in our study of the laser-driven ^{2}H(d,p)^{3}H reaction. The track diameters were given for the proton energies from 0.3 MeV to 2.5 MeV (12 energy points) and for seven different etching times from 4 hours to 28 hours. Finally, we recommended the optimal etching times to be 8-20 hours at the typical etching conditions of 70°C in 6.5 mol/L NaOH. The present calibration results will be very helpful for identifying the reaction products emitted from the ^{2}H(d,p)^{3}H fusion reaction.

Acknowledgment

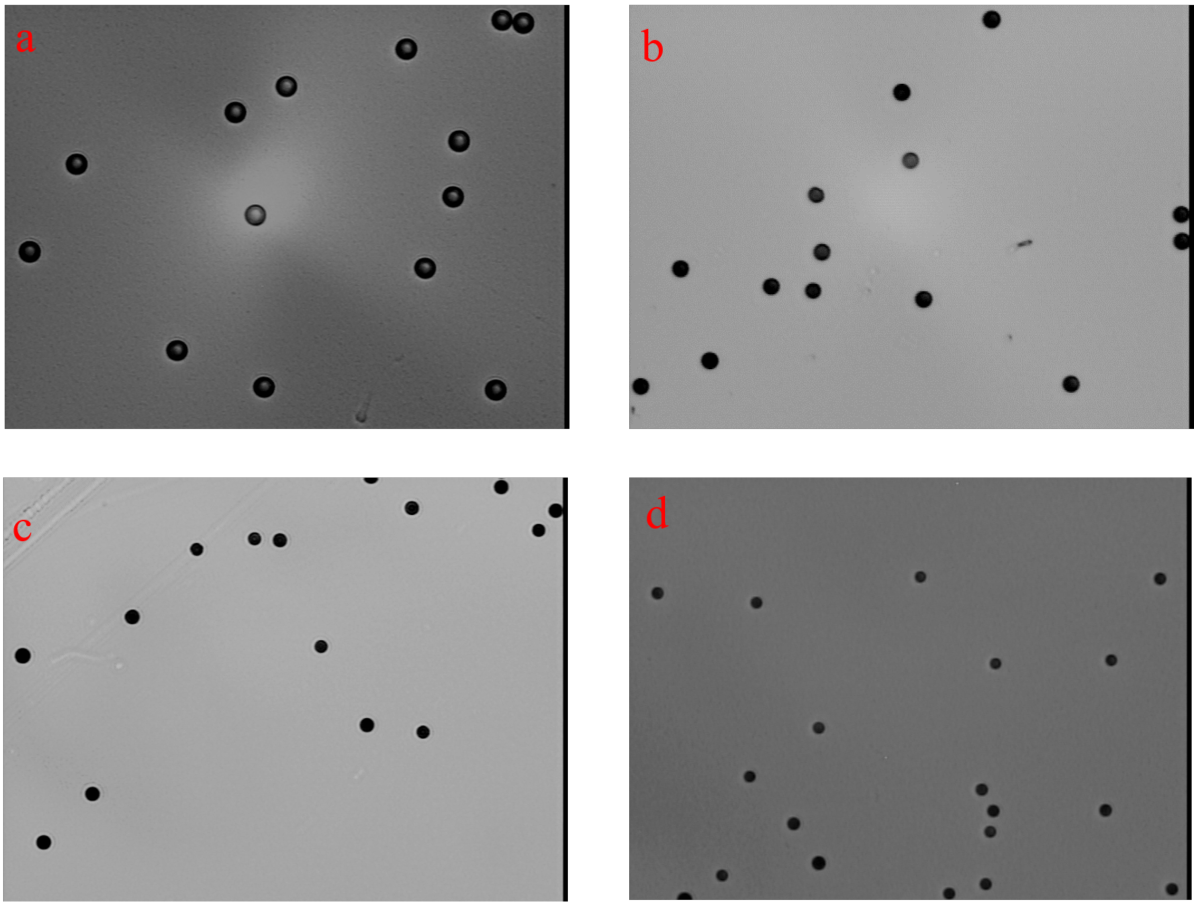

Figure 2. Microphotographs of tracks from normally incident protons: a) 0.3 MeV protons (4 h chemical etching); b) 0.5 MeV protons (4 h chemical etching); c) 1.5 MeV protons (4 h chemical etching) and d) 1.9 MeV protons (4 h chemical etching).

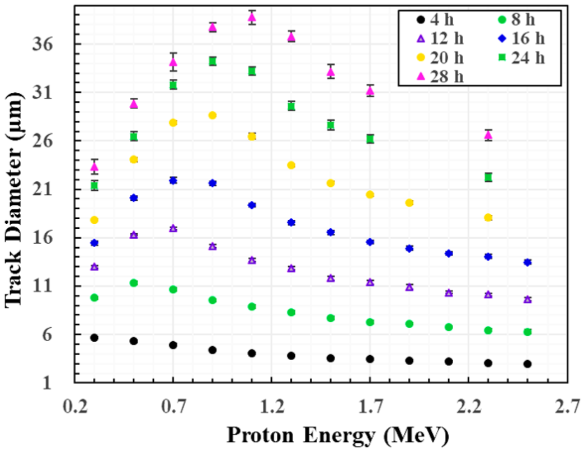

Figure 3. Track diameter vs. proton energy.

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