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Calibration of CR-39 solid-state track detectors for study of laser-driven nuclear reactions

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Abstract It is of particular interest to investigate nuclear fusion reactions generated by high-intensity lasers in plasma environments that are similar to real astrophysical conditions. We have experimentally investigated $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$, one of the most crucial reactions in big bang nucleosynthesis models, at the Shenguang-II laser facility. In this work, we present a new calibration of CR-39 solid-state track detectors, which are widely employed as the main diagnostics in this type of fusion reaction experiment. We measure the dependence of the track diameter on the proton energy. It is found that the track diameters of protons with different energies are likely to be identical. We propose that in this case, the energy of the reaction products can be obtained by considering both the diameters and gray levels of these tracks. The present results would be very helpful for analyzing the $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ reaction products recorded with the same batch of CR-39 solid-state track detectors.

Keywords Big bang nucleosynthesis · Laser-driven nuclear reactions · CR-39 detectors · Gray levels

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1 Introduction

Nuclear fusion reactions 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 $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ fusion reaction plays a key role in the design of future fusion power plants and in the understanding of the primordial abundances in big bang nucleosynthesis models [3]. Therefore, this reaction has been studied using accelerators in the past several decades (see [4] and references therein). It is of particular interest to investigate reactions of this type when they are generated by high-intensity lasers in plasma environments that are similar to real astrophysical conditions. In recent years, with the rapid development of high-intensity laser technologies, it has become possible to produce this type of plasma environment in the laboratory [5–9].

Recently, we have performed experimental investigations of the $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ reaction using laser-driven counter-streaming collisionless plasmas at the Shenguang-II laser facility at the Shanghai Institute of Optics and Fine Mechanics of the Chinese Academy of Sciences. In these measurements, difficulties arise in the identification and quantification of the reaction products (such as electromagnetic pulses), which can interfere with electronic devices. To date, considerable effort has been made to develop detectors and investigate their performance for the study of laser-driven nuclear reactions, for example, the CR-39 and 4H-SiC detectors [10, 11]. We used CR-39 solid-state track detectors to record the energy and quantity of protons generated by the $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ reaction. The CR-39 solid-state track detector [12, 13] is an ideal ion detector because it is sensitive mainly to ions but is insensitive to backgrounds such as electrons and photons [14]. When the ion energy is higher than 100 keV, the efficiency of the CR-39 solid-state track detector is nearly 100%. The energy threshold of CR-39 solid-state track detectors could be approximately 20 keV [14–16]. The performance of these detectors typically varies from batch to batch even when they are produced in the same factory [17]. Thus, one must calibrate each batch of CR-39 solid-state track detectors with monoenergetic protons like those used to study the $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ fusion reaction. There are several requirements for the calibration of CR-39 solid-state track detectors. (1) It is necessary to avoid long-term exposure to air and ultraviolet radiation. (2) Because the particle track should be clearly identified, the beam current on the detectors needs to be less than $10^{5}\ \mathrm{cm}^{-2}$. (3) In the calibration experiment, the beam of particles recorded by CR-39 solid-state track detectors should be monochromatic; because a proton beam with a large energy divergence is equivalent to a combination of protons of various energies, a detector calibrated by this method cannot accurately indicate the energy characteristics and track parameters of the detector. (4) In a single energy calibration experiment, multiple CR-39 solid-state track detectors need to be irradiated. There are several methods of irradiating CR-39 solid-state detectors with a proton beam produced by a traditional accelerator [14, 18–22] or a laser accelerator [23]. The Rutherford backscattering method [18, 19] and nuclear reaction method [20] are typical approaches using a traditional accelerator.

These pioneering results demonstrated that there is not a one-to-one correspondence between the proton energy and the track diameter in the energy region [14, 18, 19, 22, 23]. Consequently, there is an uncertainty when different proton energies are distinguished using their track diameters. Therefore, to analyze the $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ reaction products recorded with a single batch of CR-39 detectors, research on methods of identifying the particle information is desirable.

In this work, we used a monoenergetic proton beam to irradiate a CR-39 detector, measured the dependence of the track diameter on the proton energy, and demonstrated a method of distinguishing different energies by considering both the track diameters and their gray levels. Note that in the laser-driven $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ experiment, the energies of the incident deuterons are below 100 keV, and those of the outgoing protons and tritons are approximately 3 and 1 MeV, respectively. To stop deuterons and tritons, the CR-39 slices were coated with a 30–40-micron aluminum film. The proton energies were therefore reduced to approximately 2 MeV after the Al film. Thus, we used proton beams with energies ranging from 0.3 to 2.5 MeV for the calibrations.

2 Experiment

Proton beams with an intensity of approximately 20 pA and energies ranging from 0.3 to 2.5 MeV in 0.2 MeV steps were delivered by the GIC4117 tandem accelerator at Beijing Normal University. A schematic layout of the experimental setup is shown in Fig. 1. The protons are vertically incident onto the CR-39 detectors in the calibration because the CR-39 detectors are placed perpendicular to the direction of outgoing products in the laser-driven $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ reaction experiment. The proton beam reaches the CR-39 detector through an aperture with a diameter of 1 cm and a slit with a width of 0.439 mm. CR-39 solid-state track detectors (Fukuvi Chemical Industry, Tokyo, Japan) are attached to a large rotating plate in a circular arrangement. The geometrical dimensions of each CR-39 solid-state track detector slice are $10\,\mathrm{mm} \times 10\,\mathrm{mm} \times 0.8\,\mathrm{mm}$. In each measurement, the controllable target plate was rotated only once. We measured the time at which the laser passed through two adjacent holes using a He–Ne laser. The irradiation time on each CR-39 detector was deduced to be approximately 12.5 ms, as shown in Fig. 2. The proton irradiation of a CR-39 solid-state track detector can be estimated as

$$N \approx \frac{S_2 I}{S_1 Q} t, \tag{1}$$

where I is the current connected to the slit, t is the time of the CR-39 solid-state track detector passing through the

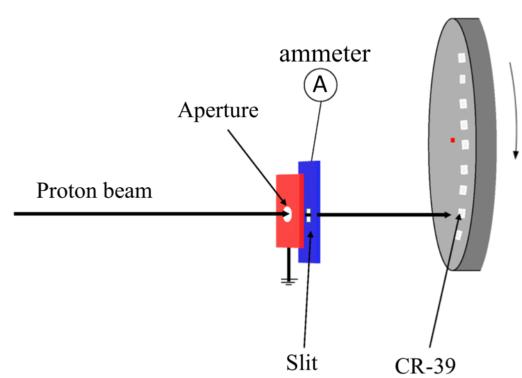

Fig. 1 (Color online) Layout of experimental setup. The aperture has a diameter of 1 cm, and the slit has a width of 0.439 mm

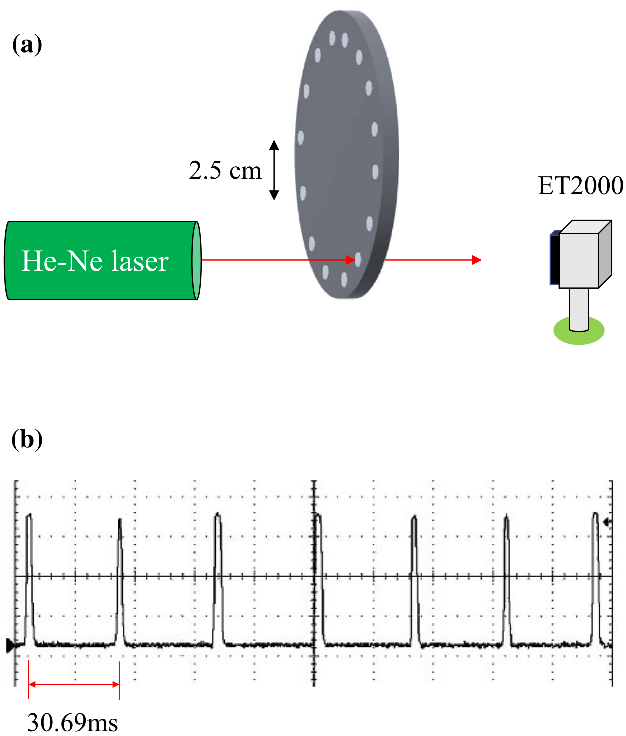

Fig. 2 (Color online) **a** This irradiation duration was measured using a He–Ne laser, a photodiode (ET2000), and an oscilloscope. **b** The time interval between two holes 2.5 cm apart is approximately 30.69 ms. The irradiation time on each CR-39 detector was deduced to be approximately 12.5 ms

slit, Q is the charge of a proton, S_1 is the area of the aperture, and S_2 is the area of the slit. The proton number N per unit area of a CR-39 slice is approximately 5×10^4, according to Eq. 1.

The CR-39 detectors should be chemically etched in an aqueous solution of NaOH or KOH at an appropriate concentration and temperature. In this experiment, the CR-39 solid-state track detectors were etched in a 6.5-mol L^{-1} NaOH solution and kept at a constant temperature of $70 \pm 0.1\,°C$. After etching, we processed the CR-39 detectors in six steps, as shown in Fig. 3. Step 1: Wash the CR-39 detector in 700 mL of deionized water for 5 min to stop etching. Step 2: Wash the detector in 500 mL of deionized water for 5 min to clean it. Step 3: Wash the detector in 250 mL of dilute nitric acid (10%) for 5 min to neutralize alkaline substances. Step 4: Soak the detector in 600 mL of deionized water for 5 min. Step 5: Wash the detector in absolute ethanol (analytical purity) for 1 min. Step 6: Place it in a Petri dish and place the detector and dish in a self-sealing bag.

After an appropriate chemical etching treatment, the damage trail (called a latent track) induced by the ionized particles in the CR-39 solid-state track detector can be visualized under an optical microscope. In this work, the

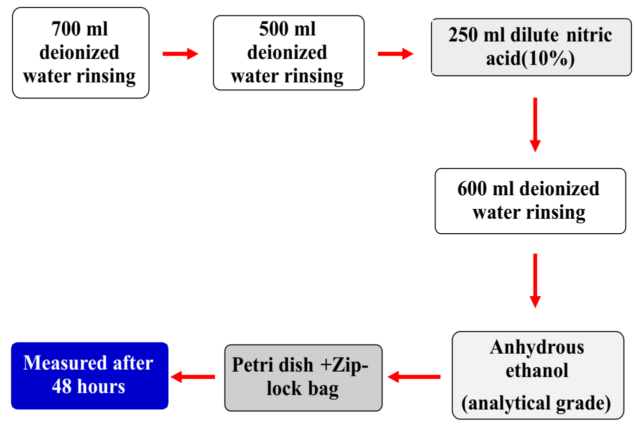

Fig. 3 (Color online) Post-processing of the CR-39 solid-state track detector

track diameters of protons were measured using an automatic track image analyzer. First, the images from an optical microscope were acquired using a CCD camera. Then, the analog pictures were converted to digital ones by an image acquisition card. Finally, the track diameters were measured using image processing.

3 Experimental results

In Fig. 4, we plot the dependence of the proton track diameter on the proton energy (0.3–2.5 MeV) after the detector was etched at 70 °C in a 6.5-mol L^{-1} solution of NaOH for various etching times. An etching time of $\leq 20\,h$ was suggested in our previous work [24]. The dotted lines in Fig. 4 are drawn as guides for the eyes. For the calibration curves corresponding to etching times longer than

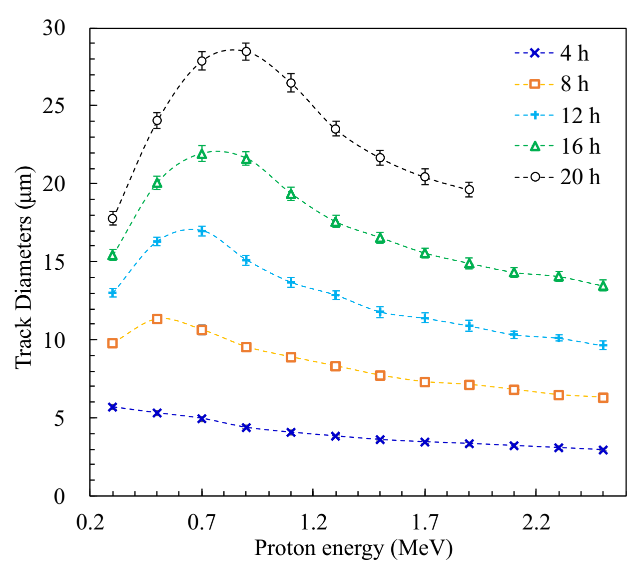

Fig. 4 (Color online) Track diameter versus proton energy

or equal to 8 h in Fig. 4, two proton energy values correspond to the same track diameter. Consequently, the energy cannot be determined using only the diameter. Fortunately, as shown in Fig. 5, the tracks for higher-energy protons are much darker than those for lower-energy protons. Thus, one can distinguish the proton energies by the gray levels of their tracks, even if the track diameters are identical.

It should also be mentioned that the gray level along each track varies, and its distribution is not regular. This fact reflects the complex structure of the track, which makes the digitization of gray levels at high precision very difficult. Thus, we combined the quantitative analysis of the track diameters and the qualitative analysis of the gray levels to study the incident ions, which was proved to be an effective method of proton energy identification (Figs. 4, 5).

4 Summary and conclusion

In summary, we present new calibration results for CR-39 solid-state track detectors, which are widely employed as the main diagnostics in fusion reaction experiments and ion acceleration by superintense lasers, because they are sensitive mainly to ions but insensitive to backgrounds such as electrons and photons. We use a slit and a rotating plate to reduce the beam intensity. Using this method, we measure the dependence of the track diameter on the proton energy. The results suggest that it is difficult to determine the proton energy using only the track diameter. In this case, the energy of the reaction products can be obtained by combining a quantitative analysis of the track diameters and a qualitative analysis of the gray levels. The present results can be very helpful for analyzing the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction products recorded with the same batch of CR-39 solid-state track detectors.

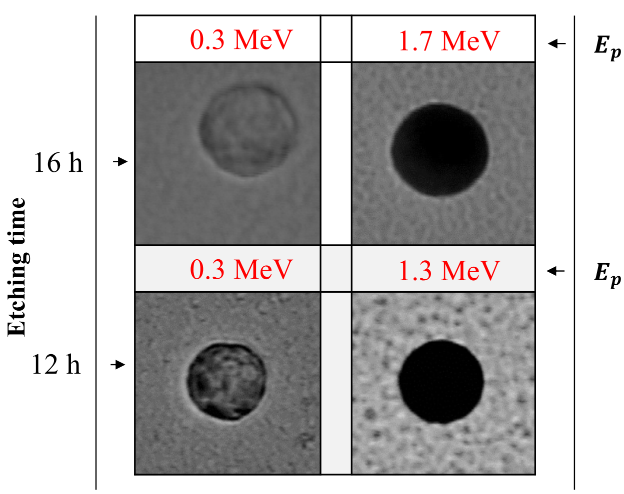

Fig. 5 When the diameters are the same, the proton energy level can be distinguished according to the gray level of the track

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References

1. E.M. Burbidge, G.R. Burbidge, W.A. Fowler et al., Synthesis of the elements in stars. Rev. Mod. Phys. **29**, 547–650 (1957). https://doi.org/10.1103/revmodphys.29.547
2. G. Wallerstein, I. Iben Jr., P. Parker et al., Synthesis of the elements in stars: forty years of progress. Rev. Mod. Phys. **69**, 995–1084 (1997). https://doi.org/10.1103/revmodphys.69.995
3. R.H. Cyburt, B.D. Fields, K.A. Olive et al., Big bang nucleosynthesis: present status. Rev. Mod. Phys. **88**, 015004 (2016). https://doi.org/10.1103/RevModPhys.88.015004
4. Y. Xu, K. Takahashi, S. Goriely et al., NACRE II: an update of the NACRE compilation of charged-particle-induced thermonuclear reaction rates for nuclei with mass number A <16. Nucl. Phys. A **918**, 61–196 (2013). https://doi.org/10.1016/j.nuclphysa.2013.09.007
5. P. McKenna, K. Ledingham, T. McCanny et al., Demonstration of fusion-evaporation and direct-interaction nuclear reactions using high-intensity laser-plasma-accelerated ion beams. Phys. Rev. Lett. **91**, 075006 (2003). https://doi.org/10.1103/PhysRevLett.91.075006
6. V. Belyaev, A. Matafonov, V. Vinogradov et al., Observation of neutronless fusion reactions in picosecond laser plasmas. Phys. Rev. E **72**, 026406 (2005). https://doi.org/10.1103/PhysRevE.72.026406
7. L. Robson, P. Simpson, R.J. Clarke et al., Scaling of proton acceleration driven by petawatt-laser-plasma interactions. Nat. Phys. **3**, 58–62 (2007). https://doi.org/10.1038/nphys476
8. C. Labaune, C. Baccou, V. Yahia et al., Laser-initiated primary and secondary nuclear reactions in Boron-Nitride. Sci. Rep. **6**, 21202 (2016). https://doi.org/10.1038/srep21202
9. L. Torrisi, Nuclear reaction in plasmas generated by high intensity lasers. Radiat. Eff. Defects Solids **172**, 61–73 (2017). https://doi.org/10.1080/10420150.2017.1286657
10. H.J. Fu, L.J. Wang, H.W. Wang et al., The R&D of 4H-SiC detector for laser plasma products measurement. Nucl. Tech. **42**, 020501 (2019). https://doi.org/10.11889/j.0253-3219.2019.hjs.42.020501. (**in Chinese**)
11. C. Han, X.Z. Cui, X.H. Liang et al., Study of the characteristics of an irradiated 4H-SiC charge particle detector. Nucl. Tech. **42**, 050501 (2019). https://doi.org/10.11889/j.0253-3219.2019.hjs.42.050501. (in Chinese)
12. R. Fleischer, P. Price, R. Walker, Ion explosion spike mechanism for formation of charged-particle tracks in solids. J. Appl. Phys. **36**, 3645–3652 (1965). https://doi.org/10.1063/1.1703059
13. B.G. Cartwright, E. Shirk, P. Price, A nuclear-track-recording polymer of unique sensitivity and resolution. Nucl. Instrum. Methods **153**, 457–460 (1978). https://doi.org/10.1016/0029-554X(78)90989-8
14. X.J. Duan, X.F. Lan, Z.X. Tan et al., Calibration of CR-39 with monoenergetic protons. Nucl. Instrum. Methods A **609**, 190–193 (2009). https://doi.org/10.1016/j.nima.2009.08.061

15. E. Skladnik-Sadowska, J. Baranowski, M. Sadowski, Low-energy ion measurements by means of CR-39 nuclear track detectors. Radiat. Meas. **34**, 337–339 (2001). https://doi.org/10.1016/S1350-4487(01)00179-2
16. K. Malinowski, E. Skladnik-Sadowska, M.J. Sadowski, Comparison of responses of LR-115A, CR-39 and PM-355 track detectors to pulsed low-energy proton streams. Radiat. Meas. **40**, 371–374 (2005). https://doi.org/10.1016/j.radmeas.2005.01.015
17. E. Vilela, E. Fantuzzi, G. Giacomelli et al., Optimization of cr-39 for fast neutron dosimetry applications. Radiat. Meas **31**, 437–442 (1999). https://doi.org/10.1016/S1350-4487(99)00141-9
18. L. Bernardi, A. Cecchi, C. Gori et al., Studies of the response of CR-39 track detectors to protons from a 3 MeV Van de Graaff accelerator. Nucl. Instrum. Methods B **53**, 61–66 (1991). https://doi.org/10.1016/0168-583X(91)95445-J
19. Z. Lounis, S. Djeffal, K. Morsli et al., Track etch parameters in CR-39 detectors for proton and alpha particles of different energies. Instrum. Methods Phys. Res. B **179**, 543–550 (2001). https://doi.org/10.1016/S0168-583X(01)00601-2
20. N. Sinenian, M. Rosenberg, M. Manuel et al., The response of CR-39 nuclear track detector to 1–9 MeV protons. Rev. Sci. Instrum. **82**, 103303 (2011). https://doi.org/10.1063/1.3653549
21. Y. Zhang, H.W. Wang, Y.G. Ma et al., Energy calibration of a CR-39 nuclear-track detector irradiated by charged particles. Nucl. Sci. Tech. **30**, 87 (2019). https://doi.org/10.1007/s41365-019-0619-x
22. M. Seimetz, P. Bellido, P. García et al., Spectral characterization of laser-accelerated protons with CR-39 nuclear track detector. Rev. Sci. Instrum. **89**, 023302 (2018). https://doi.org/10.1063/1.5009587
23. C. Baccou, V. Yahia, S. Depierreux et al., CR-39 track detector calibration for H, He, and C ions from 0.1–0.5 MeV up to 5 MeV for laser-induced nuclear fusion product identification. Rev. Sci. Instrum. **86**, 083307 (2015). https://doi.org/10.1063/1.4927684
24. Y.F. He, X.F. Xi, S.L. Guo, et al. Calibration of CR-39 solid state track detectors with monoenergetic protons from 0.3 MeV to 2.5 MeV (submitted to EPJ conference)