Comment on "Observation of neutronless fusion reactions in picosecond laser plasmas"

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The paper by Belyaev *et al.* [Phys. Rev. E **72**, 026406 (2005)] reported the first experimental observation of alpha particles produced in the thermonuclear reaction $^{11}B(p,\alpha)^{8}Be$ induced by laser irradiation on a ^{11}B polyethylene (CH_2) composite target. The laser used in the experiment is characterized by a picosecond pulse duration and a peak of intensity of 2×10^{18} W/cm^2. We suggest that both the background-reduction method adopted in their detection system and the choice of the detection energy region of the reaction products are possibly inadequate. Consequently the total yield reported underestimates the true yield. Based on their observation, we give an estimation of the total yield to be higher than their conclusion, i.e., of the order of $10^5\alpha$ per shot.

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The observations of the thermonuclear reactions in a high-power laser-pulse irradiated target is one of the hottest topics [1–7]. The most investigated reaction is $D(d,n)^3He$ with a Q value of 3.26 MeV. There have been studies using different characteristics of laser irradiation on a wide variety of targets: solid CD_2 plastic [2,5,6], D_2 gas [4], and deuterium clusters [1]. Since the reactions produce monochromatic neutrons, the spectroscopy of these neutrons gives important information on the ion acceleration mechanism in the laser-induced plasma.

In the experiment recently carried out by a Russian group the yield of $10^3\alpha$ particles has been reported [7], for the first time, in the laser irradiation of a $^{11}B+CH_2$ composite target. Their experiment is important for a deep understanding of the ion acceleration mechanism in the laser-matter interaction. The experiment has been carried out by using a "Neodymium" laser facility with the pulse energy of up to 15 J, a laser wavelength of 1.055 μm, and a pulse duration of 1.5 ps. Before the main pulse, there are three prepulses with relative intensities 10^{-4}, 10^{-3}, and 10^{-8}, with picosecond durations for the former two and with 4 nanosecond duration for the last one.

The laser beam has been focused on the solid target at an oblique incidence of 40° to the target normal. CR-39 track detectors covered with 11 and 22 μm thick aluminum foils have been used to count the yield of α particles from the reaction $^{11}B(p,\alpha)^{8}Be$. The reaction induces three-particle decay. Either through the ^8Be ground state (α_0):

$$^{11}B+p\rightarrow\alpha_0+{}^{8}Be, \tag{1}$$

with the reaction Q value=8.59 MeV or through the ^8Be excited state (α_1):

$$^{11}B+p\rightarrow\alpha_1+{}^{8}Be^{*}, \tag{2}$$

with the reaction Q value=5.65 MeV and a large width of 1.5 MeV [8–10]. This is followed by the decay of the excited state (α_{12}):

$$^{8}Be^{*}\rightarrow 2\alpha_{12}, \tag{3}$$

and a reaction Q value=3.028 MeV. It is known that the main channel of the reaction is the second one [11,12] and only 1% of the reaction products are α_0 from reaction (1). Using energy and momentum conservation laws, the α_0 and α_1 have kinetic energies:

$$\varepsilon_{\alpha_0}=\frac{8}{12}(8.59+E)\ \text{MeV}, \tag{4}$$

$$\varepsilon_{\alpha_1}=\frac{8}{12}(5.65+E)\ \text{MeV}, \tag{5}$$

where E is the center-of-mass incident energy in the case of the conventional beam-target experiment. But in the laser-induced plasma, the incident energy of the reactions is characterized by some energy distributions, which are not known clearly. If we assume a thermal equilibrium state for the plasma, the energy distribution is given by a Maxwellian. The temperature of the plasma is estimated [13,14] to be of the order of 67 keV for a background electron temperature T_c=0.5 keV, and 84 keV for T_c=1 keV at the given laser intensity and the wavelength of the experiment. We mention that Ref. [15] gives an estimate of the nuclear temperature of 33 keV, lower than our estimation. The ions, therefore, can be accelerated up to the energies of the order of hundreds of keV at most. At such low energies, the α_0 and α_1 are estimated to have energies 5.7 and 3.76 MeV, respectively, in the exit channel. However, the energy spectrum of α_1 has a large width, Γ=1.5 MeV; consequently the α_{12} spectra spread from 0 to higher than 5 MeV [16]. An α energy spectrum obtained experimentally in Ref. [10] shows clearly these characteristics of the reaction $^{11}B(p,\alpha)^{8}Be$. The full squares connected by the thick line in Fig. 1 reproduce the data reported in Ref. [10]. The two peaks at 3.76 and 5.7 MeV are clearly visible.

In the experiment in Ref. [7], the CR-39 track detectors have been placed at angles of 0°, 45°, and 85° to the target normal. The $^{11}B(p,\alpha)^{8}Be$ reaction yield has been estimated by subtracting the background obtained in the irradiation of the pure CH_2 target. The detectors are covered with alumi-

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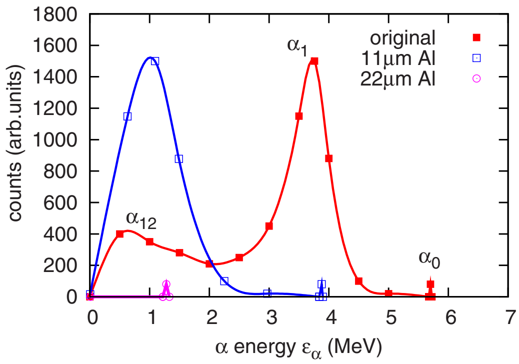

FIG. 1. (Color online) Shifts of the α energy spectrum due to the 11 and 22 μm thick aluminum foils. The alpha energy spectrum in the reaction ^{11}B$(p,\alpha)^8$Be at 660 keV beam energy from Ref. [10] is given by full squares joined by the thick line. The shifted spectra due to a 11 or 22 μm thick aluminum foils are given by the open squares and open circles, respectively, joined by thick lines. The small α_0 sharp peak at 5.7 MeV in the original spectrum is broadened and shifted to 1.27 MeV by the 22 μm thick Al foil.

num foils 11 or 22 μm thick. The reason for covering the plastic detectors is that the alpha tracks get confused with energetic ions coming from the high-momentum tail of the plasma distributions. Cutting off the track diameter below 7 μm as in Ref. [7] eliminates all the protons but not heavier ions (B and C) of the plasma which leave bigger tracks. The s of Ref. [7] observed that these "strange ions" were still dominant when a 6 μm Al foil is used. This fact prompted them to increase the thickness of the foil which caused blocking lower energy α particles as well. However this shielding of background is efficient only if the energy of the detected ions is well specified as in the case of the reaction with a two-body exit channel. By contrast in the reaction ^{11}B$(p,\alpha)^8$Be, the energy spectrum of reaction products spreads from 0 up to 5.7 MeV, as it is shown in Fig. 1. In such a case the Al foil will remove the major part of the reaction products. A 11 μm thick Al foil shields α particles with energies lower than 3 MeV. If one uses a 22 μm thick Al foil, α particles with energies lower than 5 MeV will be stopped inside the foil. We have performed simulations of the transmitted α particles through the foils by using TRIM in SRIM codes [17]. Figure 1 shows the α-particle reduction by Al foils with thicknesses of 11 (open squares) and 22 μm (open circles) together with the original spectrum (full squares). One can see clearly that the peak at 3.76 MeV is shifted and broadened passing through the 11 μm thick Al foil: 450 counts of α particles at the initial energy of 3 MeV are reduced to 16 counts at 4 keV. Using a 22 μm thick Al foil gives exclusively the α_0 peak. Thus the fusion yield in Ref. [7] underestimates the true yield. Considering the expected energies of the reaction products from all the reaction channels, there is ample room for further improvement of the choice of this detection energy region.

From the calibration data of the detectors by α sources, which is shown in Fig. 1 of Ref. [7], it is possible to convert the α-energy spectrum in Fig. 1 to one as a function of observed track diameters. In Fig. 2 we show the α-energy spectrum of Fig. 1 as a function of the track diameters on the CR-39 detectors.

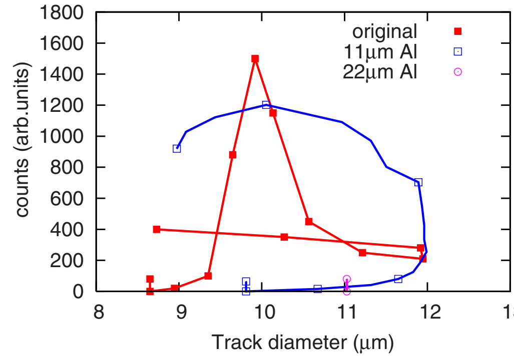

FIG. 2. (Color online) Expected track diameters on CR-39 detectors from the original and shifted α spectra. The symbols are as in Fig. 1.

The 22 μm thick Al foil shields the major part of the reaction products and gives the 5.7 MeV α_0 only which is a less important channel. In Fig. 1 one sees that the α_0 will lose its energy passing through the foil and the transmitted α_0 will have an energy of about 1.27 ± 0.08 MeV. Figure 2 shows that the α particles in this energy range will give track diameters of about 11 μm. Looking at Fig. 4 in Ref. [7], which shows the distributions of track diameters for detec-

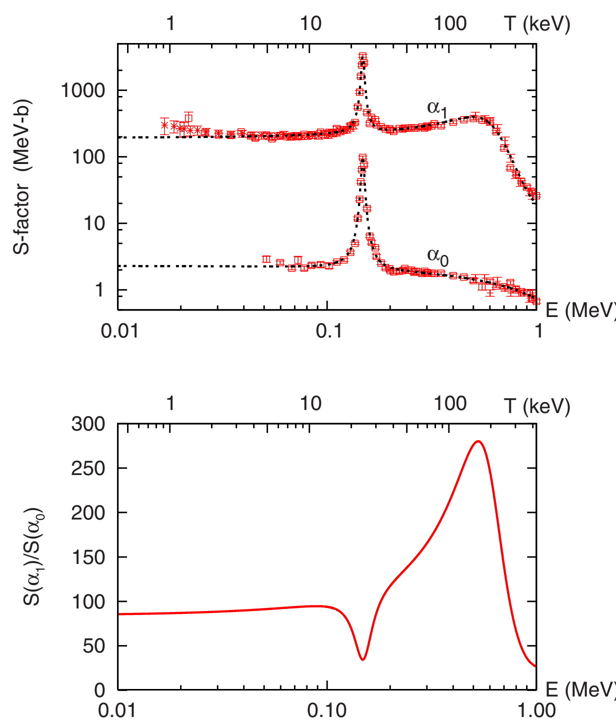

FIG. 3. (Color online) The S factors for the reaction ^{11}B$(p,\alpha)^8$Be as a function of the incident center-of-mass energy (the abscissa) and of the plasma temperature (the mirror of the abscissa) for two reaction channels (top panel). Experimental data are taken from [11] (squares) and [19] (crosses). The dotted fitting curves to the data are obtained using polynomial expression for the nonresonant contribution and Breit-Wigner formula for the resonant contribution. In the low energy region the screening effect due to bound electrons is not included. In the bottom panel, the ratio of the S factors in the α_1 and α_0 channels is shown.

tors covered with 22 μm Al, an excess of tracks above the background with diameters around 11 μm is, indeed, recognized. If this estimation is correct, we can conclude that the yield of α_0 is about $1.5\times10^3/4\pi$ Sr, from the values tabulated in their Table I, under the assumption of an isotropic distribution of the reaction products.

From this result, we might be able to estimate the true fusion yield by considering the ratio of the astrophysical S factors [18], which is directly related to the reaction cross section, in reaction (2) to reaction (1) [12]. Figure 3 shows the S factors for the two channels and their ratio both as functions of the incident center-of-mass energy E of colliding nuclei and the plasma temperature T. The correspondence between E and T is obtained by the relation between the plasma temperature and the so-called "most effective energy" at that temperature [18,20]. For the purpose of taking the ratio, the experimental data of the S factors [11,19] have been fitted by a polynomial expression combined with the Breit-Wigner resonance formula. The resulting curves, as well as the experimental data, are shown by the dashed lines in the top panel. In the bottom panel of Fig. 3, the curve shows the ratio of the S factors. The ratio is almost constant up to the temperature of 20 keV but varies from 30 to 280 in the temperature region where two resonances at $E=148.5$ and 660 keV dominate the S factors. The increase in the ratio is attributed to the presence of a broad resonance at 660 keV exclusively in the α_1 channel. Provided that the ratio of the S factors is from 100 to 170 in the range of the plasma temperature from 33 to 84 keV, the total fusion yield is estimated to be about 130 times of the observed value with 22 μm Al foil, i.e., more than 2×10^5 fusions per shot. This value becomes 4×10^4 if we use the averaged value over bursts reported in Ref. [7].

In conclusion we have discussed the expected energy range of the reaction products from the thermonuclear reaction ^{11}B$(p,\alpha)^8$Be induced by an irradiation on a ^{11}B polyethylene composite target, whose first quantitative observation has been given by Belyaev *et al.* [7]. Their experiment is essential not only to seek a possibility of aneutronic fusions but also to promote a better understanding of the ion acceleration mechanism in the laser-matter interaction. In this connection, it is highly desirable that more precise measurements of the angular distribution of the reaction products will be performed [21]. We have demonstrated that the observed yield in their experiment is underestimated at least by a factor of 100 due to both the background-reduction method in their detection system and their selection of the detection energy region.

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