

# MeV particles from laser-initiated processes in ultra-dense deuterium D(−1)

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**Abstract.** Fast particles from laser-induced processes in ultra-dense deuterium D(−1) are studied. The time of flight shows very fast particles, with energy above MeV. Such particles can be delayed or prevented from reaching the detector by inserting thin or thick metal foils in the beam to the detector. This distinguishes them from energetic photons which pass through the foils without delays. Due to the ultra-high density in D(−1) of  $10^{29} \text{ cm}^{-3}$ , the range for 3 MeV protons in this material is only 700 pm. The fast particles ejected and detected are thus mainly deuterons and protons from the surface of the material. MeV particles are expected to signify fusion processes D+D in the material. The number of fast particles released is determined using the known gain of the photomultiplier. The total number of fast particles formed, assuming isotropic emission, is less than  $10^9$  per laser pulse at  $< 200 \text{ mJ}$  pulse energy and intensity  $10^{12} \text{ W cm}^{-2}$ . A fast shockwave with  $30 \text{ keV u}^{-1}$  kinetic energy is observed.

## 1 Introduction

Nuclear fusion reactions can be caused by laser-initiated release of fast D atoms in ultra-dense deuterium D(−1) [1,2]. The density of this material is close to  $10^{29} \text{ cm}^{-3}$  or  $140 \text{ kg cm}^{-3}$  as shown in several publications [3–10]. From this high density it is concluded that multiple-scattering events will take place of particles released with high energy from fusion reactions and Coulomb explosions (CE) as observed in refs. [1,2]. This scattering will strongly modify the results relative to a low-density case. Broad time-of-flight (TOF) distributions give no specific particle information. However, sharp TOF peaks were detected from delayed T or  $^3\text{He}$  after two collisions with H atoms [1]. With an increased amount of D(−1) around the laser focus, most particles are delayed by multiple scattering due to their short mean-free path in the ultra-dense material. The actual processes may further be modified by the superfluid property of D(−1) even at room temperature [10]. We now report on a few striking features related to the delay of fast massive particles and verify the ejection of MeV particles. This is motivated by the need to understand the steps in the nuclear fusion processes in D(−1) which involve violent CE processes.

Ultra-dense deuterium is named D(−1), since it appears to be an inverted form of D(1) [6] with orbital angular momentum  $l = 1$  for the deuterons. It is a quantum material which may involve formation of vortices

in a Cooper pair electron fluid as suggested by Winterberg [11,12]. The clusters forming this material are to a large extent “bead” or chain clusters of the form  $\text{D}_{2N}$ , where each  $\text{D}_2$  pair rotates around their common center of mass [10,13]. The mass centers of the pairs seem to lie along the vortex in the cluster. The short bond distance in D(−1) of 2.3 pm may give a small rate of spontaneous fusion. However, the intention here is to study the processes involved in the more violent nuclear fusion processes taking place in D(−1) under laser impact. Similar experiments have been carried out, for example, using intense laser pulses at  $10^{16}$ – $10^{18} \text{ W cm}^{-2}$  in low density deuterium clusters [14,15]. It is expected that such processes will be much easier to initiate in D(−1) [11,12], allowing the use of much weaker lasers for initiation of nuclear fusion. Recently, the number of fast particles released from D(−1) was found to increase rapidly with laser pulse energy [2].

## 2 Theory

Under impact of laser pulses, Coulomb explosions (CE) take place in the ultra-dense material D(−1) [3,4,6]. A single CE involves only two ions formed in a D(−1) cluster. The excitation of one electron in the material may be sufficient to form these two ions. The potential energy between the two exposed charges is

$$W = \frac{e^2}{4\pi\epsilon_0 d}, \quad (1)$$

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**Table 1.** TOF and ranges for some fusion products at the detector distance 1120 mm. The databases at NIST [17] are used for the alpha and proton ranges. For the neutrons, the quantity  $(\sigma n)^{-1}$  is used as an approximate range with  $\sigma$  from ENDF [16].

	Energy (MeV)	TOF (ns)	Range in D(-1) (nm)	Range in Al ( $\mu\text{m}$ )	Range in scintillator ( $\mu\text{m}$ )
$p$	3.02	46.6	0.66	80	150
	14.7	21.1	12	1300	2500
$n$	2.45	51.7	50	$\gg 1$ m	$\gg 1$ m
	14.1	21.6	150	$\gg 1$ m	$\gg 1$ m

where  $d$  is the distance between the two ions. This energy is transformed almost completely to kinetic energy between the two ionic fragments during their mutual rapid repulsion.

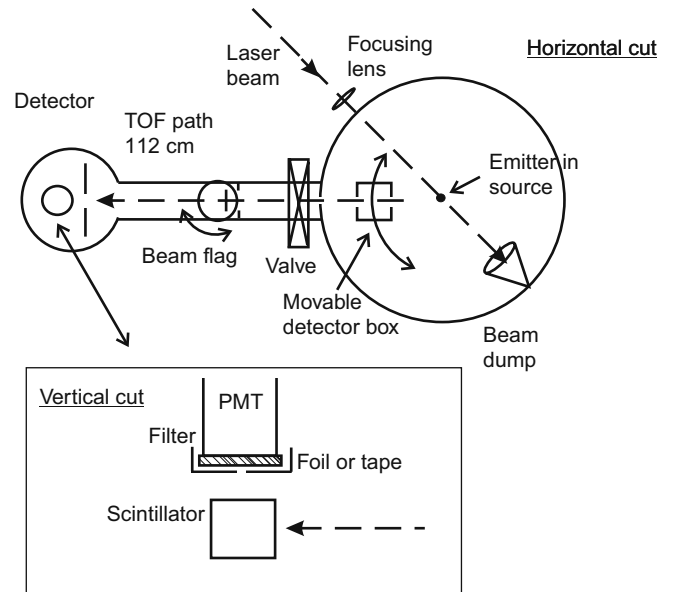
Deuterons are observed with kinetic energy at least up to the kinetic energy release (KER) of 630 eV corresponding to  $D^+ \leftrightarrow D^+D_N$  with  $N$  large [3,4]. Such processes will give nuclear fusion D+D in collisions between fast deuterons, albeit with a low probability. In a dense D(-1) region, several steps of CE are possible [7], and a small fully ionized region may drive the outermost layer of the region to very high energies, providing a mechanism for shockwave formation. Such a high-energy shockwave will easily give high enough energies for D+D fusion. Also other processes giving high-energy deuterons may exist.

Due to the large density of ultra-dense deuterium, collisions of charged particles like protons inside the material may decrease the particle energy and fluxes from the laser focus considerably. Similar processes will also decrease the flux of neutrons from the material due to collisions inside the ultra-dense deuterium. The density in ultra-dense deuterium is approximately  $10^{29} \text{ cm}^{-3}$ , using the measured interatomic distance of 2.3 pm [3,4]. A calculation of the mean-free path for high-energy neutrons released by D+D fusion inside this material can be done, using the  $n$ - $d$  cross-section of 2.37 barn at 2.45 MeV and 0.81 barn at 14 MeV [16]. These data give mean free paths of 50 nm at 2.45 MeV and 150 nm at 14 MeV in ultra-dense deuterium, very short for neutrons. These energies correspond to neutrons formed by D+D fusion. See table 1, which gives the published ranges [17] for protons and neutrons. The ultra-dense D(-1) material is dispersed in a less than 1 mm thick layer, forming clusters and filaments, and neutrons created at a depth in the material may leak out as thermalized neutrons.

Collisions  $p + d$  will also take place in the material. Using the PSTAR program [17] to estimate the range of 3 MeV protons in ultra-dense deuterium D(-1) gives a value less than 1 nm, and a range of 12 nm for 14 MeV protons. Thus, such particles can only escape from a very thin surface layer of D(-1), which indicates that most particles in the flux to the detector are from the very surface of D(-1).

### 3 Experimental

In the present studies the main method used is time-of-flight (TOF) measurement, giving the corresponding par-



**Fig. 1.** Principle of the apparatus used. The source has the catalyst emitter mounted at the bottom, close to the center of the vacuum chamber. The movable detector in the main chamber is here only used to block particles moving to the outer detector.

ticle kinetic energy per unit mass from their flight time. The particle detection used fast plastic scintillators. This method was for example used by Ditmire and coworkers in a series of successful laser-induced cluster fusion studies (see [14,15] for a few examples). The horizontal layout of our experiment is shown in fig. 1 [4,18]. A Nd:YAG laser with an energy of  $< 200 \text{ mJ}$  per each 5 ns long pulse at 10 Hz is used at 532 nm. The laser beam is focused with an  $f = 400 \text{ mm}$  lens at the center of the ultra-high vacuum (UHV) chamber. The laser intensity is  $10^{12} \text{ W cm}^{-2}$  at the beam waist as calculated for a Gaussian beam. Close to the center of the apparatus, a potassium doped iron oxide catalyst sample [19,20] in the lower end of a vertical Pt (platinum) tube is used as the emitter to produce D(-1) from deuterium gas ( $> 99.8\% \text{ D}_2$ ) at a pressure up to  $1 \times 10^{-5} \text{ mbar}$ . The emitter is heated by an ac current through the tube to a temperature  $< 500 \text{ K}$ . This source is described in detail elsewhere [9]. In some experiments, the D(-1) material is collected on a sloping surface below the source. The amount of D(-1) formed is probably larger than that in ref. [8], thus  $> 3 \times 10^{16}$  atoms or  $> 40 \text{ nmol}$  of D atoms with total mass 80 ng. The amount of D(-1)

in the laser focus is at least of the order of  $10^{13}$  atoms or 10 pmol D atoms [8].

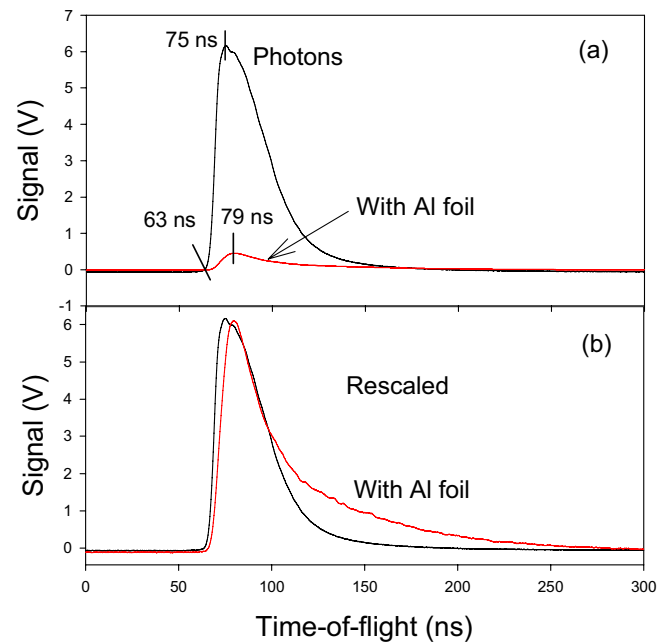
The detector is located at a distance of  $112 \pm 2$  cm from the laser focus. Two different scintillators have been used, a thick and a thin form. The 5 cm thick plastic scintillator (BC-408, Saint-Gobain Crystals) has an entrance area of  $20 \times 26 \text{ mm}^2$  for the particle flux from the laser focus. The thin scintillator is mounted at an angle to the particle beam. It is 0.1 mm thick with Al deposited on the back side to increase the light reaching the PMT. The scintillator gives blue photons which are observed by a PMT (EMI 9813B with single-electron rise time of 2 ns) behind a 6 mm thick blue-violet glass filter (BG37,  $T = 8 \times 10^{-6}$  at 532 nm). The PMT is mounted in a metal container attached to a glass window in the vacuum wall. By this construction, stray laser photons and other photons generated by the laser at impact are suppressed. The signal due to the 532 nm photons in the laser pulse is too small to be observed by the PMT. Since the whole experiment is inside a metal chamber, no stray or background light is of any importance. A preamplifier (Ortec VT120) with bandwidth 10–350 MHz is sometimes used to improve the decay time of the signal. Here, the signal is mainly studied and recorded on a fast digital oscilloscope (Tektronix TDS 3032, 300 MHz) which displays the entire signal behavior. Some experiments with pulse counting using a fast MCS (Ortec Turbo-MCS) are also shown. A photodiode close to the laser gives a fast pulse which triggers the MCS and the oscilloscope.

In the particle beam at a distance of 35 cm in front of the scintillator, one or several  $15 \mu\text{m}$  thick Al foils on a stainless-steel holder (a beam flag) can be moved into or out from the beam. As shown in table 1, a proton flux with 3 MeV energy is blocked by five Al foils. All protons with energy  $< 1$  MeV will be blocked by two Al foils [17]. Thus any delayed signal measured behind such a flag originates in MeV particles. The flag is mounted with an offset on a rotating flange, and can thus be rotated completely out of the beam. To block the TOF tube cross-section entirely when the flag is in place, a circular stainless-steel plate with a central opening is fitted into the tube in front of the foil holder. Often, a similar plate is also mounted behind the foil holder. The surface of the front plate is painted with Aquadag to decrease reflected light.

The actual photon generation in the scintillator is mainly due to fast charged particles like deuterons and protons from the laser focus, and to relatively fast secondary particles from the metal foils. Neutrons give a weak signal in the scintillator, creating not more than one photoelectron in the PMT per 2 keV of energy [21] at large distances between the emission events in the scintillator. Protons are detected by the scintillator with a much higher signal per distance covered (number of photons created) than neutrons. Thus, it is likely that the signal observed is mainly due to protons (and deuterons). Detectors more sensitive to neutrons exist but do not give any useful TOF information (see the discussion). Thus, a proof for MeV massive particle ejection as given here cannot employ such detectors.

**Table 2.** TOF in ns at the detector distance 1120 mm for linear (central) scattering of particles ejected from D+D fusion processes. The first collision with D gives the energy in the third column, and the TOF to the detector in the fourth column. A second collision with D gives the results in the two last columns 5 and 6.

	Energy	+D	TOF	+D	TOF
	(MeV)	(MeV)	(ns)	(keV)	(ns)
<i>p</i>	3.02	0.33	141	37	420
<i>p</i>	14.7	1.62	64	180	190
<i>n</i>	2.45	0.27	156	30	470
<i>n</i>	14.1	1.55	65	175	195

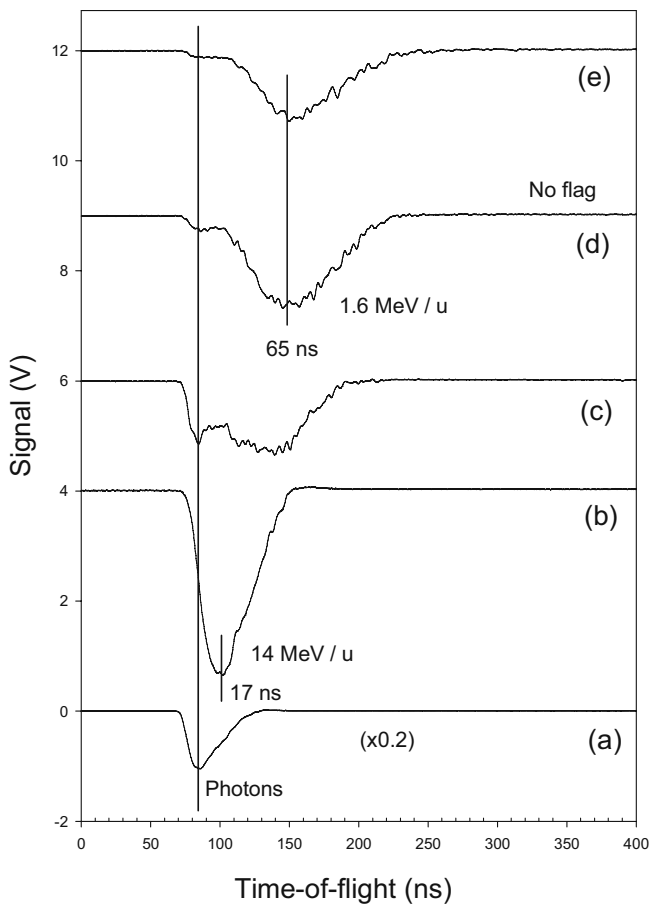


**Fig. 2.** The general timing properties of the first signal peak with no flag and with a thin Al flag ( $15 \mu\text{m}$ ). In (b) the signal with Al flag is rescaled so that the loss of signal prior to the peak is observed clearly. The thin Al flag blocks light and slow particles. Oscilloscope traces, average signals.

## 4 Results

In previous studies, scattering energy loss in the ultra-dense material D(-1) was observed [1]. It is straightforward to calculate the energies of the particles formed in the fusion reactions after collisions with one or two consecutive D atoms in the D(-1) material. Such results are collected in table 2 for *p* and *n* from the D+D fusion. Due to the low mass of *p* and *n*, they are primarily expected to be observed after two collisions with D since one collision will reflect them back into the D(-1) region again.

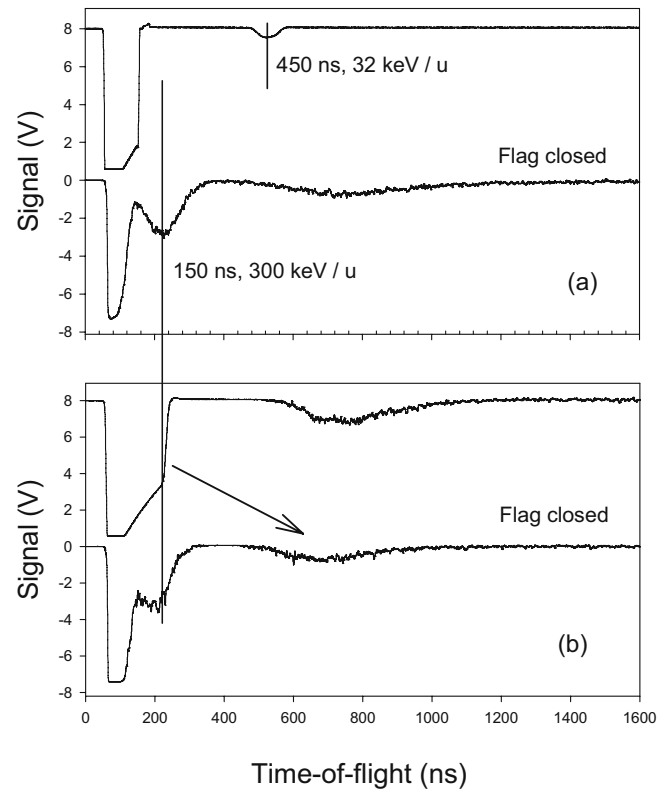
Starting from the shortest TOF, the first signal peak is shown in fig. 2 with and without a thin Al flag moved into the beam. A fast oscilloscope is used for these measurements. The first peak at 75 ns after the trigger or 12 ns after the onset of the signal is due to high-energy photons like X-ray photons. It is largely removed by the Al foil.



**Fig. 3.** Oscilloscope TOF spectra showing various fast peaks from a combination of blocking with  $45\ \mu\text{m}$  Al flag, with the inner detector box and through selecting the position of the laser beam on the emitter. A small opening only to the PMT. Trace (a) is decreased in intensity by a factor 0.2. Average mode in oscilloscope with preamplifier. The flag removes protons at 3 MeV and lower. See further the text.

(The direct laser peak can be observed with signal onset at 51 ns and peak at 79 ns by a small leakage of light into the PMT in separate experiments. No such laser peak is observed here.) The second peak in fig. 2 is found at 79 ns and is due to photons which are partly transmitted through the foil, thus probably gamma photons. However, the signal tail seems to be due to particle scattering. The kinetic energy at half peak height is  $20\ \text{MeV}\ \text{u}^{-1}$  at 17 ns delay relative to the maximum signal. This is close to the expected energy of 14 MeV for protons and neutrons from fusion processes.

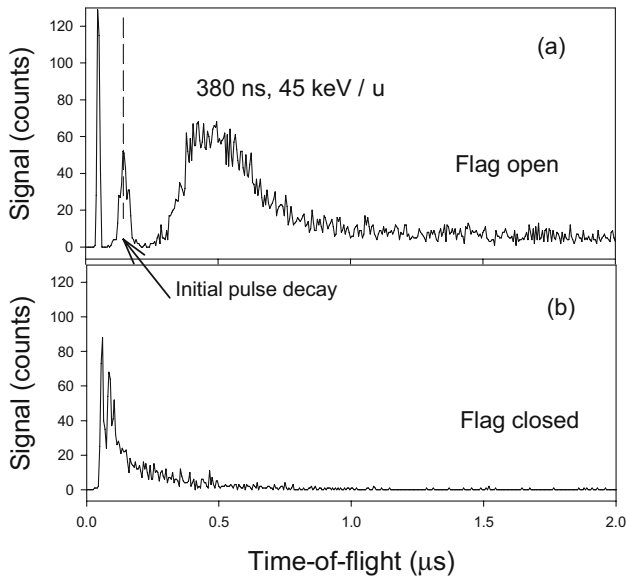
It is possible to suppress different types of particles by moving the inner detector (stainless steel box) into the flux to the detector and also by moving the laser beam to the far side of the emitter relative to the detector. A few such oscilloscope spectra are shown in fig. 3. A flag with  $45\ \mu\text{m}$  Al foil is used in the beam in all but one trace. Trace (a) shows the photon beam passing through the beam flag. It is similar to that in fig. 2, but slightly delayed in time due to the preamplifier used. Trace (b) shows the signal passing through the inner detector plates and



**Fig. 4.** Oscilloscope TOF spectra with open and closed  $30\ \mu\text{m}$  Al thick beam flag, at two different positions of the inner detector box. A sloping metal plate below the source was the laser target. Average mode in oscilloscope, thin scintillator in detector. The preamplifier caused the slope of the initial overloaded peak. The arrow in (b) indicates the origin of the delayed peak.

the Al flag. With its maximum at 17 ns after the photon peak it agrees well with that expected for 1 u particles with energy 14 MeV, as shown in table 1. Trace (c) shows both a photon peak and a particle flux delayed by collisions in the plates and the flag. By selecting the laser and emitter positions suitably, trace (d) shows a peak of particles which are delayed in the D(-1) material with no beam flag, thus blocking photons only by the inner detector. The main peak at 65 ns after the photon peak indicates an energy of  $1.6\ \text{MeV}\ \text{u}^{-1}$ . This is the energy expected after a linear collision by 1 u particles at 14 MeV with D in D(-1). See table 2 for further details. Trace (e) shows the effect of the beam flag, delaying and decreasing the intensity slightly through scattering in the Al foil. The considerable delay of the signal flux proves that the signal is due to particles with mass, not to photons.

The detector box inside the main chamber gives also the possibility to select the position on the laser target which is observed, blocking particles from other positions. Two examples where fast particles are delayed by the Al foil flag are shown in fig. 4. In the upper pair of oscilloscope traces in fig. 4a, a delayed particle signal is formed by the beam flag, peaking at 100 ns after the intensity removed by the flag. This corresponds to particle energy of  $60\ \text{keV}\ \text{u}^{-1}$  after the flag. The apparent shockwave (see further below)

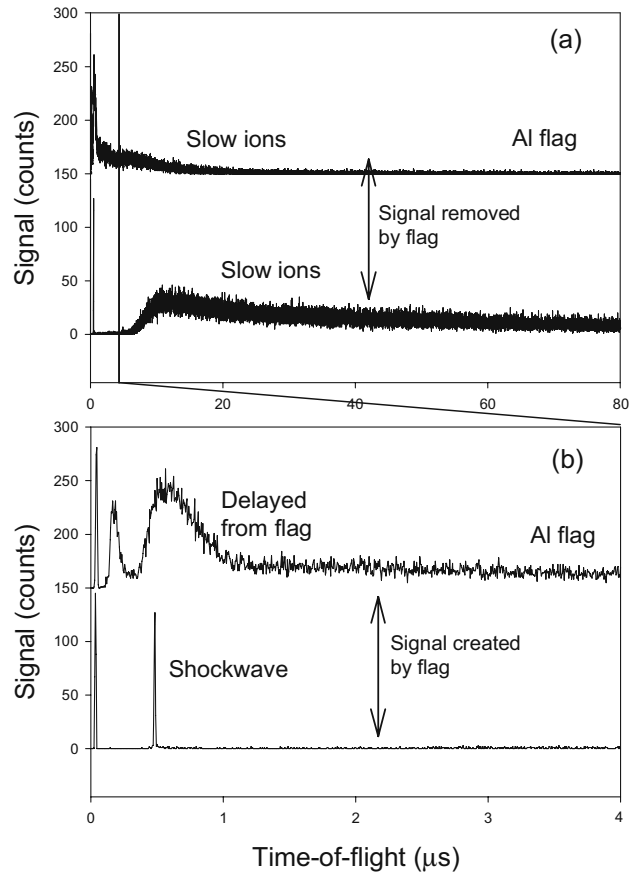


**Fig. 5.** Pulse-counting TOF spectra with open and closed  $30\ \mu\text{m}$  Al thick beam flag. A sloping metal plate below the source was the laser target. Thin scintillator in detector.

at 450 ns after the laser pulse in the upper trace with open beam flag seems to be delayed to 700 ns by the beam flag in the lower trace in fig. 4a. In the pair of traces in fig. 4b, the peaks observed with the beam flag closed both appear to be formed from the flux removed at 100–150 ns after the laser pulse (note the arrow in the figure), since the broad peak observed with the beam flag closed arrives earlier than the similar peak with the flag open. The energy of this initial particle flux at 100 ns is  $500\ \text{keV}\ \text{u}^{-1}$ , while the peak at 600–700 ns with the beam flag open corresponds to particles with energy  $< 20\ \text{keV}\ \text{u}^{-1}$  which are removed by the beam flag as observed.

In experiments with a relatively thick layer of D(-1) on a laser target below the source, the detector box inside the chamber can be used to also give relatively slow particle peaks, probably by delay of MeV particles from the laser target. One such example is shown in fig. 5. The broad peak in fig. 5a at 380 ns after the laser pulse has energy of  $45\ \text{keV}\ \text{u}^{-1}$  at its peak. This peak is removed by the foil beam flag in fig. 5b as it should be, since the particle energy is too low to give any penetration through the flag. The remaining signal at times shorter than 500 ns is caused by particles that are in the MeV range before reaching the beam flag. The almost exponentially decaying part of this signal may also be due to photons ejected from the beam flag by very fast particles.

The behavior found at long times by using the beam flag is shown in fig. 6. The upper part of the figure shows the full spectrum up to  $80\ \mu\text{s}$  TOF, while the lower part shows the expanded  $0\text{--}4\ \mu\text{s}$  region. The Al foil removes slow particles in the range  $5\text{--}80\ \mu\text{s}$  with maximum energy of  $300\ \text{eV}\ \text{u}^{-1}$ , while it creates particles in the range  $300\ \text{ns}\text{--}20\ \mu\text{s}$ . The peak close to 500 ns is due to the

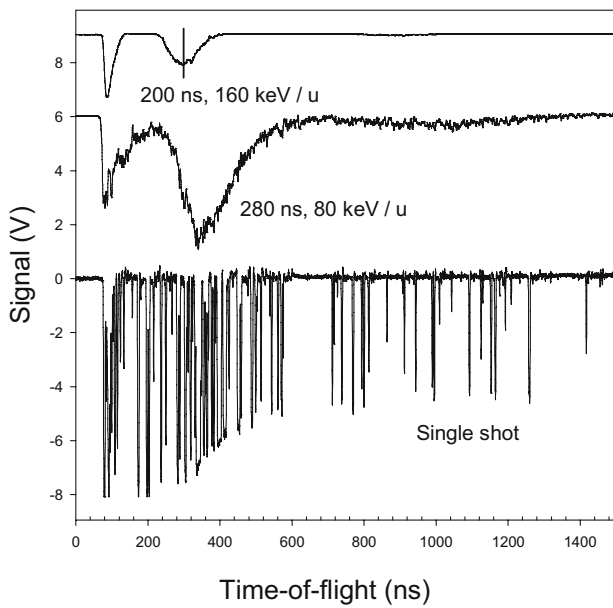


**Fig. 6.** Effect of the Al flag ( $30\ \mu\text{m}$  foil) on the detected flux using pulse counting (MCS). In (a) slow particles from the target are removed by the Al foil. In (b) the Al foil gives relatively fast particles from the impact of fast protons. Thin scintillator in detector. See further the text.

shockwave formed (see below). The particles formed by the flag emanate from faster particles in the initial peak (not resolved in fig. 6).

Quite simple spectra can be found if the laser reaches the emitter surface on the side not facing the detector. The emitter material then blocks most photons and fast particles directly from the laser focus. Three such experiments are shown in fig. 7. The main peak is due to particles with TOF of 200 ns and above. This corresponds to a peak energy of 175 keV or slightly less. In the bottom trace in the figure, the peak at 280 ns is shown as a single shot which proves that it is due to photon peaks and not to a shockwave.

The total number of particles created by a laser pulse is determined at low PMT voltage settings, assuring that the oscilloscope peak signal varies linearly with the gain of the PMT, as given by the manufacturer. Thus the quantity  $S/G$  with  $S$  the signal on the oscilloscope and  $G$  the gain given by the PMT manufacturer should be a constant. This works correctly with a thin  $15\ \mu\text{m}$  Al foil in the beam but not without the foil. (It is possible that



**Fig. 7.** Oscilloscope TOF spectra showing peaks at 200–300 ns. Laser hits the emitter on the backside relative to the detector. The two top spectra used average mode at two different PMT voltages (1300 and 1700 V), while the bottom spectrum was single shot. The flag was  $45\ \mu\text{m}$  thick Al.

the signal without Al foil is saturated and thus that the gain does not give the peak size correctly in that case.) No preamplifier was used in this measurement. At a typical value of 1300 V over the PMT,  $S/G = 3 \times 10^{-5}\ \text{V}$ . The formula used then is  $(S/G)\Delta t/(eR)$  where  $\Delta t$  is the FWHM of the peak,  $e$  is the electron charge and  $R$  is the load resistor at the oscilloscope ( $50\ \Omega$ ). This gives  $1.1 \times 10^5$  photons to the PMT in the first peak or approximately the same number (or less) of particles giving a signal. Since the scintillator covers  $3.3 \times 10^{-5}$  of the sphere, the total number of particles emitted by the laser pulse is calculated to be  $3 \times 10^9$  particles assuming isotropic emission. However, many of the particles observed by the scintillator in the peak could possibly be photons. A check in fig. 2b indicates that approximately half the signal in the distribution with the Al foil is due to delayed particles (with energy  $< 14\ \text{MeV}$ ), thus not to photons. Thus, more than  $10^9$  particles giving photons in the scintillator are created per laser pulse. If a large number of photons are formed by each proton in the scintillator, the number of incident particles is in fact proportionally lower than this, while the use of a realistic small viewing factor of the PMT on the scintillator instead would increase the true number of particles entering the scintillator. Single-shot experiments with the oscilloscope indicate that a particle which has low energy in the range 10–100 keV may form several photon pulses ( $< 10$ ) in the scintillator. Faster particles may generate more photons but this is difficult to observe directly in the experiment and the photon peaks may in fact overlap in time. According to the datasheet for the scintillator, the light output increases almost linearly with particle energy. It is concluded that somewhat less than  $10^9$  particles

are formed at MeV energy per laser pulse due to the number of photons formed per fast particle (proton) in the scintillator.

## 5 Discussion

Both protons and neutrons formed in the D(-1) material will collide after very short distances with the D atoms in D(-1) due to the large density of D(-1). See table 1. Single D collisions of 2.45 MeV neutrons and 3.0 MeV protons will give signals at 140–150 ns, thus in a range where intensity exists in almost all cases shown. However, no clear peaks are found since the intensity in this region is normally high. Since both neutrons and protons are lighter than D, they will be reflected backwards in a central (linear) collision with D. This means that two such collisions are generally required to bring the proton or neutron to continue its motion out from the D(-1) layer towards the detector. Thus, it appears more likely to observe particles delayed by two D collisions than by just one D collision. As shown in table 2,  $p$  and  $n$  from fusion and double scattering would be observed at approximately 200 and 450 ns. Peaks at these TOF are observed in figs. 4, 5 and 7. Thus, it is likely that such scattering processes are observed. A similar effect with scattering in two steps was observed in [1]. In that case the particles from nuclear fusion were T and  $^3\text{He}$  scattered against two H atoms. The heavy particles were scattered in the forward direction and any singly scattered particles were not observed due to overlap with other intensity.

The present experiments are designed to give proof for massive MeV particles, not for the intensity ratio of  $n$  relative to  $p$ , even if this ratio certainly is of interest. It is difficult to distinguish between  $n$  and  $p$  generated signals in the scintillator, but since the sensitivity to protons is much larger than to neutrons, the main part of the signal observed is due to protons (and deuterons) [2]. A distinction between  $n$  and  $p$  may be found by using very thick foils, but the TOF information needed for the particle identification is then lost. More selective detectors for neutrons exist (like  $\text{BF}_3$  and  $^3\text{He}$  proportional counters) but they are slow (in the  $\mu\text{s}$  range) and require the neutrons to be thermalized, introducing long delays in the detection process. This means that no timing information is retained and that practically no information on the direct fusion reactions is found using such detectors. Information on the fast processes in D(-1) is needed for designing efficient fusion devices. The D(-1) material is a quantum material which is superfluid [10] and probably also superconductive [22] at room temperature. The handling and transport of this material for useful energy production present some already recognized difficulties.

One interesting aspect of the CE mechanism of particle ejection from the surface of D(-1) is the shockwave normally observed at 460 ns or  $30\ \text{keV}\ \text{u}^{-1}$ . This effect is observed in figs. 4 and 6. It agrees in energy with protons initially at 3 MeV scattered twice by D atoms. However, it is observed experimentally to have special features. At the start of the laser pulsing, a peak with this energy does

not exist but only a broader band of photon pulses. When the laser is running at repetition rate 10 Hz, the intensity in this range is, within 10 s, contracted to a 460 ns peak which then becomes smaller and shows no clear separate photon peaks. This provides its appearance in fig. 4 as a continuous peak. It is similar in appearance with slower shockwaves observed in the present system [10]. Thus, it is considered to be a shockwave peak from the plasma formed by the laser pulse, with energy of  $30 \text{ keV u}^{-1}$  or a velocity of  $2 \times 10^6 \text{ m s}^{-1}$ . There is very little jitter in its position due to laser pulse intensity variation. It thus appears that its energy and timing is provided by the process of protons colliding with two consecutive D atoms as suggested by the results in table 2. Recent studies have also shown more complex features in the TOF range of this shockwave that may be due to self-compression of D(-1) (to be published). It cannot be excluded entirely that some of the intensity in this TOF range is due to afterpulses in the PMT, but the behavior of the shockwave signal does not agree with such an effect. It is concluded that a shockwave exists with energy of  $30 \text{ keV u}^{-1}$  but that it may contain contributions both from delayed protons and from deuterons ejected by self-compression.

## 6 Conclusions

This study shows that a large number of MeV particles are formed by each laser pulse impacting on ultra-dense deuterium D(-1), as expected for nuclear fusion D+D. The method used is time of flight with selective blocking of particles with energy  $< 1 \text{ MeV}$  by metal foils and delaying still faster particles, thus observing them conveniently well separated from the initial photon pulse. The total number of MeV particles formed is less than  $10^9$  per laser pulse. Due to the short mean free paths or ranges of the energetic particles in the D(-1) material, they may become collisionally delayed before being ejected from the material. The MeV particles are thus ejected from a thin surface layer of the material.

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