MeV particles in a decay chain process
from laser-induced processes in ultra-dense deuterium D(0)

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The ejection of particles with energy up to 20 MeV \( u^{-1} \) was reported previously from laser-induced processes in ultra-dense deuterium D(0). Studies of the kinetics of particle formation and decay, and of particle penetration through thick plates are now reported. Magnetic deflection is used to remove charged particles like electrons formed at the target. The signals at a collector in the beam at 0.9 m distance and a shadowed loop collector behind a 1.5–4.5 mm thick steel plate at 0.6 m are compared. The signal at the distant collector matches an intermediate particle B in a decay chain A \( \rightarrow \) B \( \rightarrow \) C with formation and decay time constants of 5–15 ns. The signal at the loop collector is delayed relative to the more distant collector, thus showing a delay of the particles penetrating through the steel plate. The signal at this collector is due to pair production with charge cancellation. Compton electrons from gamma radiation are observed at peak current densities of 1 mA cm\(^{-2}\) at the distant collector.

Keywords: Ultra-dense deuterium; laser-induced MeV particles.

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1. Introduction

Ultra-dense deuterium D(0) is a quantum material which is superfluid at room temperature.\(^1\)–\(^3\) Laser fragmentation and mass spectroscopy studies have revealed much of its structure,\(^4\) mainly as chain-like clusters D\(_{2N}\) with \( N \) integer. The D–D pairs rotate around the axis in the cluster.\(^2,5\) In the normal spin state \( s=2 \), the D–D distance is \( 2.3 \pm 0.1 \) pm\(^1\)–\(^3\) while also a lower \( s=1 \) state exists with a theoretical D–D distance of 0.56 pm.\(^4\) The D(0) clusters show a Meissner effect at room temperature,\(^6\) which indicates that D(0) is superconductive. This material forms a thin superfluid film on metal surfaces but not on polymer surfaces.\(^7\) A similar material p(0) with protons instead of deuterons exists.\(^8\) Both materials are named ultra-dense hydrogen H(0). The quantum properties of D(0) were discussed by
A method to form very dense interstitial regions of hydrogen in a hydrogen-dissociating Pd metal layer has been demonstrated by Lipson et al. They observed anomalies in conductivity and magnetic susceptibility below 70 K, which were attributed to ultra-dense hydrogen filamentary superconductivity. The relation to D(0) was further discussed in Refs. 12 and 13. Ultra-dense hydrogen (deuterium) was also discussed in Ref 14 as a means of producing a MeV flux of ions for ion-beam induced ICF fusion.

The massive MeV particles ejected by laser-induced processes in D(0) have been studied by time-of-flight (TOF).15–17 They are mainly neutral cluster fragments, with energies in the range 1–20 MeV u⁻¹. This study is a further step in the ongoing investigation, using special arrangements of collectors to analyze the TOF signal. The focus here is on the neutral MeV particles which can penetrate through mm thick steel plates and on the time variation of the particle signal, which is due to particle decay and not to a thermal particle distribution as suggested previously.

2. Theoretical Background

The neutral H(0) particles, ultra-dense protium p(0) or deuterium D(0), have kinetic energy up to 20 MeV u⁻¹ and were studied previously.15–17 Particles Hᴺ(0) composed of protons and electrons are bosons, as are the deuterons possibly also existing in the H(0) material ejected from the laser-induced processes on the target. Some H(0) particles are shown to penetrate through thick metal plates in the present experiments. As shown previously, such particles give pair production in materials.18 Due to the finite distance of motion of electrons and also of positrons caused by inelastic collisions in the metal collectors, there exists an escape depth¹⁹ of the electrons and positrons from the metal. This means that the penetrating H(0) particles create charges that can escape from the collectors only close to the front and back surfaces. The escape depth effect means that the thickness of the collector in some cases does not directly influence the signals obtained. The energy of the escaping particles will on average be relatively low, if the thickness of the collectors is large enough to slow down the electrons and positrons formed inside the collector plate. A positron formed will in the end annihilate with an electron, after losing most of its kinetic energy by collisions with electrons, for example, in a metal part.²⁰ This can take place either in the collector material or, after escape from the collector, at other surfaces in the chamber. The annihilation process normally gives two gamma photons each with energy 0.511 MeV,²⁰ thus further pair production by these photons is not possible.

Pair production and other processes give secondary electrons from the collectors, which is the most important type of signal measured in the experiments. The time variation of the signals is well described by an intermediate particle M which is formed and decays like A → M → N. The time dependence of the signal M is easily
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derived from the rate equations for $A \xrightarrow{k_1} M \xrightarrow{k_2} N$,

$$-\frac{dn_A}{dt} = k_1 n_A, \quad (1)$$

$$\frac{dn_M}{dt} = k_1 n_A - k_2 n_M, \quad (2)$$

as

$$n_M = \frac{k_1}{k_2 - k_1} n_A 0 (e^{-k_1 t} - e^{-k_2 t}), \quad (3)$$

where $n_A 0$ is the number density of the precursor $A$ at time $t = 0$ thus during the laser pulse. This assumes that the initial number density $n_M 0$ is zero. The curve shape in Eq. (3) is used to match the decay results presented here. The results are given as time constants $\tau = 1/k$.

3. Experimental

The layout of the experiments is shown in Fig. 1. A Nd:YAG laser with pulse energy of < 400 mJ pulses at 1064 nm and 10 Hz repetition was used. The laser beam was focused with an $f = 50$ mm lens onto the D(0) surface layer on a metal target in a small vacuum chamber. This means a laser intensity of $< 4 \times 10^{13}$ W cm$^{-2}$ for a Gaussian beam. The lens can be moved from the outside around the center of the target. In this way, different parts on the target can be probed with the laser beam. In the present experiments, a piece of Ir metal in cylinder form (3.5 mm diameter) was normally in the laser focus. The source for producing D(0) is similar to a published construction$^{21}$ modified for higher pressure operation. In the source,

![Fig. 1](image-url)

Fig. 1. Principle of the apparatus used for the experiments with the shadowed loop collector. The pin collector can be moved sideways (perpendicular to the paper) to observe particles deflected by the magnetic field. Vertical cut. A similar source for D(0) is described in Ref. 21.
a potassium doped iron oxide catalyst sample\textsuperscript{22,23} forms D(0) from deuterium gas (99.8\% pure). The D(0) formed falls down to the horizontal target plate below the source and is partially adsorbed on the Ir surface. The D\textsubscript{2} gas pressure in the chamber is 0.1 mbar with constant pumping.

The information about the laser-induced processes is obtained from collectors located in the direction normal to the target plate, at two distances from the target as shown in Fig. 1. The shadowed loop collector is a wire loop above a stainless steel plate with a 10 mm diameter central aperture. The loop has a projected area for the flux of 4.0 cm\textsuperscript{2}, at a distance of 63 cm from the target thus a solid angle

![Diagram](image-url)

Fig. 2. Collector signals with $-50$ V bias, with 1.5 and 4.5 mm steel plate as the dividing wall. The best matching intermediate particle distributions are shown by dashed curves and the time constants are given.
of 1.0 × 10^{-3} sr seen from the target. The stainless steel plate is 1.5 mm or 4.5 mm thick. It is mounted light-tight against the wall of the chamber. At this aperture a holder for four small permanent magnets is located (cylindrical neodymium magnets with diameter 14 mm, length 8 mm) in pairs on each side of the central beam. The distance between the pole faces in each pair is 5 mm. The magnetic field strength is measured with a Hall effect sensor (Allegro A1326 giving 2.5 mV G^{-1}). The field strength at a distance of 8 mm from the pole of one magnet was 0.1 T, and thus the field between the magnets in the beam was > 0.4 T. The total length at this field strength along the beam was approximately 28 mm. Just in front of the magnets, a central opening of 4 × 4 mm in a thin steel foil was used to define the beam. The movable pin collector is at a distance of 92 cm from the target. It can be moved sideways to measure particles slightly deflected in the magnetic field. It covers a solid angle of 2.4 × 10^{-5} sr with its projected area of 0.2 cm^2. The collectors are connected directly to an oscilloscope via a short 50 Ω coaxial cable. The oscilloscope used is a fast digital 2-channel oscilloscope (Tektronix TDS 3032, 300 MHz). The impedance of the oscilloscope input is 50 Ω. A 50 Ω RF attenuator is used with large signals to give a factor of three (−10 dB) lower signal at the oscilloscope. This introduces a signal delay of 7 ns but no change in the curve form. A shielded 50 V battery can be inserted into the signal path at the feedthrough in the vacuum wall to give positive or negative voltages on the collector, still giving a 50 Ω connection to the oscilloscope. It may introduce a small delay of the signal of maximum 3 ns. In another signal extraction construction, a variable voltage up to ±400 V can be fed to the collector, with the signal taken to the oscilloscope through a 1 nF high-voltage capacitor and a 50 Ω cable.

The magnetic field is used primarily to prevent relatively slow ions or electrons from interfering with the signal of interest here. To pass the slits and then reach the pin collector at a distance of 29 cm from the slits with a deflection < 1 mm requires an energy of > 100 MeV for a proton. Such particle energies have not yet been observed by TOF from laser initiated processes in D(0)^{15−17} and the highest energies observed are found for neutral particles. Of course, heavier ions will have smaller deflections. Electrons with nonrelativistic energies will deflect strongly in the magnetic field.

4. Results

The signal measured with −50 V bias is mainly the secondary electron signal ejected from the collectors by the impinging particles or photons. With such a bias on the collectors, the signals in Fig. 2 are found with thin (1.5 mm) and thick (4.5 mm) steel plate as the intermediate shield. The signal with the thin plate is larger, especially in the case of the loop collector. That the signal at the pin collector also is increased using the thin plate means that a fraction of the signal observed at the pin is also due to penetration through the plate. However, moving the pin sideways gives a strong drop in the signal at a distance of 7 mm from the centerline. Thus,
most of the signal to the pin collector is central through the $4 \times 4 \text{mm}^2$ opening. For the loop collector, the signals are broadened and almost thermal in shape. This means that the particles giving this signal are massive and have interacted with other atoms during their transport, giving the quasi-thermal TOF shape. However, as seen in the figure the signal pulse shape is also similar to an intermediate particle in a decay chain (dashed curve), with time constants given in the figure. The distributions at the pin collector are sharper than thermal and agree even better with an

Fig. 3. High-voltage TOF distributions with negative bias. The signal at the loop collector increases steadily with bias voltage, indicating pair production. The best matching intermediate particle distributions are shown by dashed curves and the time constants are given.
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intermediate in a decay chain. The peaks of the distributions are all at 20 ns after the laser pulse, indicating a very short time (<1 ns) for transport from the loop to the pin, as expected for very fast nuclear particles. A photon contribution could of course also show such a timing behavior.

A clearer conclusion on the type of the signal pulse at the pin collector can be drawn from the results in Fig. 3, where a larger negative bias voltage is used. The signal to the pin collector changes its shape with increasing bias voltage and reaches a constant limit. In the experiments, larger voltages than ±400 V have not been used due to the risk of discharge processes in the gas at 0.1 mbar. It is apparent that the faster TOF distribution at higher negative bias indicates the removal of space-charge limiting at the start of the pulse. The constant shape at large negative bias agrees very well with an intermediate particle in a decay chain, as shown in the figure. Thus, the main signal at the pin collector is not due to photons but to intermediate decaying particles. The number of such particles is at least \(1 \times 10^9\) per laser pulse at the pin collector assuming one charge released per particle. This means at least \(4 \times 10^{13}\) particles per laser pulse and sr.

The situation at the loop collector is different in Fig. 3, showing an increase in the signal with large negative bias voltage and no limiting shape. This indicates pair production as described previously.\(^\text{18}\) In this process the charges cancel each other at low collector bias, thus low or no signal will be detected at low bias. With increasing collector bias, the asymmetry of the charge retained at the collector increases. In Fig. 3, it can be seen that the signal to the loop collector increases with negative bias voltage without limiting and with largely unchanged shape of the signal. This is the expected behavior for pair production.\(^\text{18}\) The time distribution does not agree very well with that expected for an intermediate particle in a decay chain, so particle penetration and pair production are mainly responsible for the loop signal. The total signal at the loop in Fig. 3 is smaller than at the pin, also here assuming that one charge is generated per particle. The total number of particles at the loop is then \(4 \times 10^8\) per laser pulse, or \(4 \times 10^{11}\) per laser pulse and sr. This indicates that just 0.01 of the total number of particles seen by the distant pin collector interacts with the loop. Several reasons for this are possible, like low penetration through the steel plates which is unlikely (see further below) or an accelerated decay in the metal to an undetectable particle of type N as described in the theoretical section.

With zero bias, only high energy electrons from the collector will contribute to the signal, and pair production at the collector will give zero contribution. Such results are also shown in Fig. 4, also measured for thin and thick shielding plate as in Fig. 2. In these cases, the signal changes much less due to the plate thickness. The loop signal is almost unchanged by the thick plate, which indicates that the signal is due to easily penetrating particles. It does not have the same peaked shape as all the other collector signals and is much smaller, which means that it is due to a balancing of positive and negative signals as expected for pair production.\(^\text{18}\) The large oscillations observed in this signal also indicate a large particle flux.
Fig. 4. Collector signals with zero bias, with 1.5 and 4.5 mm steel plate as the dividing wall. The signal at the loop collector nearly disappears with zero bias, indicating pair production. Compton electrons are observed. The best matching intermediate particle distributions are shown by dashed curves and the time constants are given.

with almost cancelling net charge. The first peak in the loop signal at zero bias is apparently a Compton scattering signal since it is much faster than all other signal maxima.

The peak for the pin signal in Fig. 4 is at 20 ns as in Fig. 2 and the distribution agrees well with an intermediate particle in a decay chain, with the same time constants as in Fig. 2. The total signal decreases only a factor of 2 relative to the
signal with $-50\text{V}$ bias in Fig. 2. Thus, the pin collector signal is not due to low-energy photoelectrons ejected by photons since a much larger difference is expected in such a case.\(^\text{18}\)

In Fig. 5, the results at positive pin bias are shown for the pin collector. The bias of $+400\text{V}$ gives a faster TOF distribution, probably by removing the space charge limiting as in the case with negative bias in Fig. 3. The signal at $+400\text{V}$ has almost the same peak size as that for $-400\text{V}$ bias in Fig. 3, but with a much slower peak and thus much larger intensity, at approximately $1\text{MeV}\text{u}^{-1}$ instead of $30\text{MeV}\text{u}^{-1}$ at $-400\text{V}$ bias. This probably indicates a large electron current from the surrounding walls, ejected by the MeV particles and also by gamma radiation.

One easily observed gamma feature in the signals is the initial positive signal peak measured with the collectors at $+50\text{V}$ shown in Fig. 6 with the wall of 1.5mm steel. That this signal peak is observed also at the loop collector means that it is not due to positive ions, which would not be able to reach this collector. Also the very short absolute time for this first peak means that ions are excluded. Electrons are unlikely to arrive so fast to both collectors and to pass the magnetic field, so a direct electron current and a current from the surrounding structure are both excluded. The process observed is clearly Compton scattering of gamma photons penetrating the metal plate and ejecting electrons with energy $>50\text{eV}$ from the collectors. Photons which can penetrate through the 1.5mm thick steel plate have an energy of $>90\text{keV}$. The photon generated peak current density from this effect is $1\text{mA cm}^{-2}$ at the pin collector, or $80\text{A sr}^{-1}$.\(^\text{1550026-9}\)
5. Discussion

The pin collector signal, for example, at large negative voltage in Fig. 3 agrees well with an intermediate particle in a decay chain, matching the calculated curve given by Eq. (3). The matching time constants are short at approximately 5 ns. This is also the width of the laser pulse. Gamma radiation from the laser interaction with the target could have a somewhat longer pulse length, more similar to the measured pulse in Fig. 3. However, the shape of the measured pulse in Fig. 3 is well described as an intermediate particle. The start of the pin collector signal in Figs. 2 and 4 is slower than at large negative bias in Fig. 3, while the decay of all pin signal measurements is similar. The slow start is due to space charge effects at

Fig. 6. Compton electrons at the loop and pin collectors in the fast positive peak. 1.5 mm thick steel plate as the dividing wall.
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the collector as shown in Fig. 3, preventing a fast loss of the secondary electrons from the collector surface.

Due to the laser pulse width of 5 ns, the time constants found from the matching are still not the real time constants for formation and decay. In fact, the real time constants for the particles could be shorter than 5 ns. This gives no clear indication of the particles formed. It is assumed as previously that the main particles ejected from D(0) by the laser pulse are small clusters with the ultra-dense cluster form \( D_N(0) \).\textsuperscript{16,17} They may decay with short lifetime to other particles which are not yet identified. If the particles are very fast, they may pass the pin collector before most of them decay, so that the decay time constant found here is shorter than the real decay constant. A decay time constant of 5 ns at 92 cm distance from the target corresponds to an energy of approximately 200 MeV u\(^{-1}\). This is higher than for any particles measured by TOF in the D(0) system previously, but it is not impossible that it can be created by decay into lighter particles (work in progress).

The pair production process observed at the shadowed loop collector is symmetric, such that equal numbers of charges are generated with positive and negative signs. Since free electrons are formed also by photoionization, it is often difficult to observe the symmetric charge generation which gives charge cancellation in the signals. Here, this problem is circumvented by using a shadowed or hidden loop collector which is not directly exposed to photoionizing photons. However, the very energetic gamma photons ejected directly after the laser pulse give Compton electrons even at the loop collector, as seen in Fig. 5. Otherwise, most photons are blocked by the 1.5 mm thick steel plate and pair production exists due to the massive particles that penetrate through the steel plate. The signal with zero bias in Fig. 5 is only 10–20\% of the signal with −50 V bias in Fig. 4 not including the first Compton electrons. This indicates that the signal is strongly influenced by the bias and that charge cancellation exists with zero bias. The process which can give such results is pair production as described previously.\textsuperscript{18} Since electron–positron pairs only require 1.02 MeV for their production while the massive particles ejected by the laser have up to 20 MeV u\(^{-1}\) as found in several studies,\textsuperscript{16,17} such pairs may be produced quite easily.

The oscillations observed in the loop signal in Fig. 4 and also in Fig. 2 can be caused by pair production and charge cancellation. This means that an instantaneous positive signal on the collector increases the ejection of positive charges over negative charges, which gives a more negative voltage of the collector and decreases the ejection of positive over negative charges. This feedback process giving signal oscillations exists until the particle flux ends at 100–200 ns in the figures. Of course, the rate of this charge balancing is influenced by the capacitance of the collector and the bias battery or circuit, which gives the period of the oscillations.

It is assumed here, as previously, that the particles giving the pair production are small clusters of the ultra-dense form \( D_N(0) \).\textsuperscript{16,17} It is expected that such particles will appear to be neutral down to a distance of the order of 2 pm, which is the interatomic distance in the ultra-dense hydrogen D(0).\textsuperscript{1–4} If the excitation state
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of the clusters is \( s=1 \) instead of the more common \( s=2 \), the interaction distance may be down to 0.6 mm before the clusters appear to be separate charges and not neutral. This gives them the possibility to penetrate through thick metal plates. A proton at 20 MeV energy has a range in steel of \(< 1 \text{ mm}\), and thus cannot give the signal observed at the loop collector.

6. Conclusions

The particle signals observed from laser-induced processes in D(0) agree with the theoretical time distributions for particles formed and decaying with time constants of 5–15 ns. The distributions are not thermal contrary to what was suggested previously. The total number of such particles is at least \( 4 \times 10^{13} \) per laser pulse and sr. A fraction of the ejected particles penetrates through 1.5 mm steel with a delay of 5–10 ns. The penetrating particles interact with a hidden (shadowed) collector giving pair production, observed with no signal limiting at high bias voltage. Pair production gives almost zero signal at zero bias voltage. A large electron signal due to Compton scattering from gamma photons is observed.

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References

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