Measurement of the Ion Temperature in Laser-Driven Fusion*

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Using the time-of-flight technique, energy distribution measurements were made of the α particles emitted from laser implosions of DT gas in glass microshells. The number of nuclear reactions was determined by an absolute measurement of the number of α particles. From the width of the energy distributions, upper limits of the plasma ion temperature have been inferred.

During the last year, KMS Fusion Inc.[1] (KMSF) and Lawrence Livermore Laboratory[2] (LLL), have obtained 10^6 to 10^7 neutrons by irradiating small glass microshells containing a mixture of deuterium and tritium gases with a short laser pulse. The LLL experiments[3] involved focusing a 15-J, 100-psec, 1.06-μm laser pulse on glass microshells 40 to 90 μm in diameter. The glass wall thickness was 0.5 μm and the initial DT density was 2 mg/cm^3. For the experiments reported here, two laser beams, each with approximately 17 J, were simultaneously focused on a similar DT-filled microshell using $f/1.1$ aspheric lenses.

Both KMSF[4] and LLL[3] have x-ray images of the plasma source. These images show that the glass pusher was imploded and that the DT gas was compressed. The low-energy x-ray measurements[3] indicate that the electrons in the glass were heated to a thermal temperature of about 0.5 keV. The measured temperature and calculated density are consistent with thermonuclear burn producing the observed neutron yield. However, no measurements have been made to determine the ion temperature of the compressed DT. There are other measurements which show that electrons with energies greater than 100 keV[5,6] and fast ions[7-9] are produced from laser-plasma targets. It is conceivable that deuterons and tritons may also be accelerated to high energies and that they, in turn, produce neutrons from beam-target or beam-beam reactions. This phenomenon has been documented in both magnetically confined[10] and laser-produced plasmas.[8] Therefore, it was the purpose of this work to measure the spread in the α-particle energy distribution to determine the velocities of the interacting ions in the LLL experiments.

A unique advantage to present-day laser-fusion experiments is that the glass wall of the microshell is thin, 0.5 μm; hence, the 3.52-MeV α particles escape with little energy loss. Because the energy broadening as a function of ion temperature is the same for α particles and neutrons, application of the time-of-flight technique to the α particles rather than to the neutrons effects a large advantage in energy resolution. Since the energy E and the velocity v of the α particle are 0.25 times the energy and velocity of the neutron, then for the same temporal resolution Δt and flight path d an increase of 16 in the energy resolution is gained by measuring the α-particle dispersion:

$$\Delta E = 2E(v/d)\Delta t.$$

The experimental setup is shown in Fig. 1. The energy range of the instrument is 2.6 to 3.9 MeV. The experiment was designed so that α particles in this range that pass through the entrance aperture of the magnet are deflected by the magnetic

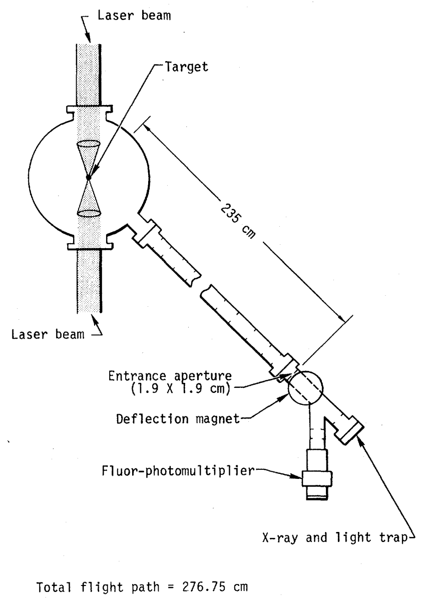
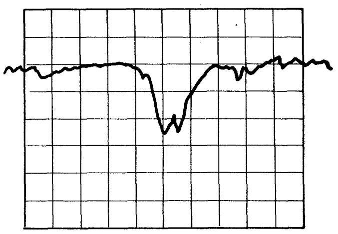
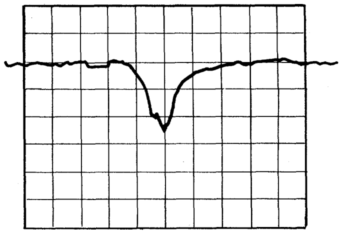


FIG. 1. Experimental setup.



Experiment 1



Experiment 2

FIG. 2. Oscilloscope traces of α particle distribution, 10 nsec/cm.

field to the scintillator. Thus, the geometry for determining absolutely the total number of α particles emitted from the source is well known. The drift tube has baffles to minimize the background signal from light and x rays. The entire pipe is pumped to 10^{-5} Torr. The scintillator is 10-mm-thick, bare NE111 coupled to an Amperex 2106 photomultiplier tube. The calibration of the pulse arrival time and the measurement of the time width of the photomultiplier were made with the detector in its shot configuration and with the same Tektronix 7904 oscilloscope and cables used to take the data. These timing calibrations were done with light from the laser operated at low power. The light was frequency doubled and reflected from the center of the chamber to the detector. With these calibrations, the arrival time of the α particles can be determined to ± 1 nsec.

The scintillator photomultiplier was calibrated absolutely with 5.8-MeV α particles from a ^{244}Cm source. To apply these calibrations at lower energies, a semiempirical relation by Birks[11] that relates the light emitted from the scintillator to the range of the α particle in the scintillator material was used. The ranges used were from Nuclear Data Tables.[12] The time response of the detector for counting individual α particles was measured to be 4 nsec full width at half-maximum (FWHM). This was used to correct for instrument response in determining the time-of-flight spreading of the α particles from the plasma. A 4-nsec width corresponds to an instrumental resolution of 130 keV for 3.52-MeV α particles.

Oscilloscope traces from two experiments are shown in Fig. 2 and pertinent data are given in Table I. The time width is the FWHM of the distribution in Fig. 2. The energy width is corrected for the instrument response. In calculating the total α-source strength, isotropic emission was assumed. The results compare favorably with the neutron source strengths measured separately.[13] The ion temperatures were calculated from the measured α-energy widths.

A background measurement was done with a 0.0013-cm-thick Mylar foil in front of the detector. The signal, normalized to the neutron measurements, was reduced the correct amount for α particles of 3.3 MeV. This measurement also showed that 1.6-MeV deuterons, which would be deflected the same angle in the magnetic field and have the same time of flight as the α particles, did not contribute to the measured signals. The estimated error in the α mean energy measurement is ± 0.05 MeV, and the estimated error in the energy width is ± 30 keV.

The energy broadening of the α distribution as a function of ion temperature θ_i was calculated from the kinetic equations for the reaction. Monte Carlo averages were taken over the angle between the incident particles, and over the angle between the emitted α and the center-of-mass motion. It was assumed that each particle species had a Maxwell-Boltzmann velocity distribution. The reaction rate was computed by folding the velocity-

TABLE I. Summary of α-particle distribution measurements and calculated ion temperatures.

Experiment	Time width (nsec)	Average α energy (MeV)	Energy width (keV)	Ion temp. (keV)	α source strength ($\times 10^6$)	n source strength ($\times 10^6$)
1	12.2	3.27	340	3.7	4.0 ± 0.8	3.9
2	10.5	3.36	315	3.2	5.5 ± 1	4.7

dependent distribution function with an empirical cross section function. The calculated α-particle distribution is approximately Gaussian with a FWHM, $\Delta E = 177\sqrt{\theta_i}$ keV, in agreement with the analytical expression of Brysk.[14] A second calculation was performed to determine the α-particle distribution that would be produced by beam-target interactions; i.e., a beam composed of an equal number of deuterons and tritons of equal energy spherically converging on a cold DT target. The distribution is square with a width $\Delta E = 150\sqrt{E_{\mathrm{D,T}}}$ (keV), where $E_{\mathrm{D,T}}$ is the energy of the deuterons or the tritons in keV. Another calculation was done for the extreme case of a deuteron beam interacting with a triton beam of the same energy. The α-particle distribution from these reactions has a width $\Delta E = 75\sqrt{E_{\mathrm{D,T}}}$ keV. The measured widths would require either a beam energy of about 5 keV in a cold target or colliding beam energies of about 20 keV. Other situations, e.g., a beam interacting with a Maxwellian ion distribution, fall between these two calculated cases.

The inferred ion temperatures represent an upper limit because other effects contribute to the α width: nonuniform or time-varying energy losses in the DT fuel and glass wall, Doppler broadening by the gross hydrodynamic motion of the fuel, and straggling. Using temperature density profiles taken from numerical simulations that reproduce the total DT yield and the measured x-ray spectrum, we estimated the energy loss through the glass shell to be 300 keV for experiment 1 and 120 keV for experiment 2 at the time of peak thermonuclear burn. Table I shows losses of 250 and 160 keV. The calculated increments to the α broadening were approximately 150 and 180 keV. After the experimental values are corrected for this broadening, the average widths of the two experiments resulting from kinematic broadening alone are 305 and 260 keV. These widths correspond to DT temperatures of 3.0 and 2.2 keV. This is in good agreement with 1.6- to 3.0-keV values calculated by numerically modeling these imploding microshells with the two-dimensional Lagrangian magnetohydrodynamic code LASNEX.[15]

The measurements show that the reactions took place inside the glass microshell, because the α-particle energies are shifted 0.2 MeV below their original 3.52-MeV value. Thus, these experiments have demonstrated that the ions are heated and interact inside the microshell and have energies comparable to those found in a Maxwell-Boltzmann distribution with an upper limit temperature of 3.2 to 3.7 keV. This is significant evidence that the reactions are thermonuclear.

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