LA-UR- 96-1650

CONF-9606208--6

Title:

NEUTRON TIME-OF-FLIGHT FROM EXPANDING OR CONTRACTING SPHERICAL SOURCES.

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JUN 11 1996
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Submitted to:

11th High Tempaturte Plasma Diagnostic Conference
Monterey, CA
June 13-17, 1996
Will also submit to Review of Scientific Insturments

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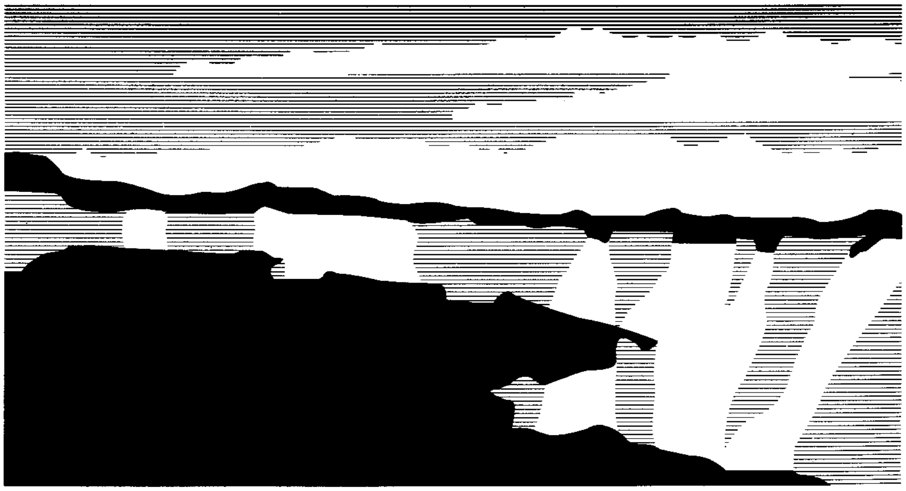

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Neutron time-of-flight signals from expanding or contracting spherical sources

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The width of the energy distribution of fusion-produced neutrons is often used as an indication of the temperature of the reacting ions. The Doppler broadening of the neutron energy is due to the center-of-mass velocity of reacting ion pairs and is characterized by the ion temperature for a Maxwellian distribution of ions with zero collective velocity. If there is bulk fluid motion or turbulence characterized by a velocity on the order of the ion thermal speed, a significant additional broadening may introduced. Suggestions of this phenomenon have been observed for two classes of laser targets. The first is a "gas bag" target, in which a deuterated hydrocarbon gas is contained in a thin spherical membrane and illuminated uniformly. The second target is an ICF capsule with a deuterated plastic inner layer. In both cases, measured neutron energy distributions were wider than expected from theoretical ion temperatures alone would predict, and if interpreted as indicative of the ion temperature, are inconsistent with the neutron yields observed.

I. Introduction

Ion temperatures achieved in inertial confinement fusion (ICF) targets are often determined by measuring the energy spectrum of the fusion neutrons [1]. The usual method is to determine the energy of detected neutrons through their flight time [2-7]. For a detector a sufficient distance from the target, the spread in the arrival time of the neutrons can be measured and the energy distribution of the neutrons deduced.

The spread in neutron energies comes primarily from the center-of-mass motion of the reacting pairs of ions. The neutron energy can be written

$$E_n = \frac{1}{2} m_n \left(\mathbf{v}_n' + \mathbf{V} \right)^2 \tag{1}$$

where $\mathbf{v}_n'$ is the velocity of the neutron in the center-of-mass frame and $\mathbf{V}$ is the velocity of the center of mass of the reacting ions. The difference between the center-of-mass energy of the neutron and the energy in the lab frame can then be shown to be, to order V/v_n',

$$\Delta E_n = E_n' \left(2 \frac{V}{v_n'} \cos\theta \right) \tag{2}$$

From this, the center-of-mass velocity along the line of sight can be approximated

$$V_z = \frac{1}{2} \frac{\Delta E}{E_n'} v_n' \tag{3}$$

For a Maxwellian distribution of ions, the center-of-mass of reacting ion pairs is independent of their relative velocity, and therefore the distribution of neutron energies is proportional to the thermal velocity of the ions. Thus, from the width of the energy spectrum, the ion temperature may be deduced [1].

This relationship holds as long as the center-of-mass motion is a result of the thermal velocity of the reacting ions. If, however, there is also a contribution due to bulk motion of the reacting region, then there will be an additional contribution to the energy of the neutrons. Specifically, if the reacting region forms an expanding or contracting spherical region, then an additional spread of the neutron energy results. If this expansion or contraction is near the thermal velocity of the ions, then a contribution comparable to the thermal spread results.

Two classes of ICF target have shown suggestions of this phenomenon. The first is a thin plastic "gas bag" target [8] in which a 3-mm diameter polyimide sphere filled with deuterated neopentane was irradiated uniformly with ten beams of the Nova laser. The neopentane was deuterated in order to allow measurement of the ion temperature of the long-scale-length plasma thus formed. Large neutron energy spreads were measured which indicated ion temperatures inconsistent with the measured neutron yields.

A second class of target in which this phenomenon was suggested was in the implosion of deuterated plastic shells filled with hydrogen [9]. In these experiments, the surface finish of the capsules was varied to affect the amount of mix of cold pusher material (deuterated plastic) into the hot fuel (hydrogen). Direct numerical simulations using the two-dimensional radiation hydrodynamics code LASNEX [10] predicted the yield quite well, but the predicted ion temperatures were well below those derived from the neutron spectra using the assumption that the width of the neutron energy spectrum was due entirely to the temperature of the reacting ions.

II. LANL ion temperature diagnostic (Tion)

The neutron energy spectra discussed in this paper were obtained with the Los Alamos ion temperature diagnostic[11,12] (Tion), an array of approximately 1000 neutron scintillators, 1 cm diameter by 1 cm long, coupled to photomultiplier tubes and time-to-digital converters. Each detector is capable of measuring the flight time of neutrons from the target to the detector 27 meters away with about 2 ns time resolution. By operating in the mode where the number of hits is a fraction of the number of available channels a single-hit neutron spectrum with high energy resolution can be obtained by converting the time-of-flight into neutron energy.

The detector is located outside the Nova target bay and views the target though a core in a six-foot thick concrete wall which serves as a collimator for the instrument. The main purpose of the diagnostic is to measure ion temperatures from implosions, but it has also been useful in measuring neutron spectra from deuterated gas targets. Since Tion is located on the axis of Nova, the neutron spectra measured will also reflect any motion of the neutron-producing plasma with a component along the axis of the target.

Ion temperatures are determined[11,12] from measured neutron spectra by fitting with a Gaussian and using the relation derived in Ref. 1, which is only applicable for the case of a Maxwellian ion distribution. In the case of a non-Maxwellian distribution, or in the situation where flow velocities on the order of or greater than the thermal velocity exist, a more sophisticated analysis must be performed (see below).

III. Gas Bag targets

Current designs for National Ignition Facility hohlraum targets call for filling with gas, specifically helium-hydrogen mixture [13]. A number of experimental series have been performed to characterize the effects of laser-plasma instabilities in gas-filled targets with long scale lengths [14,15]. To obtain plasmas with electron densities of one-tenth critical for 3ω light, one atmosphere neopentane (C_5H_{12}) is used as a fill gas. In order to use neutron diagnostics for characterization of the plasma, deuterated neopentane (C_5D_{12}) was also used.

A large number of neutron diagnostics were used to measure the neutron yield, energy spectrum, and burn history for deuterated gas targets. These measurements show that the ion temperature derived from the width of the neutron spectrum is probably not indicative of the actual ion temperature of the plasma. The yield of DD neutrons does not vary more than about an order of magnitude, even though the reaction rate should change by about three orders of magnitude over the range of measured ion temperatures (about 1 to 8 keV).

An examination of the individual neutron spectra, measured, shows that the neutron spectra vary from the Gaussian distribution one expects for a uniform Maxwellian distribution of ions. These spectra can be explained by flows in the gas targets with flow velocities on the order of the sound speed. They probably do not reflect the actual ion temperature of the plasma.

Neutron yields from deuterated gas bags were measured using scintillators coupled to microchannel plate photomultiplier tubes operating in current mode. Since this system uses the neutron time of flight to discriminate against photons and scattered neutrons, this system is referred to at the neutron time-of-flight (nToF) system [16]. Yields are determined by integrating the neutron signal and multiplying by a calibration factor determined by a cross calibration procedure relative to an absolutely calibrated indium activation system. The neutron yields were then compared to that calculated from the ion temperature obtained if one assumes a Maxwellian ion distribution and from the known density and volume of the gas targets, assuming a 2-ns burn duration using

$$Y_n = \frac{1}{2} n_d^2 \langle \sigma v \rangle V \tau ,$$

where n_d is the deuterium density for 1 atm of deuterated neopentane, V is the volume of the target, and τ is the burn duration. (The differences in volume for the different targets is small compared to the range of neutron yields dictated by the range of ion temperatures measured and is ignored. For this calculation, the volume of a typical Gas Bag is used.) The reaction rate was calculated using the expressions derived by Peres[17]. Measured and calculated neutron yields are compared in Figure 1. As can be seen, the measured neutron yields fail to demonstrate the dramatic scaling with ion temperature expected, even ignoring the single point at 8 keV.

One could certainly hypothesize that only a small region of the plasma is at high temperature, but one must consider that the volume of hot plasma, the ion temperature in that region, and several other factors must conspire to create a situation in which the neutron yield does not vary while the width of the neutron energy spectrum does. It seems unlikely that such a model would reflect the reality of what is occurring in these targets.

Alternately, one might hypothesize that a modification of the deuterium distribution function in the vicinity of the sound speed, as might occur from the damping of ion waves, might lead to an increase in the apparent ion temperature. Such a model might explain the increase in neutron yield, but does not lead to an increase in the width of the neutron energy spectrum.

Neutron spectra from Tion reveal features that would not be expected from the simple Gaussian neutron distribution one expects with a Maxwellian ion distribution. Neutron spectra from Gas Bag targets appear in several cases to be composed of a wide plateau and a narrow peak.

The Gas Bag neutron spectra can be analyzed using a model which assumes that, in addition to neutrons coming from a stationary plasma at a given ion temperature, there are also neutrons born in an expanding shell of plasma. Figure 2 shows fits using this model for the summed spectra from all of the deuterated Gas Bags for which Tion data was available at the time of this analysis (a) and for one particular target (b). In both cases, expansion velocities of about 8×10^7 cm/s are implied (approximately twice the sound speed at T_e=3 keV), and the derived ion temperatures are significantly reduced from that obtained using a single-Gaussian fit. Scattered neutrons which arrive late at Tion may exaggerate the neutron population on the low-energy side of the peak; however, neutron spectra from implosions of deuterium-filled capsules do not show this effect (Figure 3).

IV. Implosions with deuterated plastic shells

Mix of pusher material into fuel due to growth of hydrodynamic instabilities can reduce the performance of ICF capsules. Indirect-drive experiments have been performed with ICF capsules with varying surface finish in an effort to demonstrate that mix can be measured by observing the decrease in neutron yield with increasing surface roughness [18].

A complementary set of experiments were performed in which hydrogen was substituted for the deuterium fuel, and the pusher was replaced with deuterated plastic [9]. In this experiment, mix might be expected to increase neutron yield as pusher material heats up due to its contact with hot fuel. This is shown to be a minor effect, however, as the density of the deuterium introduced decreases while the temperature increases with increasing surface roughness

The neutron yield obtained in simulations of these implosions (Fig. 4a) are in very good agreement with the measured values over the range of surface finished used in the experiments. The ion temperatures derived from the neutron spectra are, however, much larger than in the simulations. This is difficult to reconcile since the measured ion temperature would imply a reaction rate which is a factor of 200 higher than that obtained from the simulations [9].

The predicted ion temperature of about 0.55 keV would lead to a neutron energy width of about 60 keV FWHM. The measured spectra instead had a width, summed over all shots, of 99 keV [9]. If the width is increased due to a spherical contraction of the neutron emitting region, then the neutron width will increase linearly with the radial velocity of the contraction (rather than in quadrature). The measured half width of the neutron energy spectrum then is seen to increase over the predicted by about 20 keV. From Eq. 3, this corresponds to a radial velocity of 9×10^6 cm/s. This is in the middle of the range predicted by the numerical simulations for the flow speeds of the spikes during the period during which the neutrons are produced [9].

V. Conclusions

Ion temperatures derived from neutron energy spectra have been shown to be invalid under circumstances in which bulk motion of the reacting plasma is present. Expansion at velocities near the sound speed appear to be present in open geometry "gas bag" targets, producing neutron energy spectra which imply much higher ion temperatures than are consistent with the neutron yields. Likewise, flow velocities in deuterated plastic shell targets have lead to wider neutron spectra than predicted in simulations that accurately predict neutron yield.

In order to prevent future confusion in the interpretation of experimentally determined ion temperatures, the effects of flows should be included in any simulation of experiments in which the neutron-emitting region may exhibit bulk motion relative to the neutron detector. If this is done, neutron data will reveal information on the structure of flow rates in the plasma as well as information about the temperature of the reacting region.

The authors with to thank Dr. B. MacGowan for helpful discussions. This work was performed under the auspices of the U. S. Department of Energy by Los Alamos National Laboratory under Contract W–7405–Eng–36 and by the Lawrence Livermore National Laboratory under Contract W–7405–Eng–48.

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Figures

Figure 1: Neutron yields for gas targets vs. ion temperature inferred from the LANL ion temperature diagnostic.

Figure 2: Summed neutron spectra (a) from all deuterated Gas Bag targets (•), along with a Gaussian fit (thin line), and a fit which assumes both a Gaussian component and an expanding shell of hot gas (thick line). The Gaussian fit implies an ion temperature of 3.5 keV, while the modified fit implies only 1.6 keV with an expansion velocity of 8.1×10^7 cm/s; and (b) data from a single shot in which the fit corresponds to an ion temperature of 0.75 keV and an expansion velocity of 7.8×10^7 cm/s.

Figure 3: A comparison of the high-energy wings of the neutron energy distribution for the sum of all deuterated Gas Bags and for the sum of implosions demonstrating that implosions do not create the increased high-energy distribution seen in Gas Bag targets.

Figure 4: Results of experiments (●) on implosions with deuterated plastic shells compared to the results of direct numerical simulations (❑). The total yield (a) agrees well with simulations, but the ion temperatures inferred from the neutron spectra (b) are much higher than simulations.

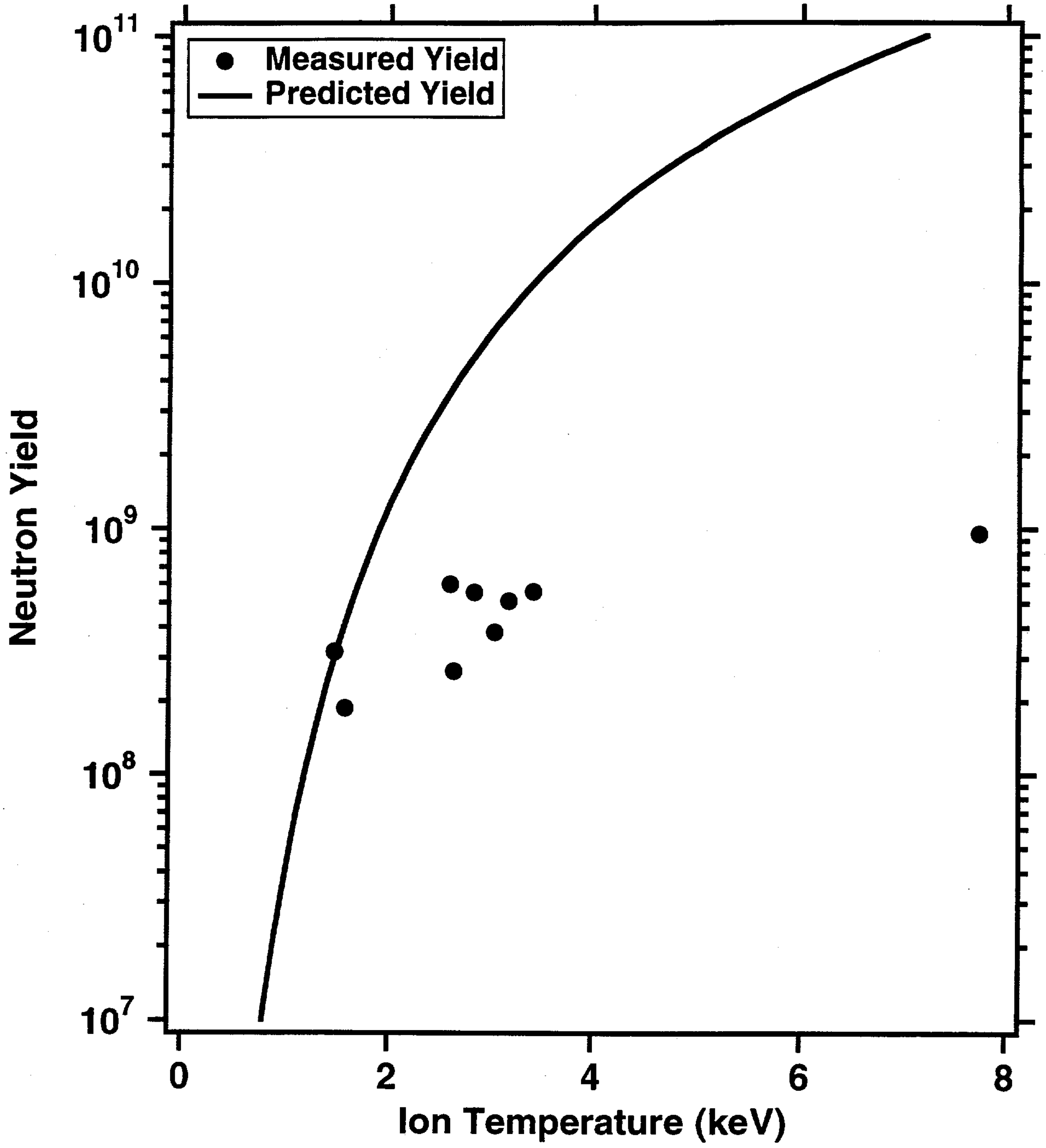

Figure 1
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Neutron time-of-flight signals
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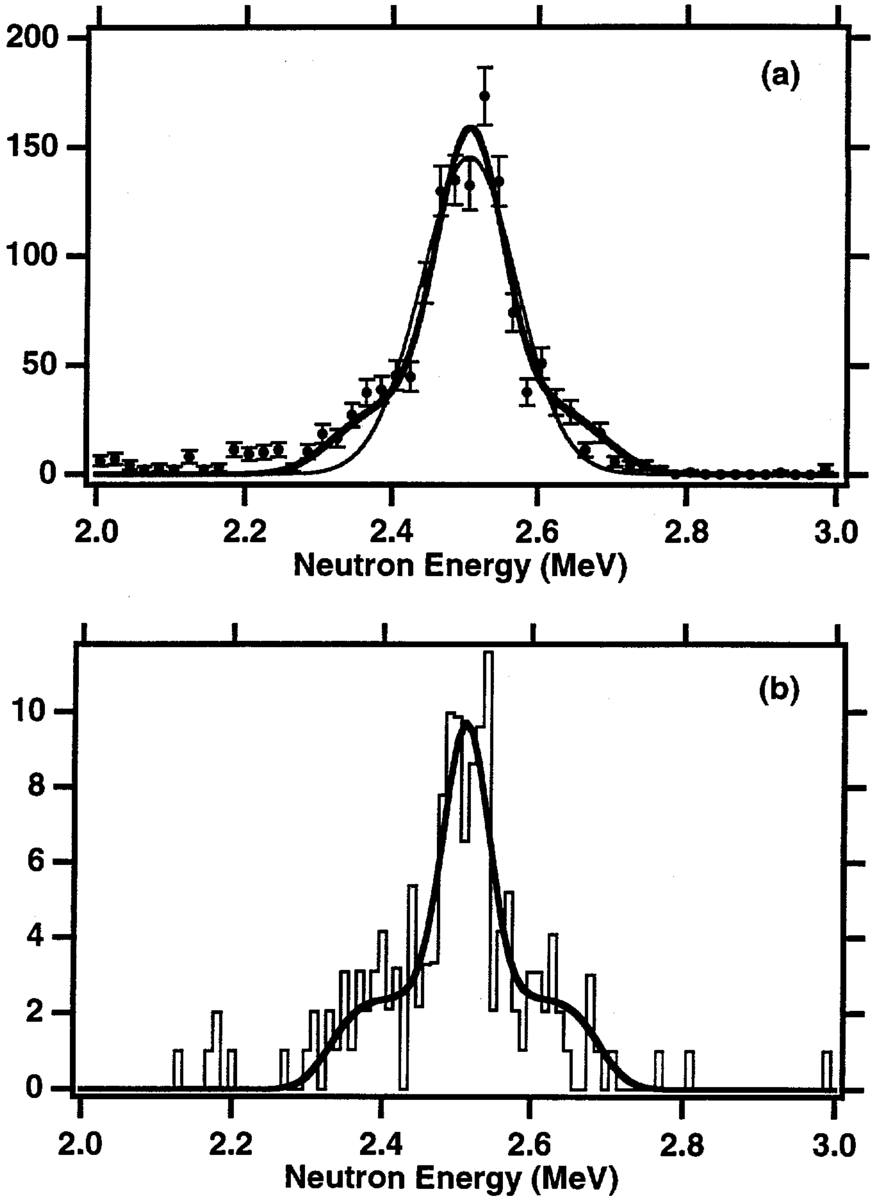

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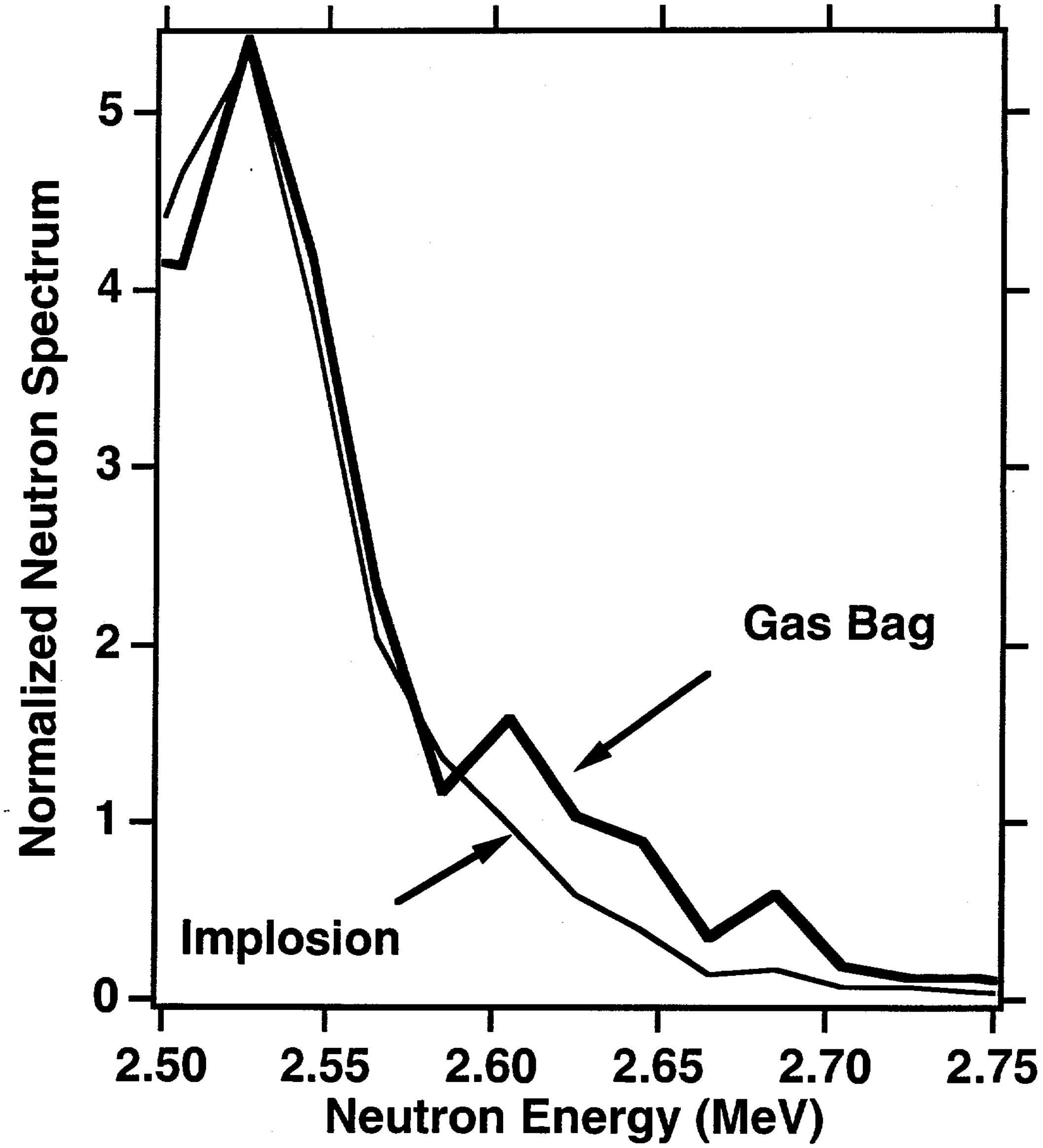

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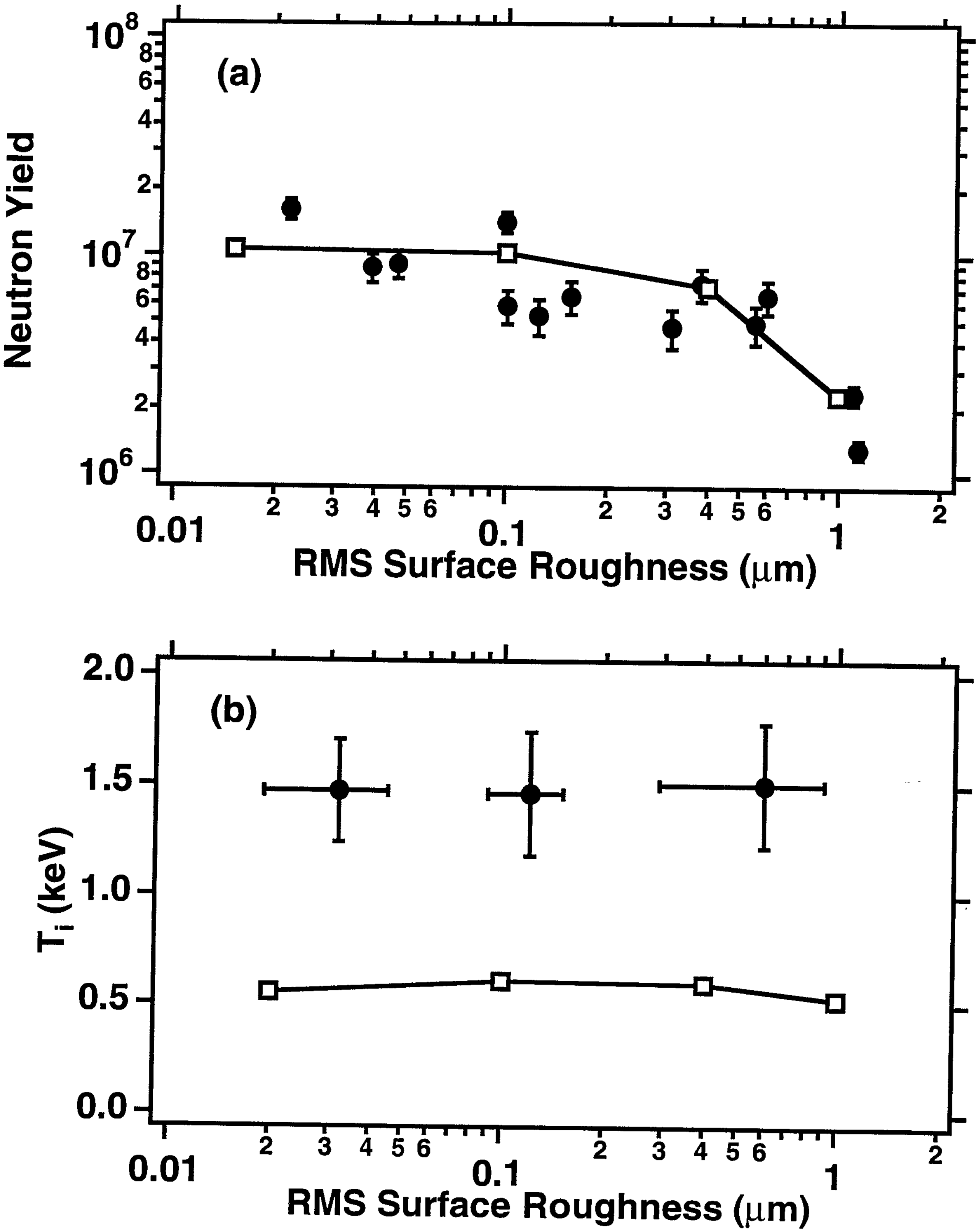

Figure 4
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