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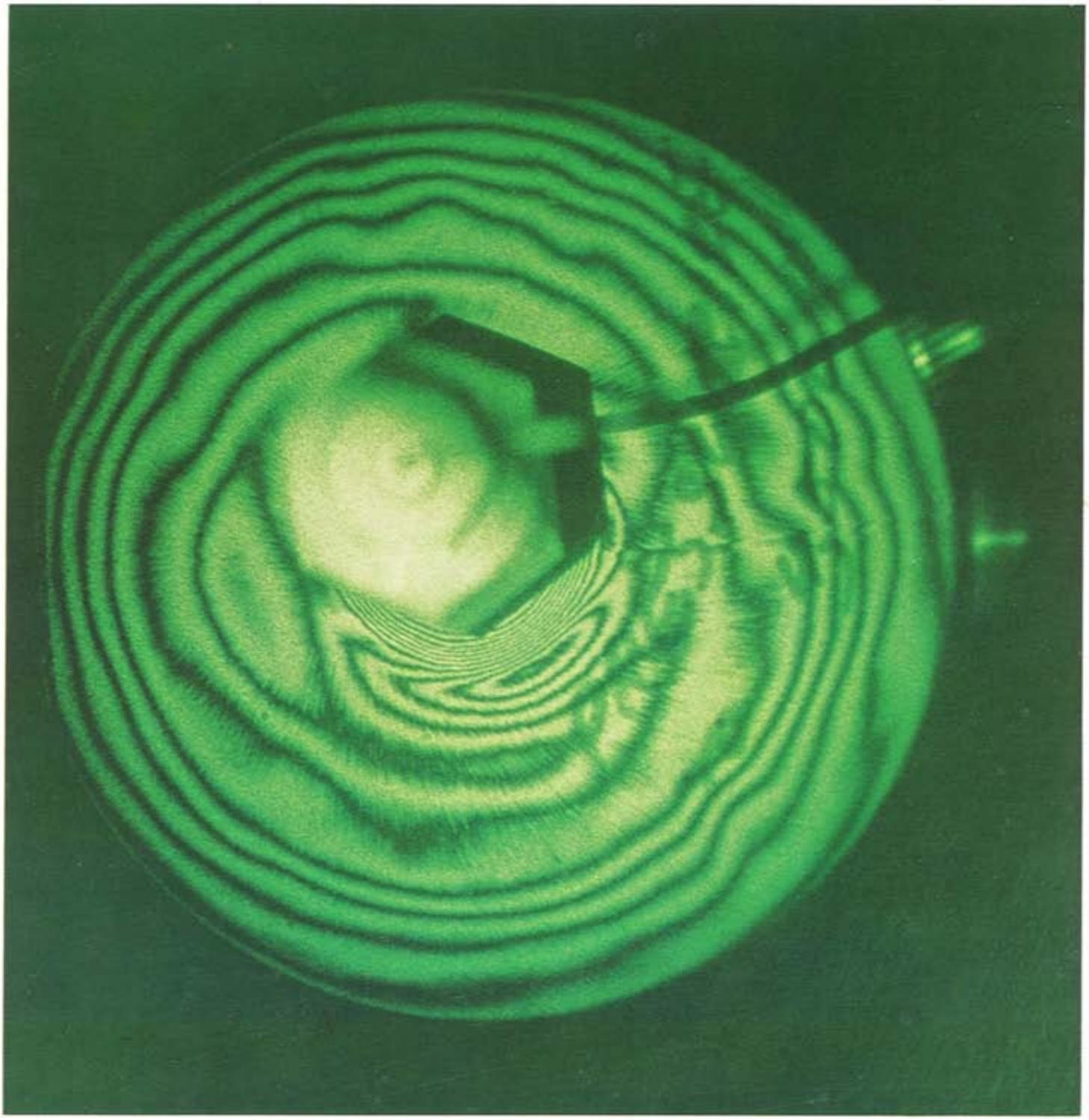

Density diagnosis of fusion targets by neutron activation

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Two critical parameters of laser fusion experiments are the temperature and the peak density achieved in the implosive compression of a deuterium-tritium fuel pellet. These parameters were relatively easy to measure for our early exploding-pusher targets, which achieved high temperatures (up to 10 keV) at relatively low densities (of the order of 0.2 g/cm^3). Target experiments performed this year and planned for the near future are designed to achieve significantly higher final densities, though at relatively modest temperatures (0.5 to 2 keV). The concomitant higher target material areal densities and low target emissivities make it hard to use the early diagnostics.

To circumvent the problem, we have developed a new density diagnostic based on neutron activation of selected materials in the targets. For a series of intermediate-density experiments (up to 3 g/cm^3) performed at Shiva, we used the short-lived (2-min half-life) aluminum-28 formed in the target by the bombardment of silicon-28 with 14.1-MeV neutrons from the D-T reaction. Our system rapidly collects a known fraction of the aluminum-28 formed, transports it to a shielded detector, and determines its radioactivity. This allows us to derive, by computer simulations, fuel densities for a number of different targets. We have also developed a simplified model that provides an independent cross check on the computer analysis. Later we will extend our diagnostic to measure fuel density directly and to address such additional features of the implosion as symmetry, stability, pusher-fuel mixing, and preheat.

The success of our inertial fusion (IF) program for civil and military applications depends on the ability of a driver (such as a laser) to both heat and compress the D–T fuel inside a microscopic shell to extremely high temperatures and densities.[1] Our 20-beam Shiva laser, with its capability for producing 30 TW in 100-ps pulses and 15 kJ in 1-ns pulses,[2] has recently performed a series of experiments on targets designed to achieve intermediate-density fusion conditions. By focusing 20 TW in 200 ps onto these targets, we achieved peak fuel conditions of 3 g/cm^3 and 1.5 keV. We hope, with the Shiva laser and advanced target designs, to increase the final density by several orders of magnitude. The limited power and energy capability of the Shiva laser, however, does not allow us to achieve both high density and high temperature.

Computer simulations indicate that we will need fuel densities of at least 200 g/cm^3, fuel areal densities (ρR) greater than 1 g/cm^2, and core ion temperatures above 4 keV to ignite and propagate a thermonuclear burn. We hope in the mid- to late 1980s to achieve conditions approaching these with the 300-TW, 300-kJ Nova laser now under construction.

Most of our IF implosion experiments have involved exploding-pusher targets (thin-walled glass microspheres, Fig. 1a) that are exposed to a short (somewhat less

than 100 ps), high-power laser pulse. The thin glass shell (the pusher) is rapidly heated to a uniform temperature of about a few million degrees by energetic electrons generated during the laser absorption process. It blows up, with about half the pusher mass imploding to compress and heat the fuel and the rest expanding outward.[3] Our exploding pushers have produced ion temperatures up to 10 keV, as many as 3×10^{10} fusion reactions, and compressed fuel densities of about 0.2 g/cm^3. Thus the resulting high yield of neutrons, charged particles, and x rays, together with the low areal densities of the fuel and pusher, offers many ways to measure the fuel density in the compressed core.

More recently, we have shifted some of our theoretical and experimental efforts to the study of a more ablatively driven intermediate-density target (Fig. 1b). The target consists of a silicate-glass microsphere, of 140 μm inside diameter and 5 μm wall thickness, filled with a 5-MPa equimolar mixture of deuterium and tritium. The microsphere is coated on the outside with a 15-μm-thick fluorocarbon–plastic ablator. Laser light is focused on the plastic coating for somewhat more than 200 ps and successively heats more and more of it to about a million degrees, ablating it rapidly. The reaction to the rapid blowoff of superheated gases implodes the glass pusher and compresses the fuel. Both the longer pulse length and the 20 μm of glass and plastic tend to make these implosions more ablative than the thin-walled exploding pushers.[4]

With these targets, experimentally determining the conditions of the compressed fuel becomes more difficult. Previously successful techniques (such as imaging x rays emitted from the compressed core region, obtaining temperature and density information from Stark broadening of line emission from a seed gas mixed with the D–T fuel,

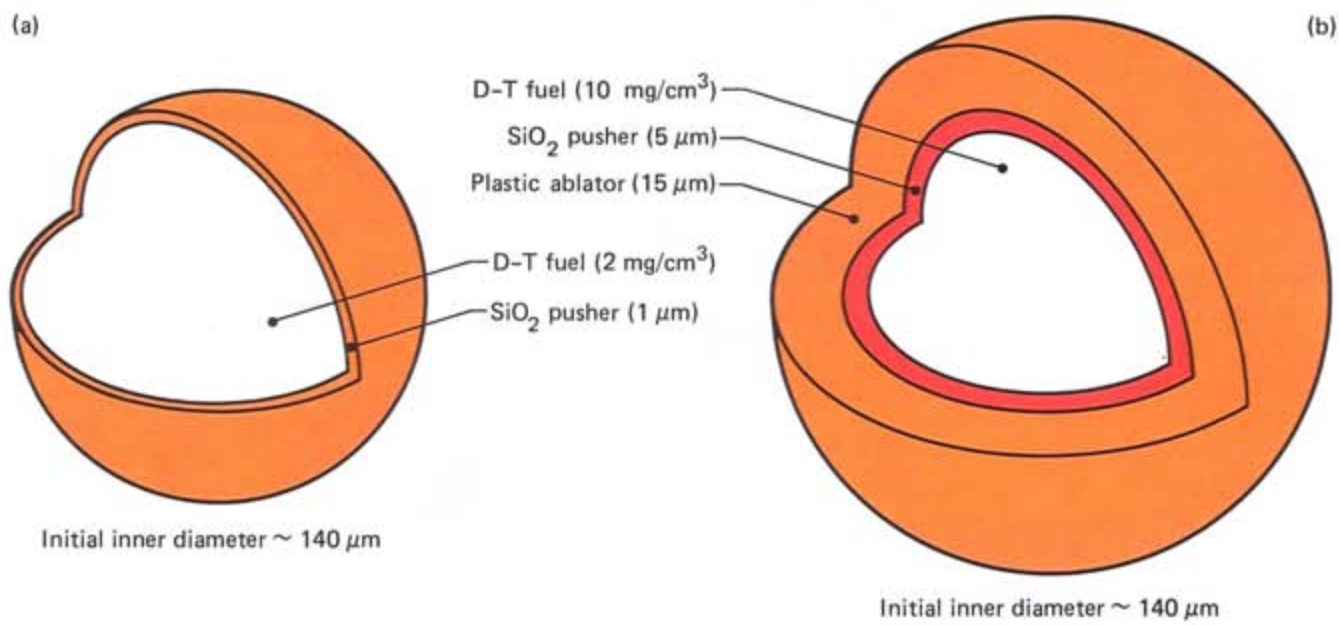
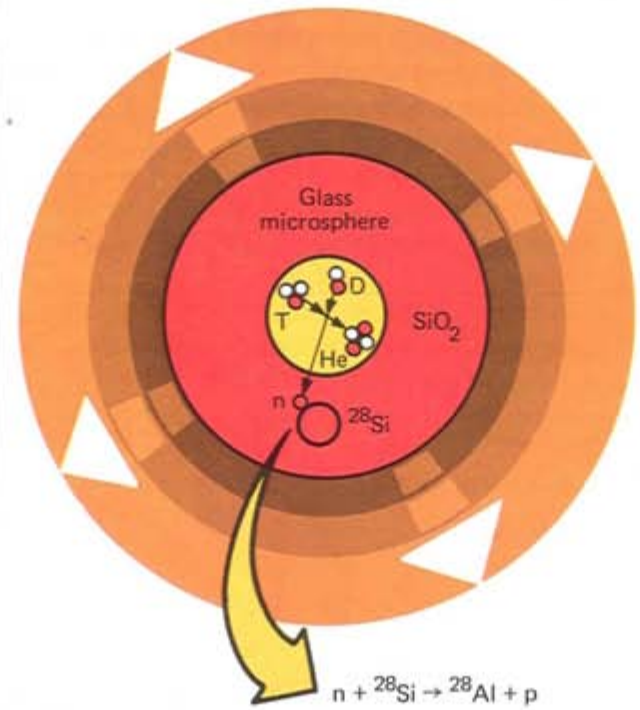


Fig. 1 *Targets used in Shiva inertial fusion experiments. (a) Exploding-pusher target. Laser irradiation heats the thin glass shell; it explodes, heating and compressing the D-T fuel. (b) Ablative target. Laser light ablates the plastic coating gradually (in comparison with an explosion) causing a sustained inward push on the glass shell. This requires a more symmetric implosion and produces a more isentropic compression than can be obtained from an exploding pusher.*

and imaging the alpha particles produced in the thermonuclear burn) are not as useful because of the low core temperatures and increased areal densities of the fuel and pusher.

To circumvent these problems, we are developing new diagnostics. One of the most promising involves detecting the radioactive nuclides produced by the interaction of the 14.1-MeV fusion neutrons with nuclei in the pusher or the fuel. We have used this neutron-activation technique to measure the pusher areal density $(\rho\Delta R)_p$ of exploding-pusher and intermediate-density targets in a series of experiments conducted at the Shiva laser facility. We have also developed both a simple physical model and computer calculations that relate the measured pusher areal density to the compressed fuel density. We are extending this method to obtain areal-density measurements simultaneously from multiple shells of the target; at the same time, we are investigating a method, for future high-density experiments, of obtaining a direct measurement of fuel areal density by seeding the fuel region with a trace gas that can be activated by thermonuclear neutrons.



$n + {}^{28}Si \rightarrow {}^{28}Al + p$

$\sigma = 22\ fm^2$

${}^{28}Al \rightarrow \beta^- + {}^{28}Si^* \rightarrow \gamma + {}^{28}Si$

$t_{1/2} = 2.24$ min

$E_{max}\ (\beta^-) = 2.86$ MeV

$h\nu\ (\gamma) = 1.78$ MeV

$$[\rho\Delta R]_p = 5 \times 10^5 \ \frac{[\text{No. } {}^{28}\text{Al atoms produced}]}{[\text{Neutron yield}]}$$

Fig. 2 *To measure the areal density of the glass pusher $(\rho\Delta R)_p$, we count the aluminum-28 activity produced in the glass by 14.1-MeV neutrons from fusion. The cross section for this (n,p) reaction with silicon-28 is 22 fm² (0.22 barns).*

Experimental technique

If we assume a spherically symmetric implosion, with a thermonuclear burn time that is short compared to the time scales for significant hydrodynamic motion and with no pusher–fuel mixing at the time of peak neutron production, the number of activated atoms (N^*) formed by the neutrons as they traverse the pusher is:

$$N^* = \sigma(A_0/A_w)f \cdot Y \cdot (\rho\Delta R)_p, \qquad (1)$$

where σ is the neutron-activation cross section at 14.1 MeV, A_0 is Avogadro's number, A_w is the average atomic weight of the pusher, f is the fractional abundance of the source nuclei in the pusher, Y is the total neutron yield, and $(\rho\Delta R)_p$ is the pusher areal density at burn time. About 25% of the atoms in our present silicate-glass pushers are silicon-28, which can readily be converted to radioactive aluminum-28 by an (n,p) reaction. Aluminum-28 decays with a 2.2-min half-life by the emission of a beta particle and a 1.78-MeV gamma ray.[5,6]

Figure 2 shows the principle of this experiment together with the

relevant parameters. If we insert the values of these parameters into Eq. (1), we find that the number of aluminum-28 atoms produced in a given experiment is:

$$N^* = 2.0 \times 10^{-6} Y \cdot (\rho \Delta R)_p, \qquad (2)$$

where $(\rho \Delta R)_p$ is in units of milligrams per square centimetre. This relationship allows us to determine, from an independent measurement of the thermonuclear yield and the total aluminum-28 production, the pusher areal density and, by extension, the compressed D–T fuel density at the time of maximum fusion burn.

It is important to recognize, however, that detailed computer simulations show that for most targets peak neutron production always precedes peak fuel compression.[4] Since our measurement of areal density occurs at the time of peak neutron production, the peak fuel density should be greater than that inferred from this measurement.

Experimentally, it is impossible to count all the aluminum-28 atoms formed in the reaction.[7] Since the amount of activity created is also usually very low, it is important to have very efficient collection and detection equipment. The short half-life also requires rapid transport of the activated debris from the target chamber to the radiation detector.

The number of aluminum-28 atoms ultimately counted depends on:

- The fraction of total target debris collected η_c.
- The time delay between production and counting t_d.
- The detection-system efficiency η_d.
- The counting period Δt.

If we take these factors into account, we find that the number of detected events N_c is related to the total number of aluminum-28 atoms produced in the implosion N^* by

$$N_c = N^* \eta_c \eta_d (1 - e^{-\lambda \Delta t}) e^{-\lambda t_d}, \qquad (3)$$

where λ is the aluminum-28 decay constant ($0.309\ \mathrm{min}^{-1}$).

There are several constraints on the design of a target-debris collector.[7] A collector that totally encompassed the target, and thus could collect all the debris, would overheat from the large energy and power deposited in the target by the laser pulse. In any event, such a large collector would be incompatible with the requirements for rapid removal, transport, and detection. The collector must therefore be small and be located some distance from the target. Since determining the number of detected events relies on coincidence counting of beta and gamma emissions from the collector, the collector must also be thin enough to pass beta particles without much loss in energy. Furthermore, it must be made of a material that forms a minimum of interfering radioactivity under neutron bombardment.

Figure 3 shows one design that satisfies these constraints. It consists of a 20-μm-thick foil of 99.9995%-pure titanium lining the

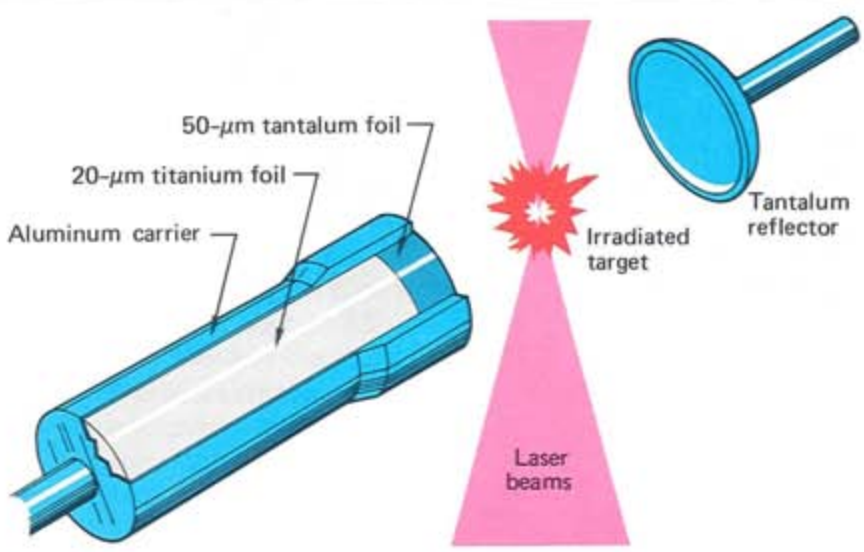


Fig. 3 *The target-debris collector for neutron-activation experiments at the Shiva laser facility. When the target explodes, part of the radioactive debris is absorbed on a 20-μm-thick foil of 99.9995% pure titanium that lines the inside of the hollow aluminum cylinder. We cover the first 3 cm of the titanium foil with a tantalum foil 50 μm thick to minimize blast damage. The tantalum reflector on the other side of the target redirects debris toward the collector, enabling us to collect 55% of the total.*

inside of a cup-shaped aluminum carrier. The carrier is 4.6 cm in diameter and 14 cm long. To protect the leading edge of the foil from blast damage we covered the first 3 cm with a 50-μm-thick tantalum foil. We placed the open end of the collector 1 cm from the target, where it subtends 30% of the total solid angle.[7]

Opposite the collector and 2.5 cm from the target we positioned a dish-shaped reflector 4.6 cm in diameter lined with tantalum foil. It subtends 13% of the total solid angle and serves to redirect some of the debris back toward the collector. Tests show that less than 1% of the debris attaches itself to the reflector.

We have severe difficulties in predicting exactly what fraction of the capsule debris will be collected, partly because more debris blows off in some directions than in others and partly because the debris may fail to stick when it first strikes the collector. These difficulties make it necessary to measure the fraction of collected debris.[7]

To do so, we exposed glass microspheres to thermal neutrons in our research reactor. About 5% of the atoms in the glass are sodium, and neutron capture converts some of them into radioactive sodium-24. The 15-hour half-life of sodium-24 makes it possible to count the activity of an actual target microsphere, then irradiate it with the Shiva laser and collect the debris in the same way as for the normal microspheres, and count the collected activity. We then found the collected fraction by comparing the collected activity with the total for the microsphere. Our underlying assumption is that sodium adheres to the collector in the same way and to the same extent as aluminum. We are planning experiments to verify the accuracy of this hypothesis.

Figure 4 shows our experimental arrangement for automatically removing the collector from the target chamber and transporting it rapidly to a shielded counting facility in the basement of the Shiva

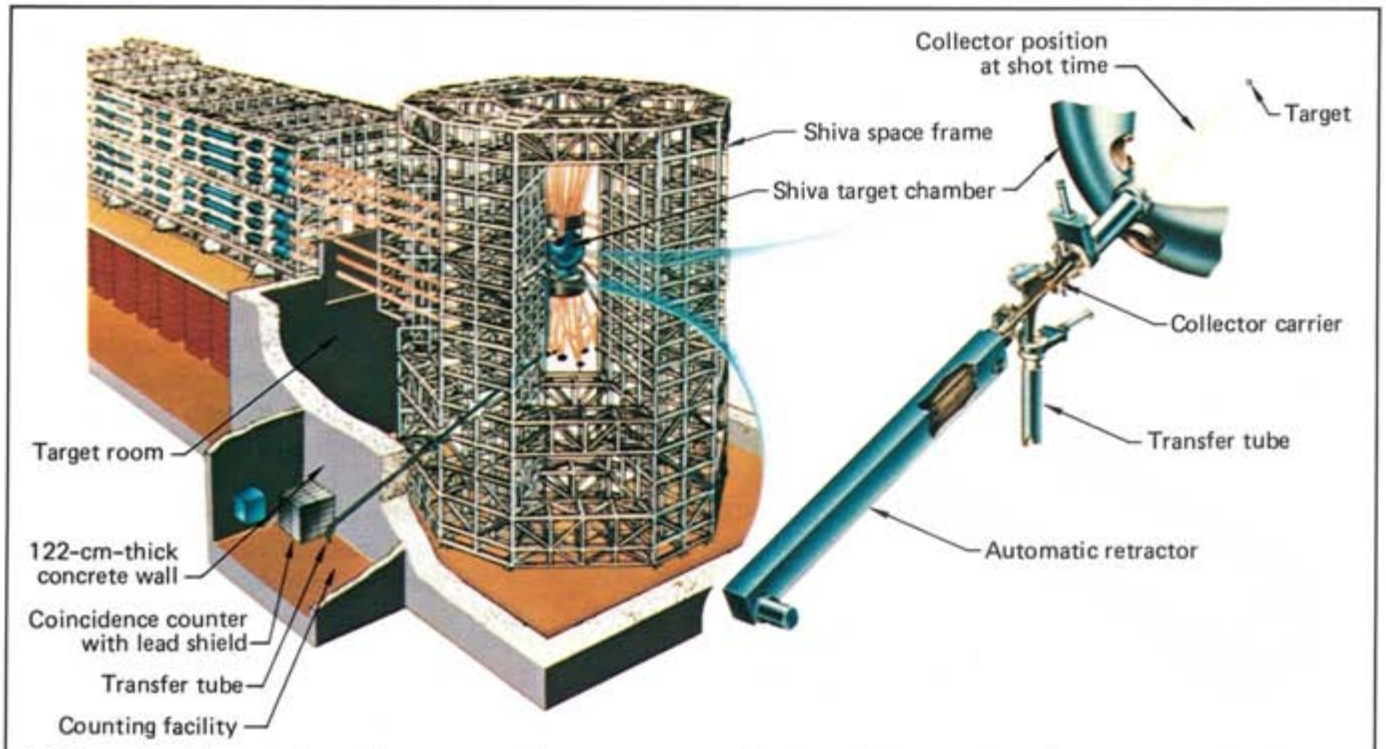


Fig. 4 *The experimental arrangement for neutron-activation measurement of pusher areal density at the Shiva laser facility. The mechanism places the foil-lined transfer capsule near the laser target during irradiation and then automatically retracts it and sends it to a shielded counting facility. Elapsed time between the laser shot and arrival of the foil at the counting station in the basement (far removed from the catcher) is 17 s.*

building. With this system we have reduced the time between the laser shot and the arrival of the collected sample at the counting station to 17 seconds.

Since some target designs make only a few hundred activated atoms to begin with (i.e., N^* in Eq. (2) is only a few hundred), it is important to minimize the background count rate and the delay from the shot to the start of counting, and to maximize the collected fraction and the detection efficiency. To do this, we use beta–gamma coincidence counting of the aluminum-28 activity.[5] Figure 5 shows the large well detector (a thallium-activated sodium iodide scintillator) for gamma counting and a unique 4π fluor for beta detection. The sodium iodide detector has a measured absolute efficiency of 43% for detecting the aluminum-28 1.78-MeV gamma ray. The 4π fluor counts aluminum-28 beta particles, out to their maximum energy of 2.86 MeV, with an overall efficiency of 95%.

The beta-detecting fluor consists of a plug (around which we wrap the collector foil) and a socket (to contain the plug). With the fluor in the well of the sodium iodide detector, we can count aluminum-28 decays with an absolute detection efficiency of 40%. A ring of Geiger–Mueller tubes operated in anticoincidence with the beta–gamma system acts as an active background shield.

To reduce the background further, we placed the entire assembly inside a 10-cm-thick lead cave in the Shiva basement under a 30-cm concrete overburden. With the system just described we routinely obtain background counting rates of 0.3 to 0.4 counts per minute. We are able to remove

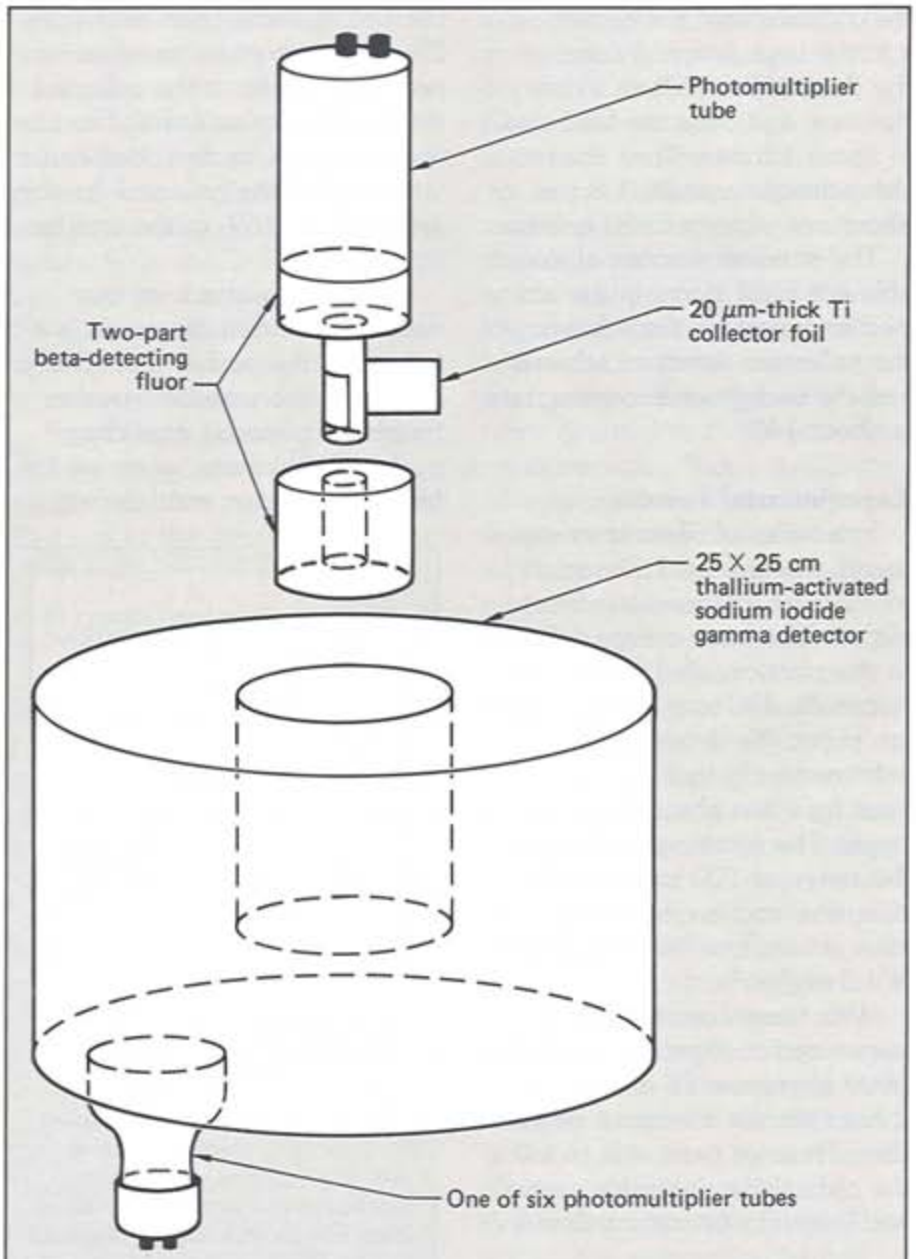


Fig. 5 *The 4π beta-gamma coincidence counting system used to detect low levels of short-lived radioactivity in the collected debris from a Shiva target implosion. We place the collector foil in the central cylinder, a special fluor for high-efficiency beta detection. Surrounding it is a large thallium-activated sodium-iodide crystal scintillator for detecting the gamma rays emitted simultaneously with the beta particles in the decay of aluminum-28. The detector system is enclosed in a ring of Geiger-Mueller tubes (not shown) operated in anticoincidence with the beta-gamma counter, and this ring in turn is surrounded with lead and concrete shielding. Background counting rates are 0.3 to 0.4 counts per minute. The overall absolute efficiency for detecting aluminum-28 decays is 40%.*

the collector from the carrier, place it in the beta-detecting fluor, insert the fluor in the sodium iodide detector, and close the lead shield in about 1.5 min. Thus the total delay time is typically 1.8 min, or about one aluminum-28 half-life.

The smallest number of detectable activated atoms in the entire pusher, based on the efficiency of the collection-detection scheme and the background counting rate, is about 140.

Experimental results

In a series of Shiva laser experiments, we have used this technique to examine intermediate-density targets. The laser energy delivered to the plastic-coated targets was nominally 4 kJ in a 200-ps Gaussian pulse. We determined calorimetrically that 20% of the laser light was absorbed in the target. The resulting yields were in the range of 200 to 800 million neutrons, and average areal densities at burn time[4] were about 5.9 $\pm$ 1.5 mg/cm^2.

With these conditions each target irradiation produced 4000 to 6000 aluminum-28 atoms, far more than the minimum detectable. Thus we were able to follow the radioactive decay for several half-lives (Fig. 6) and confirm that the counts came from aluminum-28 and not from some other contaminant activity in the collected debris or the collector foil. The auxiliary experiments described earlier indicate that the collected fraction was 55.3 $\pm$ 0.5% of the total activity.

As a further check on our neutron-activation diagnostic, we measured the pusher areal densities of some exploding-pusher targets. In previous exploding-pusher experiments, when we inferred the pusher areal density from measurements of alpha-particle energy losses, we found it to be in good agreement with computer-simulation predictions. Our newly measured pusher areal density was 0.69 mg/cm^2, which was also in good agreement with simulation predictions (0.65 to 0.75 mg/cm^2). In addition, the inferred fuel densities are in agreement with the densities inferred from alpha-particle data obtained with a Fresnel zone plate.

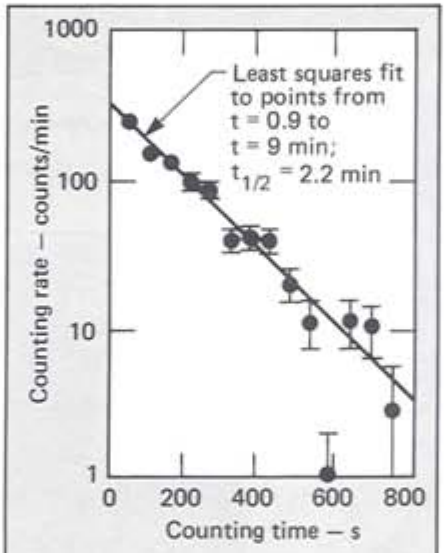


Fig. 6 *Beta-gamma coincidence counting rate as a function of time after irradiation of a target in the Shiva laser. The 2.2-min half-life observed is in good agreement with that of aluminum-28, providing added confirmation that we are indeed counting activity resulting from neutron irradiation of the silicon-28 in the glass pusher.*

Analysis

To derive fuel densities at burn time for the intermediate-density targets from neutron-activation measurements of pusher areal density, we compared our experimental results with a family of computer calculations (Fig. 7). By varying the physical assumptions used to generate these calculations, we found that a moderate range (an overall factor of 2 or 3) of D–T fuel density can be associated with any given areal-density value of the pusher.[4]

Also shown in Fig. 7 are the results of a simple theoretical model: the isothermal–isobaric pusher approximation. This model makes the following assumptions:

- The imploded pusher and fuel are still spherical at the time of neutron emission.
- There is no pusher–fuel mixing.
- The pusher and fuel have uniform, though different, densities.
- The pusher and fuel are both at the same temperature and pressure.

The last assumption constrains the compressed fuel density to be related to the pusher density by the

equations of state for pusher and fuel. The temperature of the D–T is determined with sufficient accuracy by the neutron yield because the reaction rate varies rapidly with temperature at about 1.0 keV,

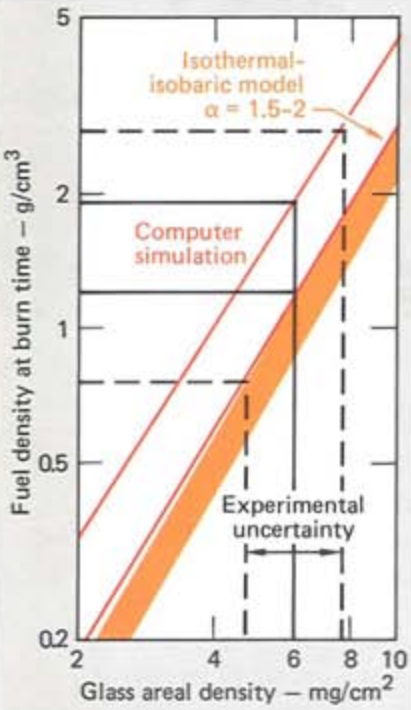


Fig. 7 *The relationship of areal-density measurements to fuel density on the intermediate-density targets. Computer calculations provide a range of fuel densities consistent with each particular areal density. Our simplified isothermal-isobaric model (based on the assumption that the fuel and pusher are at the same pressure and temperature at the time of peak neutron emission) also yields values for fuel density that are in reasonable agreement. From glass areal densities obtained with plastic-coated targets (5.9 ± 1.5 mg/cm²), we can thus infer final average fuel densities at peak neutron production of 1.2 to 2 g/cm³ (6 to 10 times the density of liquid D-T). The average result of the experiment, 5.9 mg/cm², is shown as well as the upper and lower limits due to experimental uncertainty (dashed lines).*

which is the temperature for the intermediate-density targets. For this temperature, the D–T equation of state is a perfect gas at densities less than 100 g/cm^3 (degeneracy correction is negligible). The pusher density ρ_p is thus calculated to be α times the D–T fuel density ρ_f at burn time. Inspection of the SiO_2 equation of state at 1.0 keV and relevant pressures shows that α is between 1.5 and 2.

From these simple arguments and by using typical values for pusher and fuel masses, we find that (using the conservative value of $\alpha = 2$)

$$\rho_f > (2000)[(\rho\Delta R)_p]^{3/2}. \qquad (4)$$

The inequality sign reminds us that computer calculations indicate that there will be additional compression after the peak of neutron production.

Figure 7 shows that the range of this simple model (corresponding to $\alpha = 1.5$–2) intersects much of the family of computer calculations. For example, the average pusher areal density of 5.9 mg/cm^2 yields a compressed fuel density of 1.0 to 1.2 g/cm^3.

Future applications

We are now developing a straightforward extension of these techniques to measure two simultaneous areal densities. This involves coating the glass microspheres with a material (such as copper) that has an easily distinguishable activity after neutron bombardment. Copper-63 (natural abundance, 69%) has a large cross section at 14 MeV for producing copper-62 (half-life 9.7 min). Copper-62 decays by an easily detectable positron emission.

Copper confers a further advantage; copper-63 can be activated by thermal-neutron capture to produce copper-64 (12.7-h half-life). Experiments using copper activities to determine the collected fraction would use the same element counted in the areal density measurements. They would involve no assumptions about collection efficiencies for different elements.

There are several advantages to measuring the areal densities of two separate layers simultaneously. When inferring the fuel density from a single areal density, the computer model must juggle several adjustable parameters. With two simultaneous areal densities, the permissible ranges of those parameters become more restricted. Also, the denser outer layer is more susceptible to electron preheat, and comparing the areal densities of the two layers may help us measure this effect. It may also be possible in future targets to investigate implosion stability and pusher–fuel mixing by neutron activation of multiple shells.

Another important possible application is measuring the fuel's areal density directly instead of relying on computer models. To do

this, we would add a readily activated seed gas such as bromine, argon, or nitrogen to the D–T fuel. We estimate the amount needed at only 30 kPA (about 0.6% of the fill) to reach the detection threshold of our equipment.[8] If bromine were used as the seed gas, we could attempt these measurements with only a slight improvement in the performance of high-density targets. Argon and nitrogen would require considerably greater improvement in performance before we could attempt the measurements.

Summary

The pusher areal density of inertial fusion targets at the time of maximum neutron production can be measured by counting the number of aluminum-28 atoms produced by the bombardment of silicon-28 with fusion neutrons. We have demonstrated the techniques for collecting, retrieving, and counting the target debris. Once the pusher areal density has been measured, we can infer the fuel density from either simple physical arguments or computer modeling. We used this neutron-activation diagnostic in a series of experiments on Shiva to show that average fuel densities at peak burn of about 2 g/cm^3, with individual experiments reaching up to 3 g/cm^3, have been attained by irradiating plastic-coated targets with 20-TW, 200-ps pulses from the Shiva laser.

This diagnostic technique appears exceedingly versatile. We are planning soon to extend the technique to simultaneous activation of multiple shells and direct measurements of D–T fuel areal density. It is apparent that neutron activation will be an increasingly important tool in diagnosing the performance of inertial fusion targets.

Key words: ablative compression; areal density; exploding pusher; inertial fusion (IF); neutron activation.

Notes and references

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