LOW-ENERGY CHARGED-PARTICLE FUSION REACTIONS

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Summary

We have initiated a program at Los Alamos to measure cross sections for the charged-particle reactions \( \text{D}(\text{t},\text{n})\text{He} \), \( \text{T}(\text{t},\text{2n})\text{He} \), \( \text{D}(\text{d},\text{n})\text{He} \), and \( \text{D}(\text{d},\text{p})\text{T} \) that are fundamental to the understanding of controlled thermonuclear fusion. Interest in these processes is primarily in the region below 100-keV bombarding energy, and accordingly the design range for the measurements is 10-120 keV. Our desired accuracy is 5% or less, compared with present systematic uncertainties of up to 50%. The experiment features a negative ion source and highly stable injector for the low-energy beam, measurement of beam intensity with a precision calorimeter, a windowless cryogenic target, calibration of the target density with a high-energy Van-de-Graaff beam, and a time-of-flight laser spectrometer to determine the absolute energy. Preliminary data have also been obtained on the \( \text{d} + \text{d} \) reactions while preparations are underway for introducing tritium into the system.

Introduction

Renewed interest in measuring the fusion reaction cross sections needs little justification. As fusion reactor design calculations become more accurate, the basic fusion data on which reaction rates are based become more important.

Jarmie et al. have given a detailed report on data discrepancies for the basic fusion reactions \( \text{T}(\text{d},\text{n})\text{He} \), \( \text{T}(\text{t},\text{2n})\text{He} \), \( \text{D}(\text{d},\text{n})\text{He} \), and \( \text{D}(\text{d},\text{p})\text{T} \) in the 10-120 keV bombarding energy region. This energy range corresponds, for the \( \text{T}(\text{d},\text{n})\text{He} \) reaction, to temperatures of an interacting \( \text{d} + \text{t} \) plasma of 0.5 to 20 keV, where early fusion reactions are likely to operate. Ref. 1 also shows that errors in the reactivity, based on the cross-section data, would propagate proportionately into fusion probability errors in reactor calculations.

The discrepancies in existing data sets do not inspire confidence in our knowledge of the basic cross sections for these important reactions. The findings of Ref. 1 may be summarized as follows:

1. For the \( \text{T}(\text{d},\text{n})\text{He} \) reaction, four experiments have been carried out in the energy range below 100-keV laboratory bombarding energy with stated errors from 2-10% absolute accuracy. Discrepancies of 10-30% are present between these experiments at energies of overlap, presumably arising from energy shifts between the measurements in an energy region where the cross-sections are changing exponentially. Complicating the comparisons are results on the \( \text{T}(\text{d},\text{p})\text{T} \) reaction by some of the same authors, using the same equipment, which indicate possible energy shifts in the opposite direction. Although the \( \text{t} + \text{d} \) plasma is the most promising fuel for first-generation reactors, new cross-section measurements have not been published for almost 20 years, or, in the United States, for 26 years.

2. The cross-section data for the \( \text{D}(\text{d},\text{p})\text{T} \) and \( \text{D}(\text{d},\text{n})\text{He} \) reactions are in much better shape, although the most accurate measurements below 100 keV are 26 years old. These reactions show significant angular anisotropy all the way down to 10 keV, and comparisons between total and differential cross-section measurements have relied on corrections for this effect. Nevertheless, the agreement appears to be satisfactory at the 10-15% level of accuracy.

3. Cross sections for the \( \text{T}(\text{t},\text{2n})\text{He} \) reaction are also based on four major experiments, but the laboratory bombarding energies go down to only 30 keV and, as might be expected, the discrepancies are large. The most recent measurements, from 1962-1977, were all performed in the Soviet Union, while the only US experiment was published in 1951. The interest in this process stems from reactions in a tritium plasma and the possibility of monitoring the emitted neutron flux as a diagnostic of initial ion temperature in a Tokomak fusion reactor.

The objective of our program is to measure absolute cross-sections for these hydrogen-isotope reactions from 10 to 100 keV. The experimental approach consists in using a source of negative ions to bombard a windowless, cryogenically pumped gas target. The beam intensity is determined by calorimetric means, and the important beam-energy measurement is to be facilitated by a laser-photodetachment, time-of-flight technique. The target density is calibrated by using scattering or reactions of known cross sections induced by 10-15 MeV particles from the LASL Van de Graaff accelerator. A schematic diagram of the experiment is shown in Fig. 1, and a photograph of the apparatus appears as Fig. 2.

10-120 keV Ion Beam

The dual-polarity ion source and injector system was built by General Ionex Corporation to LASL specifications. The beam originates in a standard duoplasmatron and 30-kV extraction lens, which can be operated to extract either positive or negative ions. This beam is focused by a 14-cm-diameter einzel lens through a crossed-field analyzer to a crossover at the top of an accelerating column. In the negative-ion mode, the crossed-field analyzer sweeps out the intense electron beam that accompanies the negative ions from the source, reducing current drain on the acceleration HV power supply and eliminating much of the x-ray hazard that would be generated by accelerating electrons to high energy. In the positive-ion mode, the \( \text{d} \) and \( \text{t} \)-atomic molecular ions are rejected by the crossed-field analyzer, not only reducing the load current on the HV power supply, but also minimizing the gas escaping from the terminal region. This is important for the differential pumping system described later.
The accelerating tube is a low-gradient multi-electrode structure providing low optical-strength coupling to ground potential. The final beam energy is determined by a highly-stable 0-120 kV power supply between the duoplasmatron and ground. This system allows the beam energy to be altered without affecting the extraction mechanism, and thus the beam current available and the terminal focusing is essentially independent of beam energy over a broad range. The beam, which is diverging as it exits the accelerator, is refocused by a second einzel lens to a minimum beam waist at a position beyond the exit of the 45° sector double-focusing analyzing magnet. This magnet analyzes the ion beam and bends it onto the target-chamber axis, which is also the axis of the beam line from the tandem Van de Graaff accelerator.

The beam size is delimited by a set of 4-way slits at the waist position and then focused into the target chamber by a third einzel lens. Negative hydrogen beams of 50-μA intensity and 15-mrad divergence have been obtained through a 3-mm-diameter aperture. The intensities are less for deuterium and tritium beams and for energies below 20 keV. Although positive beams of greater intensity can be produced, the negative beam is preferred for tritium because neither the crossed-field analyzer nor the inflection magnet can separate T+ ions from 3He+ which might also be extracted from a positive-ion duoplasmatron.

Vacuum System and Tritium Handling

The vacuum systems have been designed for safe handling of tritium gas, which will eventually be required in both the ion-source and target systems. A 500-l/sec turbomolecular pump, connected to the...
source einzel lens by a 30-kV insulated flange, evacuates the gas escaping from the duoplasmatron. A special 70-l/sec Hg booster pump with a forepressure tolerance of greater than 20 Torr backs the turbopump to increase the hydrogen pumping speed and allow direct recirculation of the gas to the ion source. A servo valve and pressure controller regulate the recirculated gas by maintaining a constant pressure in the arc region of the duoplasmatron. A similar system has been successfully employed for several years on the LASL polarized triton source. In addition to minimizing consumption of tritium gas, the recirculation system allows mounting of the high-vacuum pump at terminal potential.

When the injector is shut down, the gas is directed to a cryogenic collection system where the tritium is absorbed in charcoal-filled cylinders kept in dewars of liquid nitrogen. For periods when tritium is not being used, the vacuum exhaust from the collection system is directed through a mechanical forepump and bellows pump to a 10-meter-high stack, where it is combined with ventilation exhaust and continuously monitored for tritium.

Vacuum systems at the inflection magnet and on the target chamber are similar, but since these are at ground potential the vacuum exhaust goes directly to the collection system. The Hg booster pumps permit pressure in the charcoal traps to rise to 20 Torr before requiring replacement. In addition to the turbomolecular pumping, gas from the windowless target is pumped cryogenically on surfaces in the target cooled to 4K by liquid helium.

Target and Detector Chamber

A gas target with windowless beam entrance and exit ports is employed in order to reduce the uncertainty in beam energy that would be introduced by a foil window or solid target. The target cell is cooled to near hydrogen liquefaction temperature, increasing target density to about 10¹⁶/cm³ and reducing leakage from the open ports. Surfaces maintained at 4K by a liquid helium dewar surround the target and pump the gas exiting from the ports. An 80K cylinder surrounds the pumping surfaces for thermal shielding. Fig. 3 is a photograph of the target pot and cryogenic surfaces.

In addition to the 3-mm-diameter entrance and exit beam collimators, detector collimators are placed at angles of 45⁰L, 45⁰R, 75⁰R, 90⁰L, 120⁰R, and 150⁰L, where L and R stand for left and right of the beam axis as indicated in Fig. 4. The fusion reactions under study all have large positive Q-values, which allow thin foils to be used over the detection ports to reduce gas leakage without appreciably slowing down the reaction products. Silicon surface-barrier detectors are mounted in a support ring that is cooled by a thermoelectric device. Both ΔE and E detectors can be used in coincidence in order to reduce backgrounds and aid in particle identification when necessary. This is more important for the high-energy experiment used for calibration than for the low-energy beam. Fig. 5 shows typical spectra obtained under the two beam-energy conditions. An on-line computer is used to store the spectra and record most of the experimental data.

Constant target density conditions are achieved by a flow system employing an automatic pressure controller on a buffer volume and a mechanical leak and digital flowmeter to regulate flow to the target.

Beam Calorimeter

Because of charge exchange in the target, the beam intensity must be measured with a calorimeter. Our design follows that of Thomann and Benn for low-energy p-p scattering experiments. Referring to Fig. 6, the beam from the target, consisting of positive, negative, and neutral components, enters the 2.5-cm-
Fig. 5 Panels (A) and (B) show particle spectra obtained at the lab angles 45° and 130° when 10-MeV protons bombard deuterium gas. Panels (C) and (D) show particle spectra obtained at the lab angles 45° and 150° when 100-keV deuterons bombard deuterium gas.

BEAM CALORIMETER

Because of the exponential decrease in fusion reaction cross sections as a function of energy below 100 keV, the determination of incident beam energy and energy loss in the target gas are crucial to the experiment. The energy of our beam is determined by the 0–120 kV power supply which is stable to 15 V with respect to standard line, load, ripple, and temperature variations. We have also installed a precision resistor stack and digital voltmeter on the source terminal and have calibrated these instruments at the Sandia Laboratory Standards Facility, traceable to the National Bureau of Standards. We believe the source voltage is known to about 15 V absolute, well within the approximately 30 V estimated spread from the duoplasmatron.

Fig. 6 Beam calorimeter used to measure the low-energy beam intensity. The design is from Ref. 3 and has an absolute accuracy of better than 0.1%.
As a second check on the beam energy, and in order to investigate the total energy spread of the beam from the source as well as energy loss in the target gas, we are exploring a time-of-flight measurement using a pulsed laser. The apparatus mounted behind the target in Fig. 2 is designed to implement this technique, but has not yet been completely developed. The negative component of the beam emerging from the target is bent 30° into a 2-m-long tube. A Nd:YAG laser pulse at a wavelength of 1 μm will photodetect electrons from the negative beam, and a 2.5-cm diameter microchannel plate detector at the end of the tube will detect the resulting neutral beam pulse. The charged beam is swept away by a magnetic field after the laser interaction region. Flight times of about 1 μsec are expected for 20 keV deuteron beams, and the time resolution for the laser pulse and microchannel plate will be better than 1 nsec. Thus an independent check on the beam energy should be possible to a level of at least 0.1%.

Experimental Results

During a series of test measurements on the D(d,p)T reaction, we have achieved the following conditions necessary for the success of the experiment: (1) accurate control of the ion-source potential and beam optics, (2) steady target gas flow rate, (3) steady target temperature, (4) high beam transmission through the target, (5) reproducible calibration of the calorimeter, (6) demonstration of sufficient counting rate, and (7) low background in the high-energy D(p,p)D calibration experiment. These tests have yielded a set of preliminary D(d,p)T angular distributions from 40 to 118 keV with relative errors from 2 to 7% and a scale error of about 12%. These errors are expected to improve. Fig. 7 shows the data at 80 keV with a curve from the previous R-matrix evaluation of Hale and Dodder. For these results, the data are normalized to the curve by a single angle-independent factor.

After further study and calibration using the d + d system we will accelerate tritons to measure d + t and finally flow tritium in the target to study the t + t reaction.

Future Experiments

We have been considering, and have had suggested to us by others, experiments to be performed with this apparatus after our work on basic fusion reactions is completed. In brief, some of the areas under consideration are: backscattering experiments for surface analysis, (t,n) and (d,n) studies on a variety of targets for diagnostic applications in magnetic fusion devices, experiments of astrophysical interest, and use of the laser capability to investigate a variety of atomic processes.

Acknowledgments

We would like to acknowledge the participation of G. G. Ohlsen in the conception and design of the experiment, particularly in the laser method for beam-energy determination. The work of Rudy Martinez and Walter Sondheim has been essential in the construction of the equipment.

Fig. 7 Preliminary D(d,p)T cross sections at 80 keV. The errors shown are due to counting statistics and average ± 2.7%.

References


