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Ionization of Fast He^0 in the Triplet Metastable State*

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Cross sections have been measured for production of He^+ ions by the collision of 10- to 30-keV He^0 atoms in the triplet metastable state with target atoms of Xe, Kr, H_2, N_2, Ar, Ne, and He. Fast He^0 atoms are produced in the first of two gas targets in which various neutralizer gases may be present at low density. The fractions of He^0 produced in the triplet metastable state in these various neutralizer gases are known. The fraction of fast He^+ emerging from a second target containing Xe, Kr, H_2, N_2, Ar, Ne, or He is analyzed as a function of the density of the second gas target, and the cross sections for ionization of He^0 atoms from the metastable triplet state are determined. Typical values of the cross sections at 30 keV are 110 ± 40, 37 ± 17, 122 ± 58, 86 ± 42, 18 ± 12, and 65 ± 31 in units of 10^{-17} cm^2 for gas targets of Xe, Kr, H_2, N_2, Ar, Ne, and He, respectively.

Measurements of the production and loss of fast He^0 in the metastable triplet state have been reported for He^+ incident on targets of Xe, Kr, H_2, N_2, Ne, and He.[1-3] From these measurements one can calculate the cross sections for production of fast He^0 atoms in the triplet-metastable state when fast He^+ is incident on one of the various gas targets. In addition, the total cross section for destruction of fast He^0 atoms in the triplet metastable state during collisions with gas-target atoms can be derived. The total cross section for the destruction of fast metastables can be written as $\sigma_{t+}+\sigma_{ts}$, where σ_{t+} represents the cross section for production of He^+ from fast He^0 in the triplet metastable state incident on a gas-target atom, and σ_{ts} represents the cross section for production of fast He^0 in the ground state from fast He^0 in the triplet metastable state during collisions with a gas-target atom. It would be useful to have measurements of σ_{t+} and σ_{ts} individually rather than only as the sum $\sigma_{t+}+\sigma_{ts}$. This paper reports measurements of σ_{t+}, the cross section for production of fast He^+ from fast metastable triplet He^0 colliding with targets of Xe, Kr, Ar, He, H_2, and N_2. The energy range for this experiment was 10–30 keV.

The apparatus is the same as that described previously.[1,2] It consists of an ion source, focusing and steering fields, a gas target for neutralizing the He^+ beams, beam-collimating apertures, a second gas target for ionizing the fast He^0 beam, and beam-measuring equipment. The density of gas in the second target is monitored by an RCA ion gauge located in an auxiliary chamber connected to the gas-target chamber by a small aperture. The auxiliary chamber is pumped externally. We find that the readings on the RCA gauge are proportional to the pressure in the target chamber but are much lower than the actual pressure in the target chamber. The proportionality of the RCA gauge readings to the pressure in the target chamber was verified by the fact that the yields of the charge changing reactions discussed later in this paper were linear with the reading of the RCA gauge. The calibration of the actual target pressure in terms of the reading on the RCA ion gauge is described later in this paper. The density of the first target is measured with an ion gauge. At low densities of the first target, the density does not have to be known accurately since the fraction of triplet metastable He^0 atoms produced in the first target divided by the fraction of all neutrals produced in the first target is nearly independent of density for the low densities used.

The measurements were carried out as follows. A fast He^+ beam enters the first gas target. The first target contains He gas. The beam is partially neutralized by charge changing collisions with the He atoms of the first gas target. The fast He^0 emerging from this He target is known to be almost entirely in the ground state.[1,2] We assume that the fast He^0 beam is produced entirely in the ground state. Upon emerging from the first target, the charged particles remaining in the beam are swept out of the beam with a transverse magnetic field. The remaining fast He^0 beam enters a second gas target consisting of Xe, Kr, H_2, N_2, Ar, Ne, or He. The intensities of fast He^+ and fast He^0 atoms emerging from the second target are measured. There was no measurable He^- or He^{++} produced in the second target. The density of the gas in the second target was monitored with the RCA ion gauge located in the auxiliary chamber.

This procedure is then repeated, but with a gas such as Xe, Kr, H_2 or, N_2 at low density in the first gas target. The He^+ is again partially neutralized in the first target. The fast He^0 produced in the first target contains atoms in both the triplet metastable state and in the singlet state. The ratio of fast He^0 in the triplet metastable state to the total fast He^0 emerging from the first gas target, $F_t^1/$

$F_0{}^1$, is known from previous measurements, [1,2] and $F_t{}^1/F_0{}^1$ is independent of the pressure in the first target as long as the pressure is low.

A typical set of data is shown in Fig. 1. In Fig. 1 the fraction of the He beam emerging from the second target as He^+ when low-density Xe is used as the second target F_+^2 is plotted as a function of the pressure measurements indicated by the RCA ion gauge. The incident He^0 has an energy of 30 keV. The upper plot is the result of using low-density Xe as a neutralizer in the first target. The lower plot is the result of using low-density He gas as a neutralizer. The pressure measurements are proportional to the thickness of the second gas target.

Barnett and Stier[4] have measured the cross sections, σ_{0+} for ionization of fast He^0 in gas targets of H_2, N_2, Ar, Ne, and He for fast He^0 with energies from 4–300 keV. They used a thick-H_2 neutralizer for production of fast He^0. The ratio of triplet metastable to ground-state He^0 atoms emerging from a thick-H_2 target is small at the energies used in our experiment.[1,2] Therefore, we assume that the cross sections they report in the energy range 10–30 keV are the cross sections for producing He^+ from fast He^0 in the ground state σ_{S+}. With this assumption σ_{t+} is derived from our data as follows. The production of He^+ in the second target is measured when the first target is thin, first using a He neutralizer, and then using a low-density neutralizer such as Xe, Kr, N_2, or H_2 which produces a known fraction of triplet metastable atoms. For both cases F_+^2 is plotted versus the pressure readings on the RCA ion gauge. The gas density is proportional to the ion-gauge reading p, hence, $\pi = \alpha p$, where π is the target thickness in molecules/cm^2 and α is a constant.

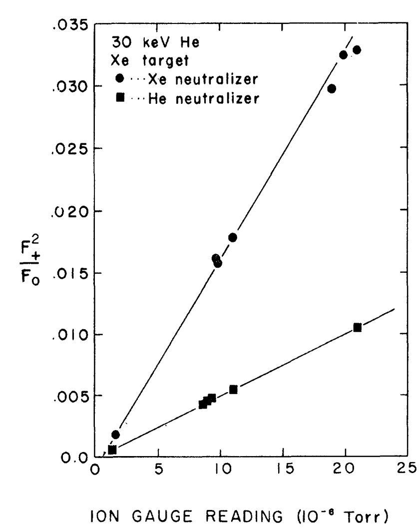

FIG. 1. The fractions F_+^2 of fast He^+ produced in low-density Xe in the second gas target.

When F_+^2 is produced from fast He that has been neutralized in a He target,

$$F_+^2/\alpha p = \sigma_{S+} .$$

Therefore, α is just equal to this initial slope divided by Barnett and Stier's value for σ_{S+}. This measurement calibrates the actual density of the second gas target in terms of the reading of the RCA ion gauge.

When F_+^2 is produced from fast He^0 that has been neutralized in thin targets of Xe, Kr, H_2, or N_2, the following equation determined σ_{t+}:

$$F_+^2/\alpha p = \sigma_{t+}(F_t^1/F_0^1) + \sigma_{s+}(1 - F_t^1/F_0^1) \ ,$$

where F_+^2/p is just the initial slope of a plot of F_+^2 versus p when a known fraction of the incident fast He^0 beam, F_t^1/F_0^1, is in the triplet metastable state.

Fogel *et al.*[5] have measured σ_{0+} for fast He^0 incident on Xe and Kr targets. The fast He^0 was produced in a mercury-vapor neutralizer. If we assume that their values of σ_{0+} are equal to σ_{S+}, we can find σ_{t+} for Xe and Kr by the same procedure that was discussed above. The values of σ_{0+}, reported by Fogel *et al.* in Xe and Kr, are used as σ_{S+} in the equations given above. This procedure may be subject to error, however, since Fogel *et al.* do not give any information about the thickness of this neutralizer, the fraction of fast metastable atoms emerging from their neutralizer, or about the uncertainties present in their results. If better values can be obtained for σ_{S+} for targets of Kr and Xe, then σ_{t+} can be redetermined using the improved values of σ_{S+} in the analysis of our data.

Table I lists the values of σ_{t+} measured in the gas targets Xe, Kr, H_2, N_2, Ar, Ne, and He for energies of the incident He^0 between 10–30 keV.

When σ_{t+} is measured for H_2, N_2, Ar, Ne, and He targets, using the value of σ_{0+} given by Barnett and Stier as σ_{S+}, the largest source of uncertainty is the uncertainty in the values of F_t^1/F_0^1.[1,2] These uncertainties ranged from 40% for 30-keV He^0 incident on Xe and Kr to 50% for 10-keV He^+ incident on Xe, Kr, H_2, and N_2. In addition, there is an uncertainty of approximately 10% in reading the slope of the graph of F_+^2 versus the pressure measurements of the RCA ion gauge. There also is a 10% reported uncertainty in the measurement of σ_{S+} by Barnett and Stier. When σ_{t+} is measured for Xe and Kr targets, the uncertainty in σ_{S+} is not known since Fogel *et al.* reported no estimate of their uncertainties. In addition, as discussed previously, the assumption that the σ_{0+} of Fogel *et al.* is equal to σ_{S+} may not be accurate. Hence, the reported uncertainties in σ_{t+} for Xe and Kr targets include only the uncertainties in $F_t{}^1/F_0{}^1$ and the uncertainties in measuring the slopes of

TABLE I. The ionization cross sections for He^0 in the triplet metastable state incident on gas-target atoms.

He energy (keV)	σ_{t+} (10^{-17} cm^2/molecule) Xenon	Krypton	Hydrogen	Nitrogen	Argon	Neon	Helium
10	130 ± 60	14 ± 8	23 ± 12	5.6 ± 3.7	21 ± 10	1.8 ± 1.8	3.6 ± 3.6
15	100 ± 50	19 ± 9	60 ± 29	28 ± 16	23 ± 11	12 ± 9	5.7 ± 5.7
20	160 ± 70	13 ± 7	43 ± 21	48 ± 20	25 ± 12	9 ± 6	34 ± 17
25	180 ± 80	32 ± 12	130 ± 63	53 ± 27	74 ± 38	16 ± 9	57 ± 27
30	110 ± 40	37 ± 17	122 ± 58	71 ± 34	86 ± 42	18 ± 12	65 ± 31

the graphs of the data.

In general, σ_{t+} seems to be about as large as $\sigma_{t+}+\sigma_{ts}$, and it seems reasonable to assume that at these energies σ_{t+} provides a major contribution to the total cross section for destruction of fast He^0 in the triplet metastable state.

Unfortunately, although the values for the sum $\sigma_{t+}+\sigma_{ts}$ and for σ_{t+} have been measured in separate experiments, a value for σ_{ts} cannot be determined. This is because the value for σ_{t+} is almost as large as $\sigma_{t+}+\sigma_{ts}$, and because the combination of the uncertainties for the individual measurements of σ_{t+} and of $\sigma_{t+}+\sigma_{ts}$ is too large to ascertain a meaningful difference between these two values.

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Nuclear Fusion Reactions in Solid-Deuterium Laser-Produced Plasma

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When focusing a 4-GW, fast-rise-time, nsec-range laser onto a solid deuterium target, neutron production is observed. We give evidence for nuclear fusion reactions, measure the electronic temperature, and estimate the number of neutrons for each laser shot.

Nanosecond laser pulse heating of solid-state deuterium targets has been carried on in our laboratory for three years. Evidence for electron temperatures of up to 500 eV was reported earlier.[1–3]

In order to deal with experimental results, a tractable theoretical model was devised.[4] It predicts a plasma temperature proportional to the two-thirds power of the incoming light flux, which is in fair agreement with electron-temperature measurements. Since 500 eV were found with only 1 GW, it was expected that a higher power would lead to plasmas in which a significant amount of nuclear DD reactions would occur.

Our approach to the problem of kilovolt plasmas produced by laser irradiation of a solid target is