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Differential Charge State Fractions of He Following Ionization by Fast H^- Projectiles

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Abstract

The differential charge state fractions of He ions produced in ionization by fast H^- projectiles have been measured at projectile scattering angles between 0.25 and 1.59 mrad and an impact energy of 1.0 MeV. These charge state fractions have been measured for each of the possible final charge states of the H^- projectile (H^-, H, and p^+). Combined with earlier measurements of simple ionization (no change in projectile charge state) by protons and of capture and ionization by protons, some systematics can be noted. The fraction of doubly charged He ions exhibits a distinct peak between 0.9 and 1.1 mrad for simple ionization . A similar peak is seen at $\approx$ 0.55 mrad for ionization accompanied by either capture by protons or by single stripping of H^-. The data for proton impact suggest that all the peaks are related to double ionization of the target. The double ionization mechanisms will be discussed in terms of their possible contribution to the observed structures.

Electron-electron correlation effects in ion-atom collisions have recently attracted increasing attention[1,2]. Such correlation effects are most generally described as deviations from the independent electron model (IEM). Within the IEM, each electron is assumed to move independently of the other electrons in the average potential of all the electrons and the nucleus. The IEM has been successfully used to model many single and multiple electron processes. However, numerous deviations from this model have also been observed [e.g. 1,3,4]. These correlation effects are generally assumed to be due to Coulomb interactions between the participating electrons. The many-body systems which exhibit correlation effects are not easy to model [2]. It is hoped that a greater understanding of correlation will help simplify the analysis of these many body systems.

The challenge facing experimentalists is to unambiguously identify correlation effects in ion-atom collisions. One method used to reduce the difficulty of this task is to observe two-electron processes in two-electron systems. The double ionization of He atoms by fast, bare projectiles is an example of one such process which has been extensively studied. Even in this simple system, the observation of double ionization does not by itself isolate the effects of electron correlation. More information, such as the dependence of the cross sections on the projectile charge [5] or on the projectile scattering angle [4] is needed.

It is useful to briefly consider some possible double ionization mechanisms. One mechanism, called the two-step-two (TS-2), attributes the ionization to consecutive, independent collisions of the projectile with each He electron and does not require any correlation of the electrons. Another, the two-step-one (TS-1), involves a collision between the projectile and a target electron followed by a subsequent collision between this recoiling electron and the remaining electron. This process contains a strong, dynamic correlation of the electrons. The TS-1 mechanism is similar to the shake-off (SO) mechanism, where there is no direct collision between the two electrons. Instead, the second ionization is a result of a final-state rearrangement following an initial binary collision between the projectile and the first electron. This rearrangement can be attributed to the initial 'static' correlation of the two electrons [2].

The present work was motivated by the results of Andersen et al. [3] on the double ionization of He by protons, p, and antiprotons, $\bar{p}$. Antiprotons were found to be approximately twice as effective in doubly ionizing He as protons within a broad range of velocities around 10 a.u. In contrast, the single ionization cross sections at these velocities were nearly identical for p and $\bar{p}$. The difference in the double ionization results was attributed to an interference of the TS-1 and TS-2 mechanisms, which produced a Z^3-dependent term in the cross section. These results have also been successfully interpreted as a charge-state-dependent correlated adjustment of the electron motion due to the presence of the projectile during the collisions [6,7,8]. This adjustment for $\bar{p}$ is such as to increase the probability of ionizing one of the electrons on the condition that the other electron is also being ionized. This is effectively a TS-2 process where the two projectile-electron collisions are correlated. With the present information, it is not obvious which of these explanations is preferable.

Additional information on this collision system can be determined by measuring the cross section differential in the projectile scattering angle. The probability for double ionization of He by fast protons accompanied by capture shows a sharp peak at a scattering angle, θ, of 0.54 mrad [4]. This peak was tentatively explained in terms of a second-order mechanism analogous to TS-1. A similar broader peak has been observed for the simple double ionization of He by protons at $\theta \approx 0.9$ mrad [9]. This peak, however, was not easily explained in terms of the proposed double ionization mechanisms. Andersen et. al. [10] have also measured the double ionization of He by H^- in coincidence with the final charge state of the projectile. They found that when the H^- projectile retained both of its electrons, the ratio of double ionization to single ionization by H^- was nearly identical to that for $\bar{p}$. We therefore found it reasonable to measure the differential cross sections for double ionization of He by a H^-.

The experiment was conducted using the apparatus shown in fig. 1. An H^- beam from the Aarhus 5MV Van de Graff was collimated and then charge state purified using the magnet M1. The beam next passed through a differentially pumped gas cell and then through deflectors which were used to separate the charge states of the beam. The projectiles were detected with a solid-state surface-barrier detector. This detector could be moved to observe the desired charge state. The configuration shown in fig. 1, for example, was used for the neutral product, H. The scattering angle was determined by annular apertures which screened the detector. The aperture for each angle was individually centered on the beam. The angular resolution given by the apertures varied from 25% for the smallest angle to 10% for the largest. During the early data acquisition, it was observed that the angular distributions were broader and perhaps distorted in the horizontal plane when compared to the vertical plane and compared to previous measurements [9]. The horizontal plane is the plane of action for the cleaning magnet M1, the recoil extraction system, and the post collision deflectors. Although ideally none of these devices should have focussing properties, it was decided to only use the scattering distribution in the vertical plane. An additional 'bow-tie' mask was used to further screen the detector.

The slow He recoil ions were extracted electrostatically from the gas cell. The He charge states were then spatially separated using the magnet M2. The recoil ion spectra were measured in coincidence with the scattered projectiles as a function of the time-of-flight difference and of the spatial dispersion of the recoil ion charge states. This double separation of the charge states significantly improved the reals-to-randoms ratio for the doubly charged ions. The ratio between the number of coincidences with He^+ ions and the total number of He^+ ions is equal to $\frac{d\sigma^+}{d\Omega}$ divided by the total cross section for formation of He^+. The latter cross section is known [11] and can be used to extract absolute cross sections. The single-ionization process is relatively well understood [3], and so we choose to present the differential charge state fraction $F_2(\theta) = \sigma^{++}/(\sigma^{++} + \sigma^+)$.

The differential fraction of doubly charged He ions produced in collision with H^- at 1.0 MeV are shown in Fig. 2 for all possible final states of the projectile: H^-, H, and H^+. For comparison Fig. 3 contains the charge-state-fractions of He following simple ionization by protons [9] and following ionization and capture by protons [4]. The later data is for a collision energy of 0.5MeV, but our earlier studies [4,9] showed that the locations of the structures in these spectra are only weakly dependent on the collision energy. It should be noted that the differential F_2 values are considerably larger than the total F_2 values for these processes which are 0.67% for simple ionization, 1.1% for ionization and single stripping, and 2.4% for ionization and double stripping. This indicates that the present angular region is beyond the region of very small scattering angles which dominates the total cross sections.

Let us first consider the case of simple ionization where there is no change in the projectile charge-state. The charge state fractions for ionization by H^- [fig 2(a)] and p [fig. 3(a)] both peak at approximately 0.95 mrad, although the peak for H^- is narrower and falls off more rapidly above the maximum. It is perhaps surprising that it is possible to scatter an H^- to these large angles without stripping an electron. A previous analysis of the total single stripping cross section for H^- on He successfully modeled H^- as one tightly bound electron and one loose electron [12]. The ratio of the orbital velocity of the loosely bound electrons to the transverse velocity given to the scattered H^- is much larger than 1.0. Therefore, it is reasonable for the H^- to survive scattering to these large angles. The similarity of these spectra suggests that the physical mechanisms for doubly ionizing He may be the same for H^- and H^+ projectiles at these large scattering angles. The double ionization by H^+ and H^- could indeed proceed via exactly the same proton-electron interactions, where in the case of H^- the projectile electrons are inactive spectators. The p/H^- differences in the total F_2 values [10] would then be due to large impact parameter (small angle) collisions. It is tempting to extend this conclusion to the

$p/\bar{p}$ differences. However, at the small impact parameters (large angles) observed here, the H^- ion most probably does not appear to the He target to be similar to the point-like $\bar{p}$.

It is not obvious that any of the proposed double ionization mechanisms can explain the peak seen for simple ionization. The structure in both cases comes at larger angles than the maximum scattering angle of a proton off a free electron, θmax=0.545 mrad. Therefore, the peak cannot be due solely to the TS-1 or SO mechanisms. Assuming these two projectile-electron collisions in TS-2 are independent, there is no reason to expect a peak from this mechanism. Two of the double ionization models which depend on a correlated adjustment of the electron motion to the projectile [6,7] are formulated in the impact parameter formulism and could yield angular differential F_2 values. These models could be considered as a correlated TS-2 mechanism and as such might explain the structures at angles larger than θmax. It is also possible that the nucleus-nucleus scattering plays an important role in reaching these large scattering angles. The TS-2 mechanism, for example, favors the small impact parameters which can produce large angle nucleus scattering. Finally, the structure may be a result of interference between some of the proposed mechanisms.

Next let us compare ionization with single stripping of H^- (fig. 2b) to ionization with single capture by H^+ (fig 3b). The spectra are similar in that both peak at about 0.6 mrad. However, the structure in the case of ionization and capture is much narrower and reaches very much higher F_2 values. This is due to the kinetic restrictions of capture in the TS-1 model, which produce a critical angle [13]. There are no such restrictions for ionization and stripping. Therefore, the similarity in this spectra is most probably coincidental. It is worth noting that the exiting projectile is in both cases neutral. However, a simple estimate shows that the absence of post-collision scattering produces a negligible difference in scattering angle at this high energy. We should also point out that the projectile electron can be stripped via a collision with a target electron, which could certainly ionize the target electron. This opens another double ionization mechanism where the target electrons are ionized in uncorrelated independent collisions with the projectile and with one of the projectile electrons. The collision of a projectile electron with a target electron does not change the projectile scattering angle. The addition of this mechanism might explain the smaller scattering angles of ionization with stripping compared to simple ionization. However, it does not help explain the observed structure itself.

Finally, consider the case of ionization with double stripping [fig. 2c]. The target may now be doubly or singly ionized without any strong projectile nucleus-target electron collisions. This would produce an F_2 relatively independent of θ as observed.

A structure has been observed in the fraction of doubly charged He ions produced in simple ionization by H^-. This structure is quite similar to that previously observed in simple ionization by H^+. Although neither structure can be explained in terms of the proposed double ionization mechanisms, their similarity suggests that the differences seen in the double ionization of He by protons and antiprotons may be due to large impact parameter collisions not studied here.

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Figure Captions

Figure 1: A schematic of the apparatus: (a) top view, and (b) side view showing details of the recoil extraction system.

Figure 2: Charge-state fraction F_2 of He recoil ions produced in collisions with H^- at 1.0 MeV. (a) simple ionization, (b) ionization accompanied by single stripping of H^-, (c) ionization accompanied by double stripping. The curves are drawn to guide the eye.

Figure 3: Charge-state fraction F_2 of He recoil ions produced in collisions with protons. (a) simple ionization at 1 MeV (ref. 9), (b) ionization accompanied by single capture at 0.5 MeV (ref. 4). The curves are drawn to guide the eye.

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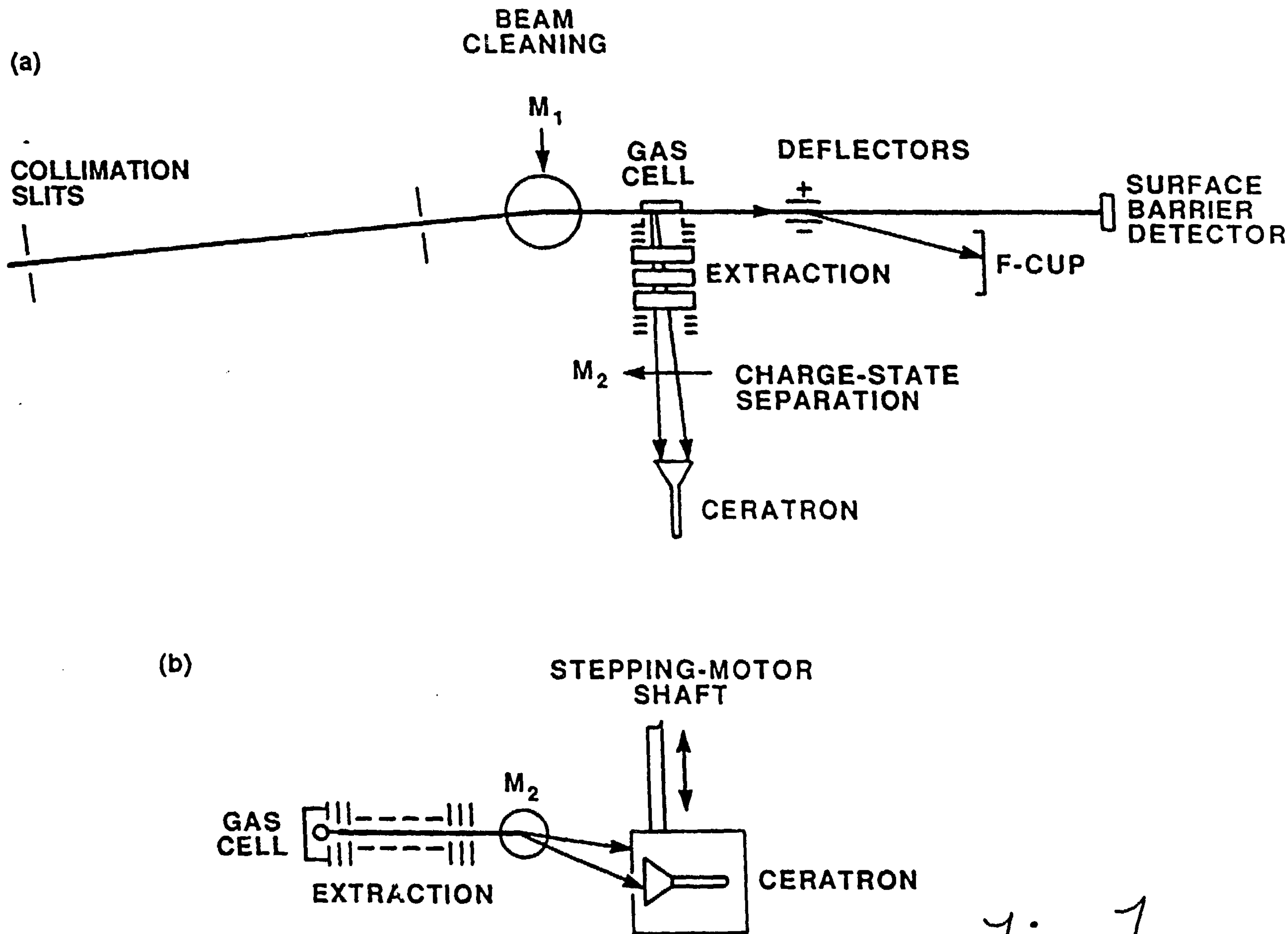
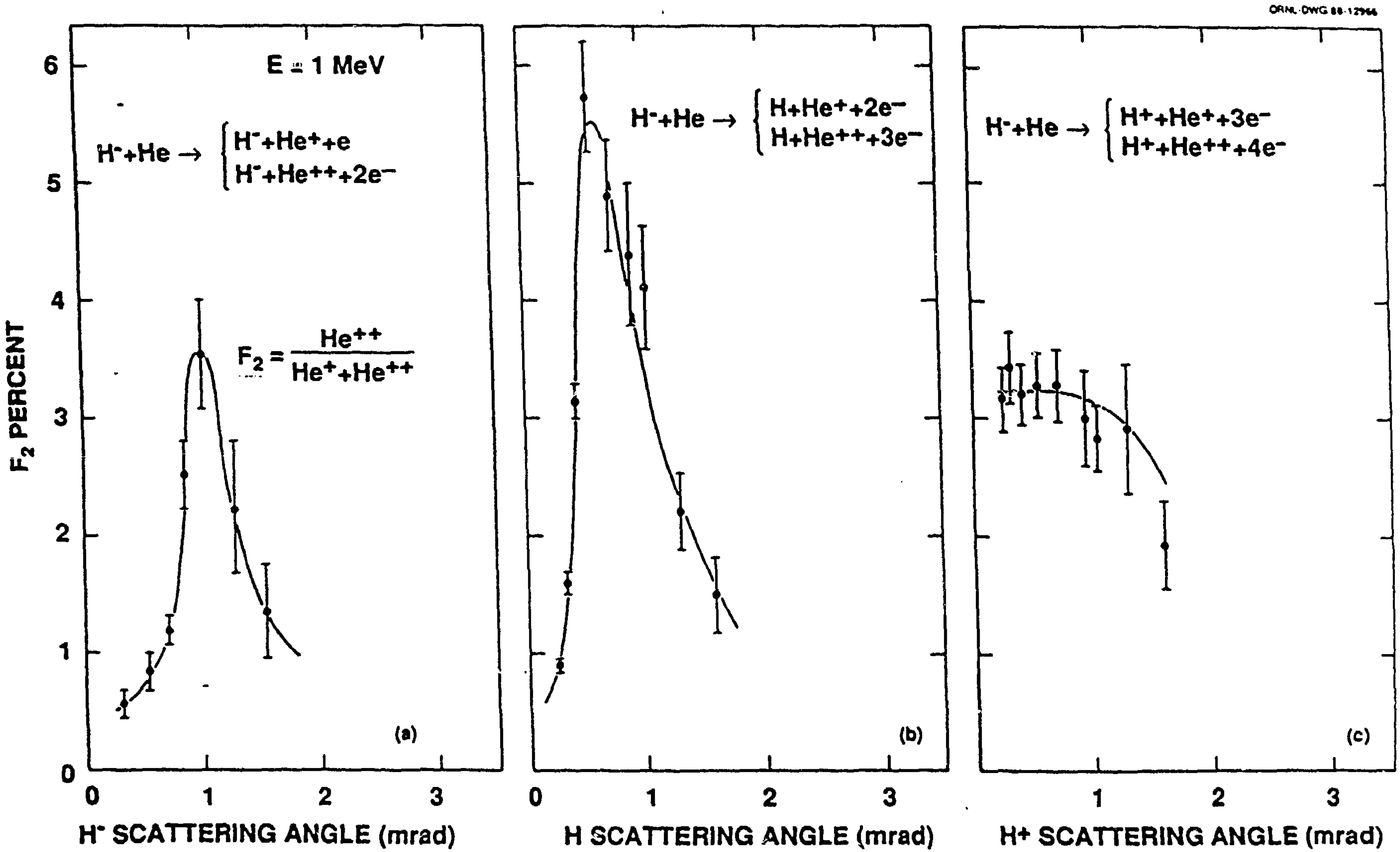


Fig. 1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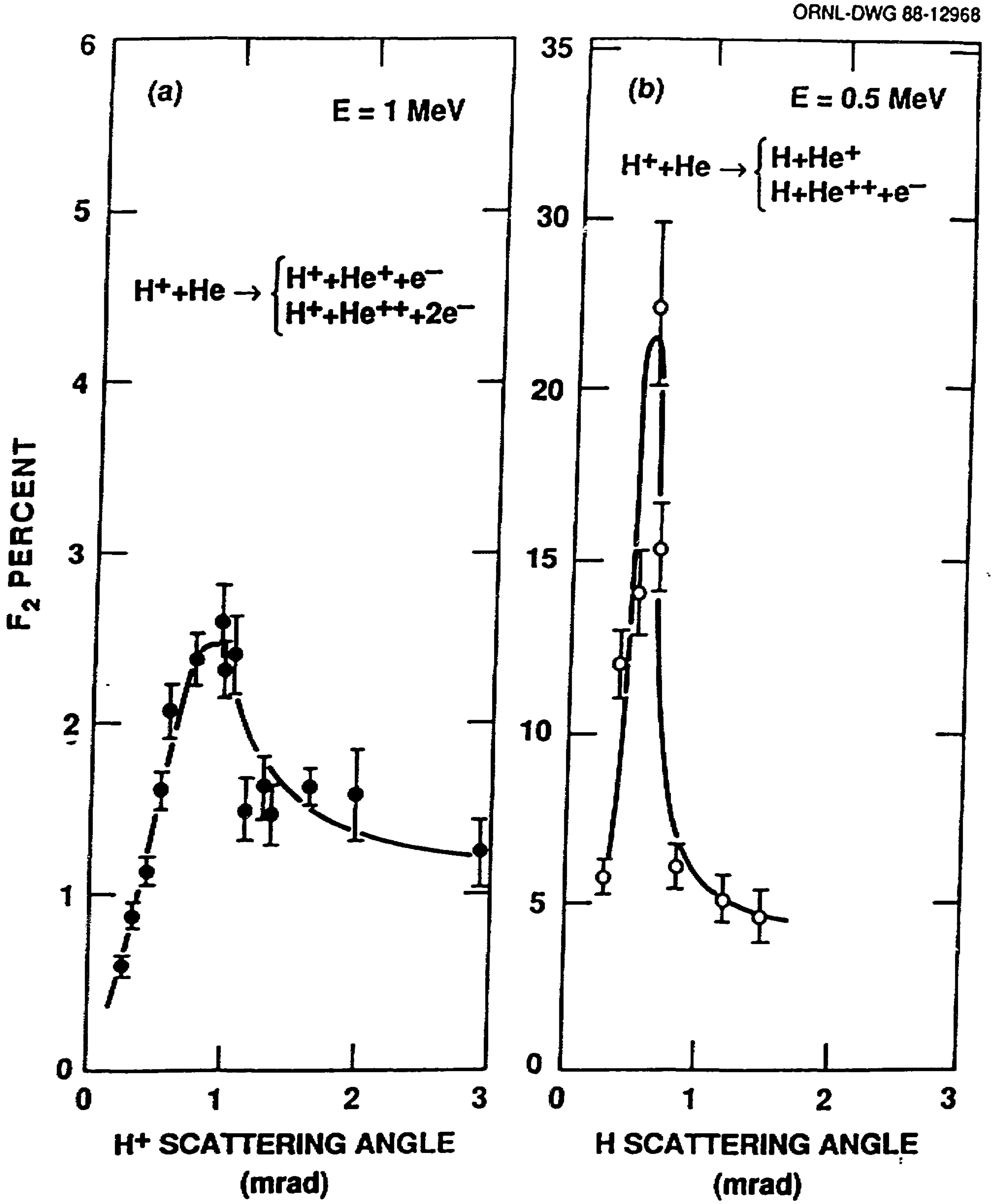
E = 1 MeV
H⁻+He → H⁻+He⁺+e
H⁻+He⁺⁺+2e⁻
F2 = He⁺⁺ / He⁺+He⁺⁺
H⁻+He → H+He⁺+2e⁻
H+He⁺⁺+3e⁻
H⁻+He → H⁺+He⁺+3e⁻
H⁺+He⁺⁺+4e⁻
F2 PERCENT
(a)
(b)
(c)
H⁻ SCATTERING ANGLE (mrad)
H SCATTERING ANGLE (mrad)
H+ SCATTERING ANGLE (mrad)

Fig. 2



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(a)
E = 1 MeV
$H^+ + He \rightarrow \begin{cases} H^+ + He^+ + e^- \\ H^+ + He^{++} + 2e^- \end{cases}$
F_2 PERCENT
0
1
2
3
4
5
6
H^+ SCATTERING ANGLE (mrad)
(b)
E = 0.5 MeV
$H^+ + He \rightarrow \begin{cases} H + He^+ \\ H + He^{++} + e^- \end{cases}$
0
5
10
15
20
30
35
H SCATTERING ANGLE (mrad)

Fig. 3