Dissociation of fast HeH^+ ions traversing thin foils*

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Distributions in energy and angle have been measured for the breakup products created when thin foils are bombarded by energetic beams of HeH^+. The resolution in both energy and angle is greatly improved over that previously used in such studies. This permits the observation of several new features. The results can be explained in terms of the electric field experienced by the trailing ion (of the two produced in the molecular breakup) when it finds itself in the polarization "wake" created by its partner.

Measurements and calculations were recently reported[1] for the distributions in energy and angle of the dissociation products created when tightly collimated beams of fast molecular ions bombard thin solid targets. At the energies employed (~1 MeV per nucleon) one expects that the electrons binding an incident molecular ion will be torn off within the first layer or two of atoms encountered in the target, and that the remaining molecular constituents will then continue as a cluster of bare nuclei exploding apart under the influence of their mutual Coulomb repulsion. The measurements revealed large and previously unknown departures from the results expected for clusters undergoing simple Coulomb explosions. An explanation for these differences was suggested in terms of the electric field experienced by the trailing ion in a cluster when it finds itself in the "wake"[2-4] (polarization wave induced in the target) of the leading ion. We have extended these studies using a new apparatus with greatly improved resolution in both energy and angle. This has permitted the acquisition of detailed data for a great variety of molecular-ion beams and targets. Our measurements reveal many features previously not resolvable, and in addition confirm the earlier observations. We report here on some new results found for the dissociation of HeH^+ ions incident upon various target foils.

The experimental arrangement is indicated schematically in Fig. 1(a). The energies of the dissociation products were determined with a 25° electrostatic analyzer having a relative energy resolution of 6×10^{-4}. Angular distributions for the charged products were measured by use of electrostatic deflectors placed just downstream from the target foil. The divergence of the incident beam was ±0.005°, and the angular acceptance of the electrostatic analyzer was ±0.008°.

Figures 1(b) and 1(c) show distributions in energy and angle for protons arising from 3.5-MeV HeH^+ ions incident on a carbon foil. Qualitatively similar data were obtained for the α particles that also arise, but the peaks were not so well resolved, since the α particles emerge inside a much narrower cone about the beam direction.

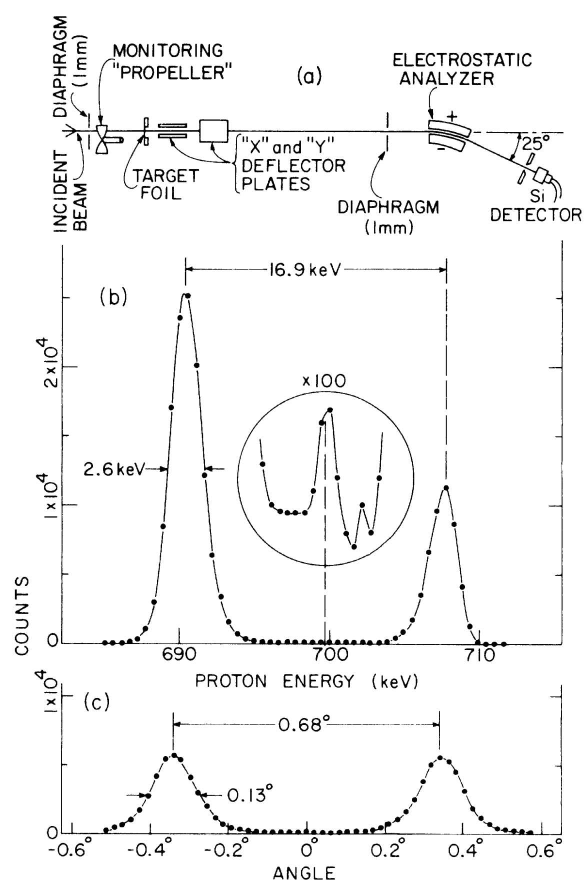

FIG. 1. (a) Experimental arrangement. (b) Energy spectrum measured in the beam direction for protons emerging from a 200-Å-thick C foil bombarded by 3.5-MeV HeH^+ ions. The uncertainty in the absolute energy scale is about 1 keV. The normal energy loss for 700-keV protons in the target is 1.2 keV. (c) Angular distribution for protons whose energies lie halfway between the two major peaks in (b).

A simple Coulomb explosion model[1] predicts that the emerging protons should be confined within a cone of half-angle $\theta_{max} = (\epsilon/E)^{1/2}$ centered on the beam direction. Here E is the kinetic energy of the proton in the incident beam (700 keV for the case shown in Fig. 1) and ϵ is the proton's share of the potential energy liberated in the Coulomb explosion [i.e., $0.8(2e^2/r_0)$, where r_0 is the initial internuclear separation]. After traversing a 200-Å-thick foil, the internuclear separation would be expected to have increased from about 0.8 to 1.4 Å. The same model predicts the existence of two equally populated energy groups at $\theta = 0$ separated by $2\Delta E_{max} = 4(\epsilon E)^{1/2}$. For protons for which $\Delta E = 0$, the angular distribution should exhibit two equally populated groups at $\pm\theta_{max}$. This simple picture will be modified when factors such as multiple scattering, electronic screening, and vibrations and rotations in the incident molecules are taken into account. For fast light projectiles traversing thin light targets, such modifications are expected[1] to be minor.

The data in Fig. 1 do, in fact, show many of the features expected from the simple model. The measured values of $2\Delta E_{max}$ and $2\theta_{max}$ both imply a value of $\epsilon = 25$ eV corresponding to $r_0 = 0.92$ Å. The ground-state equilibrium internuclear separation for HeH^+ is calculated[5] to be 0.77 Å. The difference between the two values may be largely due to the incident molecular ions arriving in various vibrationally excited states. That would have the effect both of raising the average value of r_0 and of giving rise to a wider distribution in r_0 than that obtaining for the ground state only. The measured linewidth (2.6 keV) in Fig. 1(b) corresponds to a full width at half-maximum (FWHM) of 0.5 Å in the distribution for r_0. (This agrees well with the value needed to fit previous channeling data.[1]) The line width (0.13°) in Fig. 1(c) can be totally accounted for by calculating the angular width (0.10°) implied by the linewidth of Fig. 1(b), and then adding in quadrature our measured width (0.08° FWHM) for the multiple scattering of 700-keV protons in the same target.

The most striking departures from the expectations based on a simple Coulomb explosion are in the relative populations of the peaks shown in Fig. 1. The large asymmetry in Fig. 1(b) confirms the result found earlier,[1] but with considerably more detail. There is an additional small peak at $\Delta E \approx 0$ whose origin is not yet understood. Possibly it arises from the breakup mode $HeH^+ \rightarrow He^0 + H^+$. This small peak is closer to the high-energy peak than to the low-energy one, indicating that protons in the low-energy group have suffered a larger energy loss. A further point of interest is the reduced population of the peaks in Fig. 1(c) as compared with those in Fig. 1(b). These features are illustrated in more detail in Fig. 2, which shows a complete distribution measured in both energy and angle. A simple Coulomb explosion model would predict a uniform intensity around the ring shown in Fig. 2. We believe that the asymmetry of the energy spectra for $\theta = 0$ is due to the interaction of the protons with the polarization wakes of their associated α particles for cases where the orientation of the incident molecule is such that the proton trails the α particle. In these orientations the electric field due to the wake deflects the proton towards the beam direc-

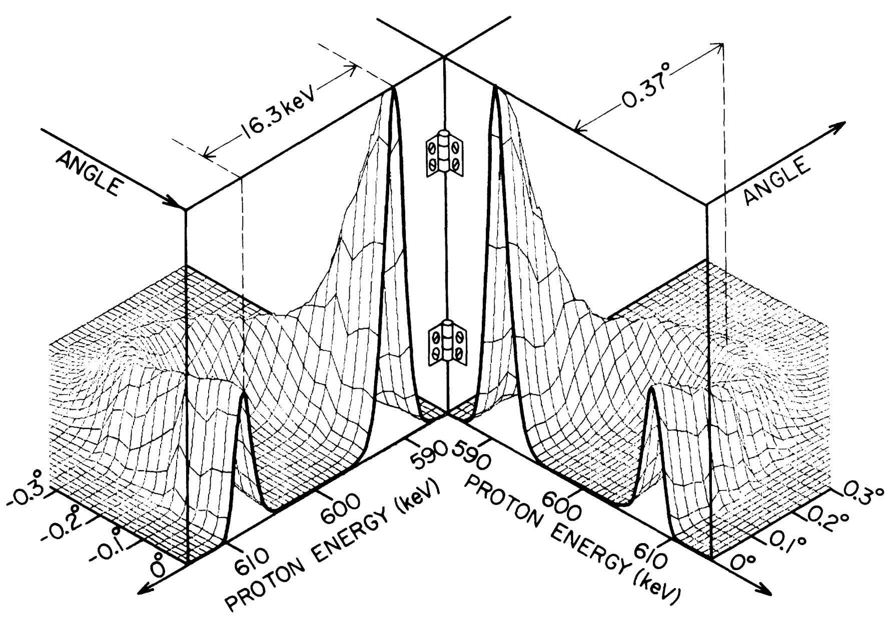

FIG. 2. Joint distribution in energy and angle for protons emerging from a 200-Å-thick C foil bombarded by 3.0-MeV HeH^+ ions. For ease in viewing, the distribution has been "opened up" about the vertical axis, as indicated by the hinges. The vertical scale, which has been omitted to avoid clutter, extends linearly from zero up to a maximum of 60 000 counts at the top of the highest peak in the distribution.

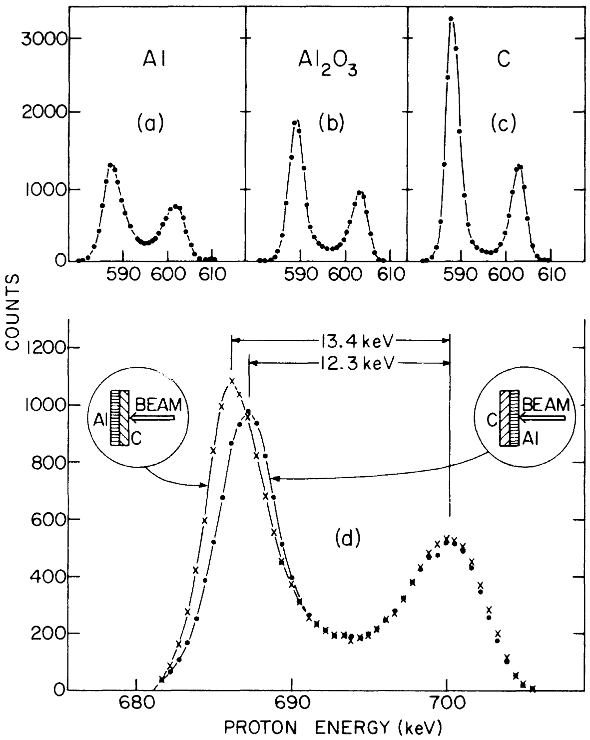

FIG. 3. Comparison of the proton energy spectra observed at 0° when foils of (a) Al, (b) Al_2O_3 and (c) C are bombarded by 3.0-MeV HeH^+. All three foils had a density of 20 $\mu g/cm^2$. The three spectra were accumulated for the same number of incident molecular ions. (d) Proton energy spectra observed at 0° when a double-layer target (10 $\mu g/cm^2$ C and 10 $\mu g/cm^2$ Al) is bombarded by 3.5-MeV HeH^+. Crosses, data obtained when the carbon layer faces the beam; open circles, data obtained for the same incident flux but with the target flipped 180°. The absolute energy scales are uncertain by about 1 keV.

tion. No such force acts on the proton when it leads the α particle. In Ref. 1 it is shown that the magnitude and direction of the wake force[4] are sufficient to cause the observed asymmetry. An additional feature seen here, viz., the depletion in the intensity of protons at larger angles, may be linked to the fact that for those initial orientations in which the internuclear vector is roughly perpendicular to the beam direction, the proton's deceleration (due to the combined wake forces) is expected to be about twice that of the α particle.

We have measured effects of the type described above for foils of conductors such as Be, C, and Al, which are known to sustain volume plasmons.[6] It is of interest to determine whether such phenomena can also be observed with an insulator such as Al_2O_3, where no plasma oscillations can exist. A comparison of results for Al, Al_2O_3, and C is shown in Fig. 3, from which it is apparent that an insulator does in fact exhibit these effects. Thus although the wake formalism developed for an electron gas[4] is not applicable, it nevertheless appears that a wake can be generated in an insulator. Presumably it is of the type originally contemplated by Bohr[2] in which bound target electrons are displaced in response to the passage of a charged projectile. In principle, knowledge of the frequency-dependent dielectric constant of the target material would permit calculation of the force due to the polarization wake.

Further evidence for the validity of the present interpretation of these effects is found in experiments that use a target composed of two layers of different materials and that compare results obtained by reversing the target with respect to the beam direction. Figure 3(d) shows the 0° energy spectra obtained for a carbon/aluminum target. The target layers are thick enough that the Coulomb explosion develops almost completely in the first material traversed by the beam. The high-energy peaks are identical for both target orientations, thereby reinforcing the idea that leading protons are not significantly affected by wake forces. Differences are seen, however, in the low-energy peaks, as would be expected for differing wake forces. In fact, the greater intensity in this peak, together with the increased separation between peaks observed when the beam enters the carbon layer first, is consistent with the larger plasmon energy for carbon (22 eV) as compared with aluminum (15 eV).[6] These results indicate the need for care in interpreting measurements[7] that show abnormal energy losses for fast clusters penetrating solids.

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[2]The concept of a polarization "wake" that trails behind a charged particle traversing a solid medium was introduced by Niels Bohr [see, for example, N. Bohr, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 18, No. 8 (1948)],

and has since been developed by several authors (see, e.g., Refs. 3 and 4) for the case of plasma oscillations excited in dense electron gases such as those presumed to exist in metallic conductors.

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