computer code OKIE for evaluating the matrix elements [Eq. (4)] and to Dr. Steven C. Pieper for sending an advanced version of the code PTOLEMY,[9] which allows the input of externally generated optical potentials in a finite-range, full-recoil DWBA calculation. One of us (R.J.A.) would like to thank Professor D. A. Bromley for the hospitality and support extended to him during the summer of 1978. This work was supported under the U. S. Department of Energy, Contract No. EY-76-C-02-3074.

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Survival of Fast Molecular Ions Traversing a Thin Foil

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Measured yields and energy distributions of H_2^+ emerging at 0° from the breakup of 2.2-MeV H_3^+ in 1.5–7-$\mu g/cm^2$ carbon foils suggest that, in traversing a solid at the same velocity, the lifetime for survival with the original electron is the same for H and H_2^+. Seen for the first time is a reversal in the 0° intensity asymmetry between the leading and trailing H_2^+ breakup fragments with changing target thickness which we interpret as the result of competing wake alignment and enhanced destruction mechanisms.

Recent studies[1,2] of neutral H atoms emerging from very thin carbon foils bombarded with MeV beams of H, H_2^+, and H_3^+ have suggested that an electron can be bound to a fast moving proton in solid and that such a system has a lifetime for survival of $(2.0\pm 0.1)\times 10^{-16}$ s.[1] In a further attempt to understand the implications of such a lifetime, we have studied the survival of H_2^+. Like the H atom, H_2^+ has only one bound electron of comparable binding energy but is presumably more fragile because of the presence of lower-energy dissociation channels. Rather than measuring the transmission of an H_2^+ beam in solid foils, we observed instead H_2^+ fragments from the breakup of H_3^+. In so doing we shed additional light on the H_3^+ breakup mechanisms as well as on the specific effects on molecular fragments caused by the perturbed electronic density behind a moving ion. We report here the new observed features.

In our measurements, a magnetically selected 2.2-MeV H_3^+ beam from a Van de Graaff accelerator was collimated to a total angular divergence of ≤ 0.2 mrad before striking the target consisting of carbon foils with thicknesses ranging from 1.5 to 7 $\mu g/cm^2$. Fragments of H_2^+ emerging within a 0.5-mrad cone centered in the beam direction were detected by a high-resolution magnetic spectrometer ($\Delta E/E \simeq 2\times 10^{-4}$).

Typical energy spectra of H_2^+ fragments emerging at 0° are displayed in Fig. 1 for three target thicknesses. The two outer peaks correspond to the trailing and leading H_2^+ fragments of the H_3^+ Coulomb explosions into $H_2^+ + H^+$. Noting that H_3^+ has a triangular shape,[3] the H_2^+ here are constrained by the detection geometry to be those whose internuclear axis is perpendicular to the beam direction. A new feature which has hereto-

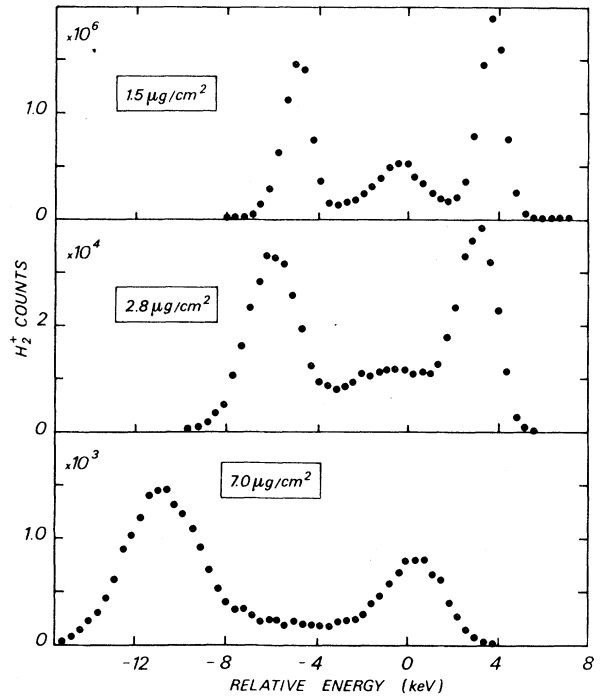

FIG. 1. Energy spectra of H_2^+ emergent at 0° following the breakup of 2.2-MeV H_3^+ in carbon foils of the thicknesses indicated and normalized to the same number of H_3^+. The zero in the energy scale refers to H_2^+ which neither received energy in the breakup process nor lost energy in the target and is taken to be the measured mean energy of H_2^+ produced in the breakup of the same H_3^+ in a thin gas target.

fore not been observed is the reversal of the asymmetric intensities of such explosion peaks with changing target thickness. Also evident is a central peak whose relative intensity decreases with increasing target thickness. The relative peak areas are displayed in Fig. 2(a) as a function of the target thickness and the corresponding dwell time t_D. From the 0° spectra, we have obtained the total yields of H_2^+ per incident H_3^+ based on the assumption that the H_2^+ are isotropically distributed in the c.m. frame. These estimated total yields are shown in Fig. 2(b). Note that the central-peak events contribute < 1% in all points here because of their much narrower angular distribution. Total H_2^+ yields from H_3^+ have been directly measured[4] previously but the results have comparatively larger spread as a result of the larger uncertainties in the target thicknesses used. The longer t_D results are nevertheless reproduced in Fig. 2(b) in order to show the general trend. That the two sets join smoothly indicates that the systematic errors in our converted data are not large.

In interpreting our data, we took note of the fact[1] that the cross section for loss of a valence electron is much larger than that for capture of a target electron at the present velocity. For a two-electron system like H_3^+ penetrating into a solid, we may expect that most of the H_3^+ are destroyed in a time period short compared to the t_D sampled here. Thus the H_2^+ observed for short t_D are direct products of the H_3^+ destruction and, implicitly, the electron attached to an H_2^+ is that of an incident H_3^+. Other processes that can lead to the formation of H_2^+ at emergence will involve target electrons and are expected to become dominant only at longer t_D. Such an interpretation seems to be a natural one if we are to simultaneously account for the large H_2^+ yield and the relative prominence of the central peak (in the 0° spectra) at short t_D and the changing systematic trend with t_D exhibited by the H_2^+ yield in Fig. 2(b).

Looking first at Fig. 2(b), the steep slope corresponds to an e^{-1} attenuation in a dwell time of $\tau_1 = (1.9^{+0.1}_{-0.2}) \times 10^{-16}$ s which, within the experimental errors, is the same as that observed[1] for the transmission of H atoms. Although the observed H_2^+ are actually fragments of H_3^+ breakup, the slope nevertheless reflects the attenuation of H_2^+ and is reminiscent of a radioactive decay in which the lifetime of the parent (H_3^+) is much shorter than that of the daughter (H_2^+). Interpreting the slope as a lifetime for survival with the original attached electron, the same value for H and H_2^+ implies that the destruction of a simple molecule in solid is akin to the loss of a comparatively bound electron in an atom.

Turning now to the central peak in the 0° spectra (Fig. 1), the near-zero peak energy at short t_D implies that the corresponding H_2^+ received little or no energy in the H_3^+ breakup process. The small energy shift can be attributed to the clusters' energy loss in the target. Two mechanisms can be advanced[2] to explain such a behavior. One is that of a violent collision in which only the partner of H_2^+ is deflected leaving H_2^+ as an unmolested spectator. This mechanism is relatively unimportant here because the central peak intensity is observed to increase with decreasing target thickness. The other is the nonrepulsive dissociation of H_3^+ into $H_2^+ + H$. Although this implies a transmission of clusters with two attached electrons, its probability at short t_D can nevertheless be finite though small. The fact that the central peak intensity is ob-

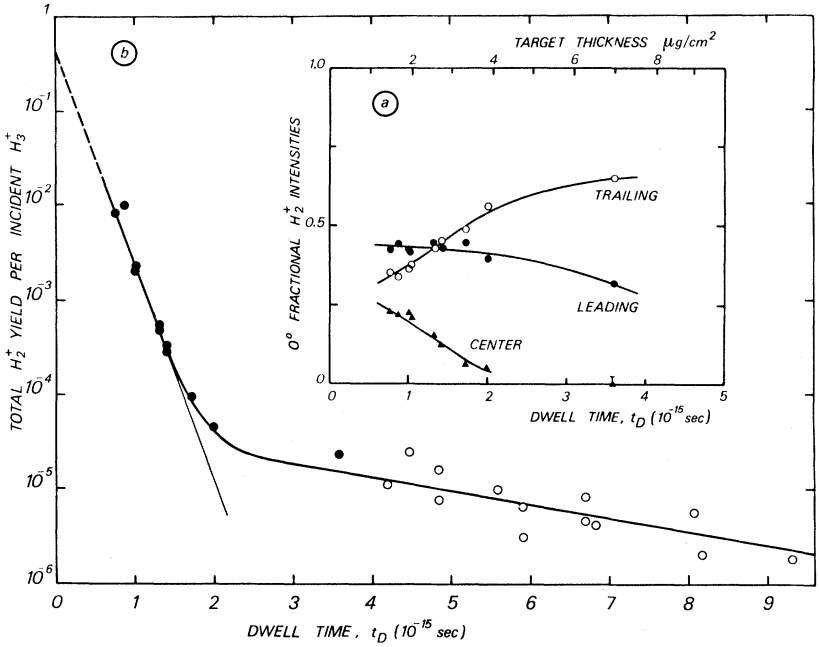

FIG. 2. (a) Fractional intensities of the three peaks in the 0° energy spectra of the H_2^+ fragments with the curves drawn to indicate the general trends. The relative and absolute uncertainties in the target thicknesses are estimated to be ±5% and ±10%, respectively. (b) Total yields of H_2^+ per incident H_3^+ converted from the measured 0° yields (closed circles) and the data of Ref. 4 (open circles). The relative uncertainties for the present set of data are estimated to be about ±15%.

served to be attenuated in a shorter t_D than that for the explosion peaks and that the corresponding angle integrated yield even at its largest value here constitutes only 0.6% of the total H_2^+ yield led us to conclude that dissociative events dominate the central peak.

With respect to the 0° intensity asymmetry of the explosion peaks, it is convenient to express the ratio of the intensities of the leading and trailing H_2^+ as an asymmetry factor $A = I_L/I_T$. Previously reported[5,6] asymmetry has been the $A < 1$ type and observed with atomic fragments. Such $A < 1$ asymmetry is successfully described in terms of polarization wake effects[6,7] whereby the leading ionic partner in the breakup induces along its track trailing polarization charges which create a potential tending to align the trailing charged partner towards the track. The attraction should be equally applicable to any trailing fragment so long as it has a net positive charge. Indeed the H_2^+ data in Fig. 2(a) show this to be the case for $t_D > 1.5 \times 10^{-15}$ s. On the other hand, a reversed asymmetry with $A > 1$ is also observed for shorter t_D. This is unlikely to be the consequence of the usual wake effects since, to our knowledge, it has not been observed with structureless breakup fragments such as H^{+}. Thus an explanation must be sought in terms of an asymmetric destruction process of H_2^+ inside the solid.

A simple mechanism for $A > 1$ asymmetry can be advanced if one notes that, at the present velocity, the destruction of an H_2^+ fragment is due mainly to the interactions with the target valence electrons. As a consequence, one may expect that a fragment trailing right behind a positive ion will encounter more target electrons due to the focusing induced by the leading ion than when it is in front, and thus will suffer an increased probability for destruction. Such a destruction asymmetry should, of course, persist for longer t_D but the wake alignment effect which draws nonaligned fragments into the track will eventually compensate for the asymmetric destruction loss and give rise to the more commonly observed $A < 1$ asymmetry. This compensation is expected to be augmented at large t_D where the processes of target-electron capture and loss are dominant.[4] The changing asymmetry in Fig. 2(a) is suggestive of such competing mechanisms.

In order to show that a target-electron focusing mechanism gives rise to an effect of the magni-

tude observed here, we have estimated the increased destruction probability for the trailing fragment over that of the leading one, P, by using a simple model of a stationary positive point charge Z illuminated by a uniform beam of electrons of the corresponding velocity. An expression for P can be obtained by taking the ratio of the numbers of electrons intercepted by a circular disk of radius r placed at an axial distance z behind the point charge for $Z = 1$ and $Z = 0$, and this is

$$P = (1 + 4bz/r^2)^{1/2}. \quad (1)$$

Here b is the limiting impact parameter for forward scattering and the expression is valid only when both r and z are much greater than b and less than the screening length a_s. For the present $H_2^+ + H^+$ case, $b = 0.038$ Å and $a_s = 2.8$ Å and we may take $r = 1$ Å (roughly the internuclear separation of H_2^+) and $z = 1$ Å (roughly the H_2^+ and H^+ separation inside the target) yielding $P = 1.08$. Since this value is reflected in the lifetime which enters in the exponent of the intensity attenuation, the predicted asymmetry factor will depend on t_D. For example, at $t_D = 0.8 \times 10^{-15}$ s, a value of 1.38 is obtained and this is reasonably close to the corresponding experimental value of $A = 1.25$ [see Fig. 2(a)] given the simple model used and the neglect of the compensating wake-alignment effect.

It should be noted that the existing wake models[6,7] predict fluctuations of electron density behind a moving ion but the magnitude of the increased density predicted for the distance concerned here is not large enough to account for the present observation. This is understandable since the models described the polarization charge density through a macroscopic dielectric function of the medium which did not take into account close impact collisions with the target electrons. Such collisions can be expected to lead to an enhanced electronic density behind the moving ion because their essential effect is just the electron focusing described in the preceding paragraph. Thus the changing asymmetry observed here may well be explained through a more complete wake model in which the contribution of close collisions is taken into account in the induced charge density. The asymmetric destruction effect will then be governed by the same electronic density which is responsible for the electric field causing the alignment effect. Finally, the competing asymmetric effects described here should be manifested by other structured breakup fragments. The only other simple case investigated[2] to sufficiently short t_D is H from H_2^+ and H_3^+ breakup. The effects seem to be present there but an accurate assessment is difficult because the H spectra contain added features and, in addition, were distorted by the use of a stripper foil.

In summary, our present study of H_2^+ from the breakup of fast H_3^+ in very thin foils is seen to yield new information on the breakup mechanisms and survival probabilities of simple molecular ions traversing a solid. Moreover, the results demonstrate that trailing ionic molecular fragments serve to provide a more detailed picture of the ion-solid interactions since they sample the electronic density induced by a moving ion as well as the electric field that it generates.

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