If $M = \sum_j \mathfrak{M}_j$, we obtain from Eqs. (13) and (15) the result

$$F_{fi}(\vec{q}) = -ike^{iM(\phi_q + \pi/2)} \int_0^\infty db\, J_M(qb) b \sum_k c_k \prod_j \sum_{L_j} A_{L_j} \sum_p D_p E(\eta) \times b^{3+n_{k,j}} [(\partial/\partial\gamma)^{1+n_{k,j}-2p-M_j} \mathcal{g}(M_j, \gamma)]_{\gamma = \alpha_{k,j} b/2}, \quad (24)$$

where $\mathcal{g}$ is given by Eq. (23). In performing the differentiations, it is useful to note that

$$(d/dz)\,{}_1F_2(a;b,c;z^2) = (2a/bc)z\,{}_1F_2(a+1;b+1,c+1;z^2).$$

Consequently, a typical term in the integrand will be $J_M(qb)$ multiplied by some power of b and by a product of ${}_1F_2$ hypergeometric functions.

Further simplifications in Eq. (24) may, of course, be effected if the inner-shell electrons are treated as part of an inert core. In that case the product over j runs over only the valence electron(s).

For the special case of scattering by hydrogen atoms, $Z = 1$ and the product over j is a single term. The integrand is therefore linear in the ${}_1F_2$ hypergeometric function and the integral may be evaluated analytically. The results reduce to those found in Ref. 7 for scattering by hydrogen atoms.

It should be noted that the only dependence on q in the integral in Eq. (24) appears in $J_M(qb)$. Consequently, obtaining an entire angular distribution by numerical integration may not be much more difficult than evaluating $F_{fi}(\vec{q})$ at one value of q.

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Polarization of the H_α Line Produced in $He^+ + H_2$ Collisions

R. D. Nathan and R. C. Isler
Department of Physics, University of Florida, Gainesville, Florida 32601
(Received 18 March 1971)

Van Brunt and Zare have noted that polarized spectral lines might be observed from many types of dissociative collisions which produce excited atomic fragments and that studies of this polarization could prove to be valuable in determining the angular distribution of the fragments. We have observed that such polarization does, indeed, exist in the H_α line produced by dissociative charge transfer of $He^+ + H_2$ collisions. Measurements have been made at 90° to the beam direction in the energy range from 45 to 700 eV.

Excited atomic fragments may be produced from the dissociation of molecules by collision processes or by the absorption of electromagnetic radiation. Van Brunt and Zare[1] have noted that measurements of the polarization of spectral lines emitted by these fragments are related to their angular distributions and could, therefore, prove to be a useful technique for investigating the differential cross sections of dissociative processes. It is necessary that two conditions be satisfied to produce polarized spectral lines: (1) an unequal population of the magnetic substates of the dissociating atoms, and (2) an anisotropic angular distribution of the dissociation products. The first condition might be expected to hold for many processes because the cross sections for the excitation of various dissociative states of the molecule (or different states of the quasimolecule formed during the collision) are expected to differ; the magnitude of this difference will usually be a function of bombarding energy. These various molecular states correlate to different magnetic sublevels of the fragments; hence, unequal populations of these sublevels might occur for many reactions. Realization of the second condition, anisotropy of the dissociation products, requires that the excitation process be dependent upon the orientation of the molecular axis with respect to the direction of bombarding particles. The atoms from a dissociating molecule move apart almost along the direction in which they were originally vibrating, a direction which is coincident with the internuclear axis if we are considering diatomic molecules. An angular dependence of the excitation cross sections to dissociative states, therefore, can lead to nonuniform distributions of the products; the more strongly peaked the distribution is toward a given direction, the larger will be the polarization.

Up to 1968 no experimental measurements indicated the presence of polarized spectral lines from dissociative collisional processes. Since then the polarization of both the Ly_α and H_α lines has been observed in collision experiments using H_2 as a target gas. Ott, Kauppila, and Fite[2] have measured the polarization of Ly_α produced by electron collisions, and Vroom and DeHeer[3] have stated some results for the polarization of H_α from electron collisions although they have not published curves of their results. Teubner *et al.*[4] have also observed polarized ultraviolet radiation from excitation of H_2 by proton impact but could not specifically assign the radiation to the Ly_α line because their gas-filled counter had several windows which transmit lines of allowed transitions of H_2.

In this Letter we show the results of measurements of the polarization of the H_α line produced by collisions of $He^+ + H_2$ system from bombarding energies of 45 to 700 eV. There exist several arguments to indicate that the excited hydrogen atoms are formed almost exclusively by dissociative charge transfer,

$$He^+ + H_2 \rightarrow He + H^+ + H^*, \qquad (1)$$

so that the measurements can be associated with a particular process for which the polarization of spectral lines has not been observed previously. The results tend to support the contention of Van Brunt and Zare[1] that several types of dissociative processes which lead to excited fragments may produce polarization which can ultimately give insight into details of the excitation process itself. Spectral lines of neutral hydrogen are produced strongly in collisions of He^+ with H_2 and measurements of the emission cross sections as a function of energy have been made for both Ly_α[5-7] and several Balmer lines.[8,9] On the basis of the adiabatic criterion and comparison of the excitation cross section for Ly_α with the total charge exchange cross section for this system, Dunn *et al.*[5] have deduced that process (1) is responsible for the dissociative excitation of H_2.

In our apparatus He^+ is produced by electron bombardment at 50 eV and the beam is extracted through an aperature around which a coil is wound to produce an axial magnetic field of about 100 G. The beam is not mass analyzed and has an energy spread of approximately 3.5-eV full width at half-maximum intensity. After passing through a buffer stage the beam enters a collision chamber in which the H_2 pressure is maintained at 7×10^{-4} Torr; the intensity of spectral lines is a linear function of pressure well above this upper limit.

The polarization of spectral lines is measured at 90° to the beam direction.[10] The polarization measurements have been made by using both a monochromator and a filter with 40-Å bandpass to select the H_α line. Both sets of measurements are qualitatively the same, but the uncertainties are minimized in the results obtained with the filter owing to the relatively higher counting rate, and it is these results which are plotted in Fig. 1. The error bars represent the spread of at least three separate measurements at each energy. Although the threshold for excitation of the H_α line is about 35 eV, reliable polarization measurements could be obtained only above 45 eV; the emission cross section, also plotted in Fig. 1, decreases rapidly as threshold is approached, thereby limiting our ability to obtain enough intensity for accurate measurements at the very low energies.

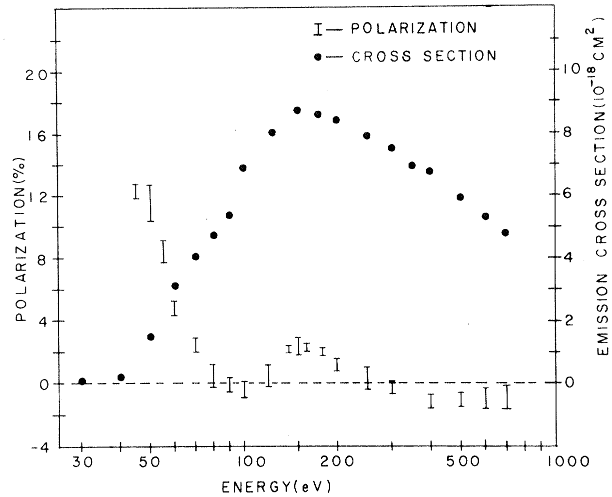

FIG. 1. Percentage polarization and cross section for emission of the H_α line produced in $He^+ + H_2$ collisions. Observations were made at 90° to the beam direction, and the cross section is plotted for the total light emission in this direction. Approximately 10% of the emission is estimated to be the result of cascading from higher states.

The polarization is seen to have a strong dependence upon the energy of the He^+ ions, reaching its largest value as threshold energies are approached but exhibiting a definite second peak around 150 eV; at about 300 eV it becomes negative but remains small up to the maximum energy investigated, 700 eV. Ankudinov, Bobashev, and Andreev[11] looked unsuccessfully for the polarization of H_α in $He^+ + H_2$ collisions at energies from 10 to 30 keV. It appears from the trend of our results that the polarization may, indeed, become very small in the energy region which they investigated.

A measurement of the polarization at a single fixed angle cannot yield the angular distribution of the dissociating particles unless a theoretical model containing only a single parameter is invoked, such as the dipolar form which is analyzed by Van Brunt and Zare.[1] Measurements at several angles of observation with respect to the beam should permit the analysis of more complicated forms of the angular distribution. Moderately high angular resolution should be obtainable for the reaction we have investigated here because the Balmer lines are produced strongly, and extensions of the present work are planned with the objective of determining the accuracy with which unambiguous results may be obtained from measurements of the polarization of spectral lines.

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