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FINAL REPORT

"Studies of Low-Energy Ionic Collisions"

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1. Resumé of Research Accomplishments

This research was initiated in September, 1963.[†] Most of the effort of the experimental phase of this work, for the first two years, was expended on the design, construction, and testing of an angular ion-scattering apparatus (AISA). The function of this apparatus is to give the angular and kinetic energy distributions of the charged products of collisions of low energy (1 - 200 eV) ions with neutral atoms and molecules. From such measurements, it has been possible to obtain detailed information regarding the dynamics and energetics of a number of types of ion-neutral collisions. Collision processes which have been studied up to the present are: (a) collision-induced dissociation (CID), $D_2^+ + X = D^+ + D + X$, where X is Ar or N_2; (b) the ion-molecule reactions: $Ar^+ + D_2 = ArD^+ + D$, $N_2^+ + D_2 = N_2D^+ + D$, $D_2^+ + D_2 = D_3^+ + D$, $D_2^+ + H_2 = D_2H^+ + H$, and $D_2^+ + H_2 = H_2D^+ + D$; (c) collisions of doubly-charged ions with diatomic molecules, such as $Ar^{++} + N_2 = Ar^+ + (N_2^+)^*$, and (d) the non-resonant charge transfer processes $He^+ + N_2 = He + (N_2^+)^*$; $Ne^+ + N_2 = Ne^+(N_2^+)^*$; and $Ar^{++} + Ar = Ar^+ + Ar^+$. In addition, theoretical research has been carried out on elastic scattering, using the JWKB approximation, and on the enhancement of experimental resolution by a numerical unfolding procedure. Each of these studies will be described briefly in the remainder of this section.

(a) Collision-Induced Dissociation

After the initial (and quite successful) performance tests of AISA, it was used in studies of collision-induced dissociation (CID) of D_2^+ ions, by Ar and N_2 targets. The D_2^+ CID studies imply that these processes proceed

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[†] This research was supported by Grant AFOSR-471-64, from September 1, 1963 to September 30, 1965. Concurrent support of this work has been received from the U. F. NASA Institutional Grant NSG-542.

by the two-step mechanism: $D_2^+ + X = (D_2^+)^* + X$, followed by $(D_2^+)^* = D^+ + D$. The nature of the product D^+ ion kinetic energy distributions indicates that appreciable numbers of the primary D_2^+ ions (which were formed by electron impact) are in highly excited vibrational states. The CID work is described in detail in paper 7, listed in the section on Publications.

(b) Ion-Molecule Reactions

The studies of the reactions $Ar^+ + D_2 = ArD^+ + D$ and $N_2^+ + D_2 = N_2D^+ + D$ are discussed in detail in paper 6, Publications. These experiments show that, over a wide range of collision energies, the ArD^+ and N_2D^+ reactions conform closely to the predictions of a simple "pick-up" model. In the pick-up (or "spectator stripping") model the incoming primary ion extracts a D atom from the D_2 target, leaving behind a D atom which is essentially at rest in the laboratory coördinate system. As a consequence of energy-momentum conservation, the ArD^+ or N_2D^+ products continue on in the primary ion direction, and have internal excitation energy which increases as the collision energy is increased. At sufficiently high collision energies, the excitation energy of ArD^+ (or N_2D^+) predicted by the pick-up model exceeds the dissociation energy for $ArD^+ = Ar + D^+$ (or $N_2D^+ = N_2 + D^+$); in this high energy region, it was found experimentally that the pickup mechanism no longer holds. Although pick-up was found to be the dominant reaction channel over most of the range of these experiments, another distinctly different mechanism was observed. This latter has the same Q as the pick-up process, but it corresponds to scattering of ArD^+ or N_2D^+ by 180°, rather than 0°, in the CM system. It is appropriate to describe this second process as a "recoil" or "rebound" collision, since in the CM system the target D_2 molecule approaches the Ar^+ or N_2^+ ion with a CM speed v_o, and the product D atom recedes with the same speed v_o, but with reversed direction. The idealized pick-up and recoil kinematic models are shown in Fig. 1, along with some pertinent kinematic information. The observed angular distributions for both ArD^+ and N_2D^+ show strong forward collimation, as would be expected from the pick-up model, and show no evidence of the "wings" in the region of the maximum laboratory scattering angle which would be expected if the reaction proceeded by means of a long-lived intermediate complex ion ($(ArD_2^+)^*$ or $(N_2D_2^+)^*$).

Extensive studies of the reactions $D_2^+ + D_2 = D_3^+ + D$, $D_2^+ + H_2 = D_2H^+ + H$, and $D_2^+ + H_2 = H_2D^+ + D$ have been recently completed (see item 10, Publications). These studies cover only the rather restricted primary ion energy range 2 - 15 eV, since usable D_2^+ currents could not be obtained below about 2 eV, and the reaction cross-sections, and product ion currents, became very small above about 15 eV. Nevertheless it was possible to obtain a considerable amount of detailed information concerning the dynamics of these reactive collisions. It was found that the most probable reaction channel for D_3^+ and D_2H^+ formation is pick-up (as was the case for ArD^+ and N_2D^+). In the case of D_3^+, another reaction channel, in which the CM velocity of D_3^+ was zero (within experimental error), was also observed. This latter process is a completely inelastic collision, in which all of the available kinetic energy in the collision appears as internal excitation of the product D_3^+. H_2D^+, which is formed by extraction of a D^+ ion from the incident D_2^+ by the target H_2, was also observed, and was also found to be produced in a completely inelastic collision. From this we infer that D_3^+ formation via the completely inelastic collision corresponds to extraction of D^+, from D_2^+, by the D_2 target.

A number of the product ion K.E. distributions were unfolded (or deconvoluted), using a computer program devised by G. E. Ioup and B. S. Thomas

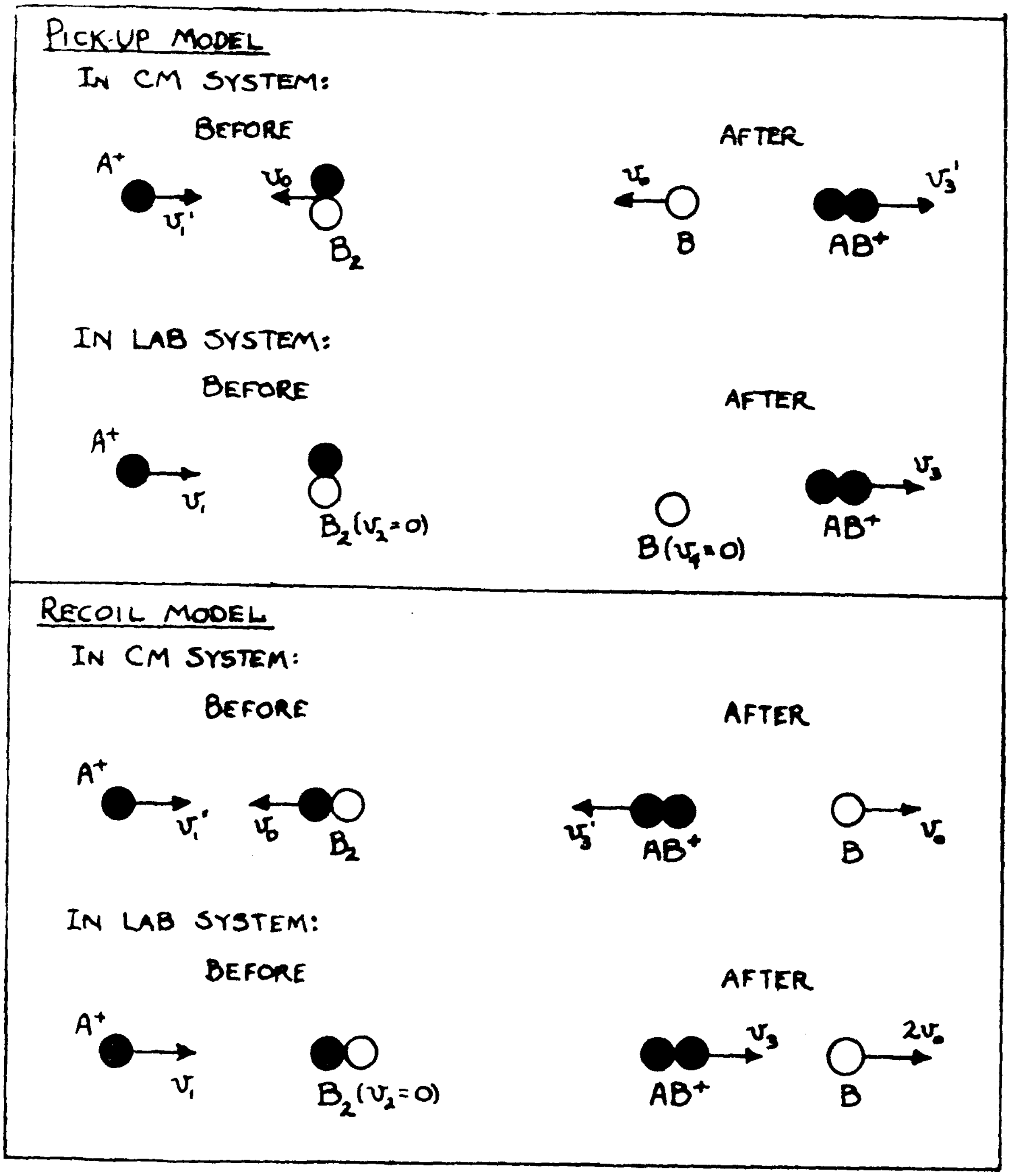


Fig. 1. Collision kinematics for $A^+ + B_2 = AB^+ + B$. Subscripts 1, 2, 3, 4, refer to A^+, B_2, AB^+, B, respectively. E_i is K.E. of ith particle in laboratory system; M_i is mass of ith particle. v_i, v_i', are speeds of ith particle in laboratory and center of mass systems, respectively. v_0 is speed of the center of mass, with respect to the laboratory system. For both pick-up and recoil, $Q = -(M_4/M_3)E_1$.

(see item 11, Publications). The unfolding procedure is described in the later section on Theoretical Work. The purpose of unfolding is to correct the observed K.E. distributions for the finite K.E. bandwidth of the primary ions, and hence to increase the effective energy resolution of the experiments. Such an unfolded K.E. distribution for D_2H^+, produced in the reaction $D_2^+ + H_2 = D_2H^+ + H$, is shown in Fig. (2b). It shows unexpected and rather remarkable structure. The principal maximum in the observed data (Fig. (2a)) is split into two distinct peaks. In addition, two additional peaks at lower energy appear. Peak A corresponds to the same Q as the pick-up process, but the CM scattering angle of D_2H^+ ions which contribute to it is $\chi = 180°$, rather than $\chi = 0°$. Thus peak A arises from the "recoil" process, which has been discussed previously, in connection with the ArD^+ and N_2D^+ reactions. The computed Q for the maximum of peak B is $Q = -E_{cm}$, where E_{cm} is the total initial CM kinetic energy of the reactant D_2^+ and H_2 species. Thus peak B corresponds to a totally inelastic encounter, in which the product D_2H^+ and H species recede from each other with zero relative velocity. All of the available collision energy in such a process of course appears as internal excitation of the product species (in this case, D_2H^+). The shoulder D appears at a K.E. equal to that of the peak in the primary D_2^+ ion distribution; it is due to a tiny amount of "contamination" of the D_2H^+ product ion current by primary D_2^+ ions. Such contamination is to be expected, since the primary ion currents are vastly larger (ca. 10^5) than the product ion currents. The fact that this contamination shows up clearly in the unfolded distribution, even though it is not at all evident in the raw data, is a strong argument in favor of the validity of the unfolding procedure. Peak C corresponds to an exothermic reaction channel, for which there is apparently no simple kinematic model.

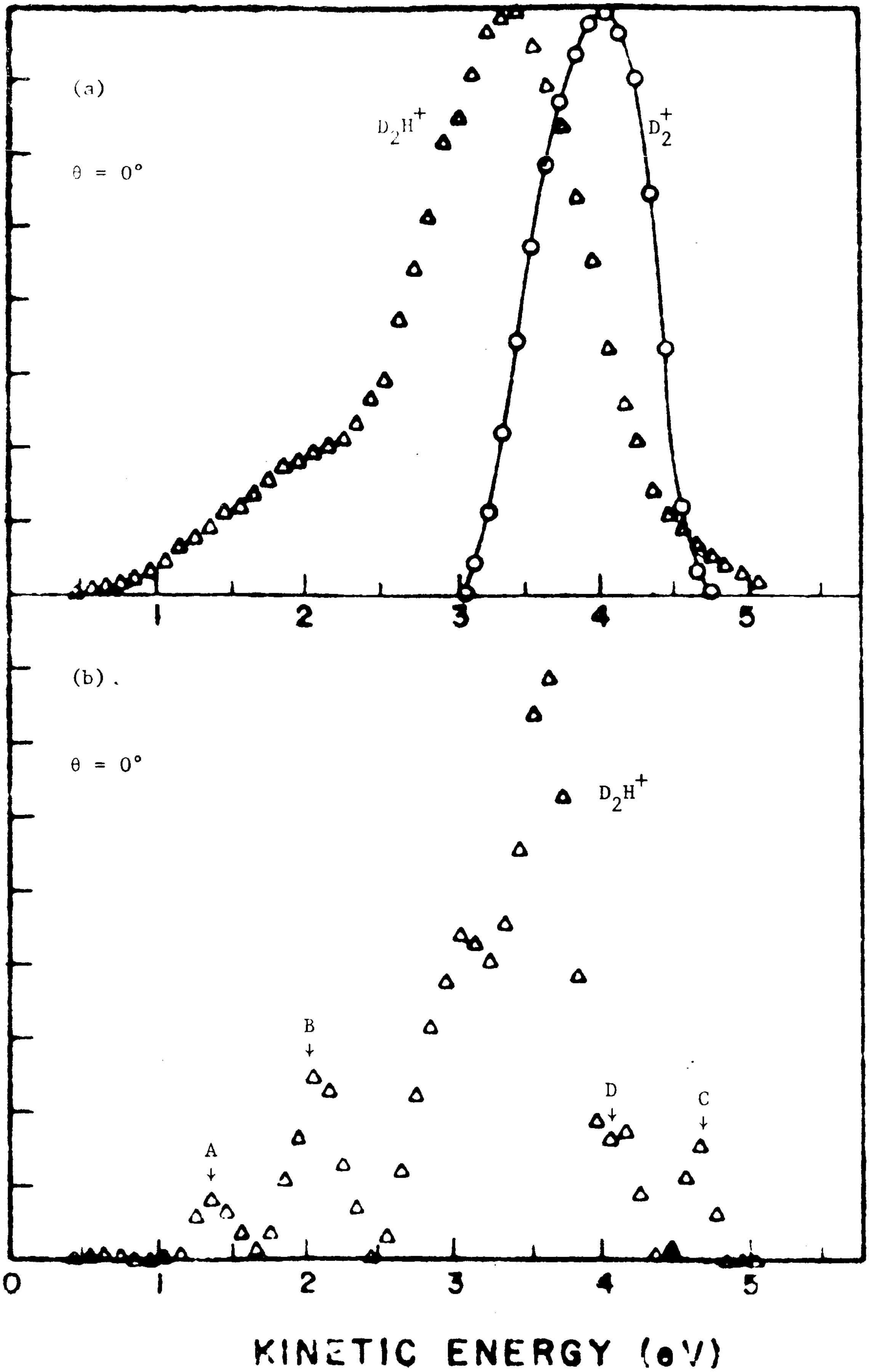


Fig. 2. Kinetic energy distributions of D_2H^+, from $D_2^+ + H_2 = D_2H^+ + H$. (a) raw data; (b) unfolded D_2H^+ distribution.

The unfolding procedure is capable of giving dramatic improvement in effective resolution, and may prove to be useful in many types of physical experiments. It must be applied with a great deal of caution, however, and a number of experimental tests of the method are planned. The considerable number of unfolded results which have been obtained so far are all physically reasonable, and we have every reason to believe in the reliability of the unfolding procedure.

(c) Collisions of Doubly-Charged Ions with Diatomic Molecules

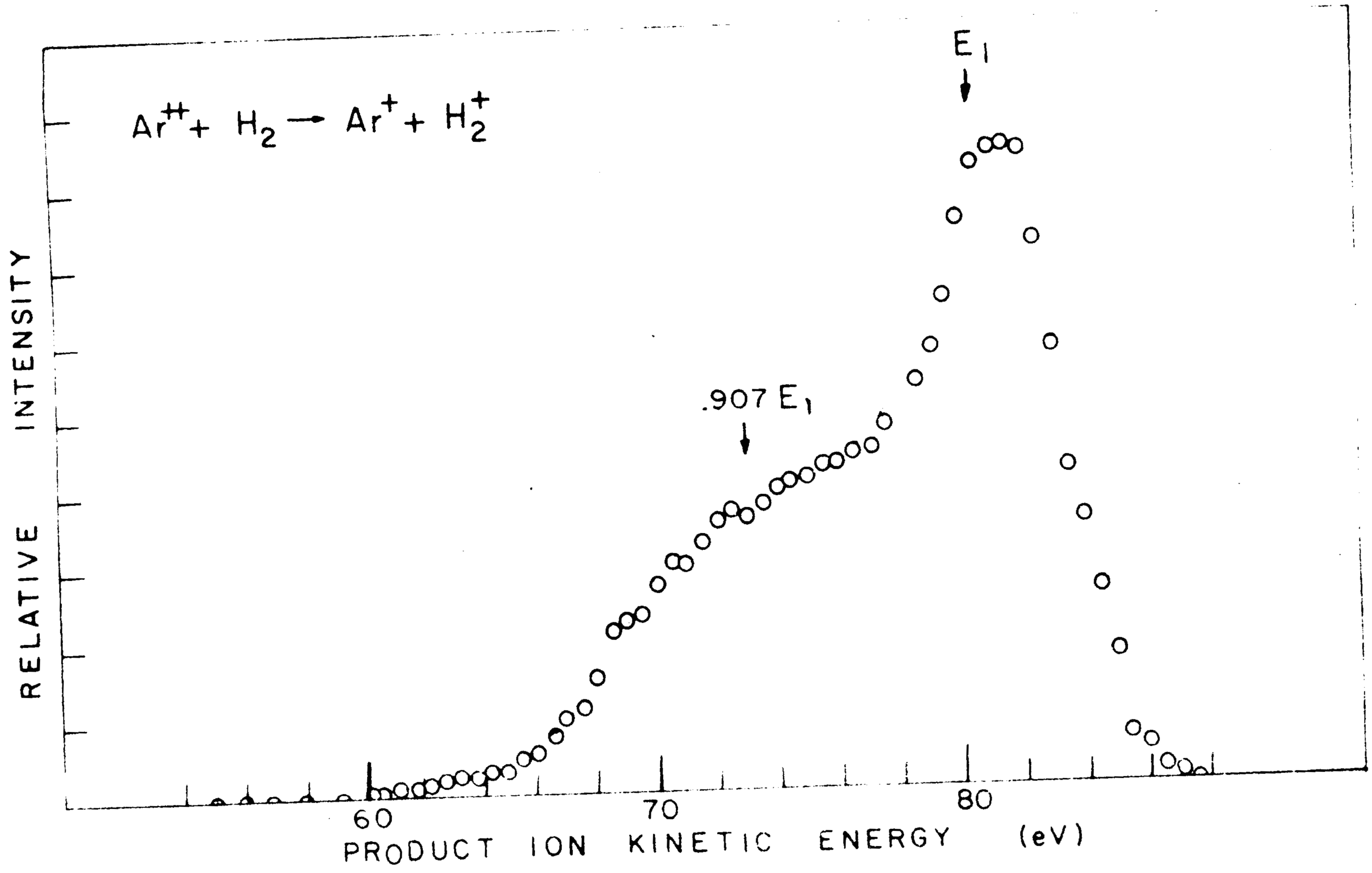
Extensive studies of the production of fast singly-charged atomic ions, A^+, from collisions of doubly-charged ions, A^{++}, with diatomic molecules, have been carried out. These experiments are of two types: (i) measurements of the angular and kinetic energy distributions of the product A^+ ions, at known primary A^{++} kinetic energies, and (ii) determination of total cross-sections for A^+ production, as a function of collision energy. The experiments (i) have been done using the apparatus AISA mentioned previously. The total cross-section measurements (ii) have employed the fixed angle tandem mass spectrometer of Vance and Bailey.

Angular and kinetic energy distributions have been determined for the following collision systems: Ar^{++}, Ne^{++}, and He^{++} in N_2; Ar^{++} and Ne^{++} in H_2, and Ar^{++} in D_2. The angular distributions show that the A^+ product ions (where A^+ is Ar^+, Ne^+, or He^+) are strongly collimated in the primary ion beam direction. For all the collisions of doubly-charged ions with N_2, and for the Ne^{++}, H_2 collisions, the K.E. distributions of the A^+ products, measured at scattering angle of $\theta = 0°$, were fairly sharp (typically, about twice as wide as the primary A^{++} K.E. distributions), with single maxima at somewhat higher energies than those of the primary ions. The angular and energetic studies imply that the A^+ product ions are formed by an initial charge transfer step: $A^{++} + B_2 = A^+ + (B_2^+)^*$, in which very little momentum is transferred to the target B_2. Since the second ionization potential of the A atom is generally considerably larger than the first ionization potential of the B_2 molecule, appreciable internal energy is available for excitation of the product $(B_2^+)^*$. In most cases, this is sufficient for its subsequent dissociation: $(B_2^+)^* = B^+ + B$. In addition, the interaction between the A^+ and B_2^+ products is Coulombic repulsion, so that these species are accelerated from the site of the collision.

From the observed A^+ product K.E. distributions, and the assumption that A^+ is formed by the initial charge transfer step $A^{++} + B_2 = A^+ + B_2^+$, information as to the collision energetics, and therefore the possible internal energy levels of the participating species, can be obtained. These results for collisions of Ar^{++}, Ne^{++} and He^{++} with N_2 are shown in Table I. The R_o values listed in Table I are calculated values of internuclear separation at which the charge transfer takes place, assuming a classical orbit picture, and assuming that the $A^+ - B_2^+$ interaction is Coulomb repulsion.

The collisions of Ar^{++} with H_2 and D_2 gave kinetic energy distrubitions of Ar^+ which were distinctly different from those observed in collisions with N_2. The H_2 and D_2 distributions exhibit a marked double-peaked structure. Two such distributions are shown in Figs. 3 and 4, where the primary Ar^{++} energy is denoted by E_1. The higher energy peaks have maxima slightly greater than E_1, in both cases, and are similar to the peaks observed in collisions with N_2. The lower energy peaks have maxima at Ar^+ laboratory energies which correspond to velocities in the CM system of <u>zero</u>, in both cases. This suggests that these low energy peaks may arise from the formation and subsequent decomposition of the complex ions, $(ArH_2^{++})^*$ or $(ArD_2^{++})^*$ via: $Ar^{++} + B_2 = (ArB_2^{++})^* = Ar^+ + B_2^+$, where B is H or D.

Fig. 3. K.E. distribution of Ar^+, at $\theta = 0°$, from: $Ar^{++} + H_2 = Ar^+ + H_2^+$.



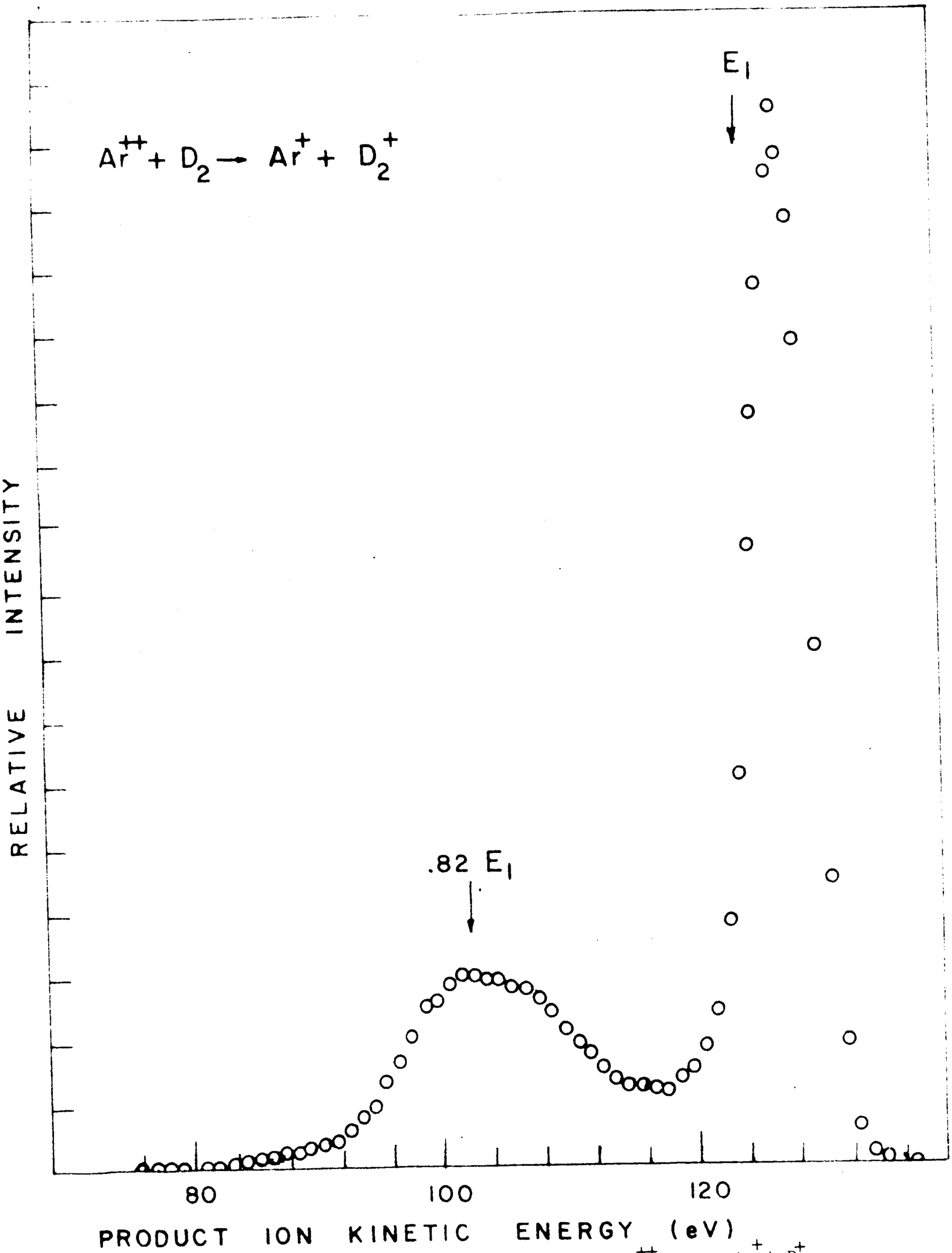


Fig. 4. K.E. distribution of Ar^+, at θ = 0°, from: $\mathbf{Ar}^{++} + D_2 = Ar^+ + D_2^+$.

TABLE I. Summary of Energetic Measurements for A^{++}, N_2 Collisions.

Collision System	Primary Ion K.E. Range	Q, R_o	α,β,γ	Remarks and Conclusions
Ar^{++}, N_2	20 - 210 eV	$Q = +8.0$ eV $R_o = 3.7$ Å	$\alpha=0,1.74,4.12$ $\beta=0$, up $\gamma=0$, 13.47, 16.4, up	[*] $\beta > 0$; $\beta = 8.0-\gamma+\alpha$ This can only be true if $\gamma = 0$, so that $\beta = 8.0+\alpha$
Ne^{++}, N_2	40 - 190 eV	$Q = +5.5$ eV $R_o \simeq 2.7$ Å	$\alpha=0,3.2,6.9$ $\gamma=0,27.0$	$\beta = 20+\alpha$
Ne^{++}, N_2	100 - 200 eV	$Q = +9.0$ eV $R_o \simeq 2.5$ Å	$\alpha = 0$ $\gamma = 0,40.8$	[†] $\beta \simeq 30.0$ eV *only*

For $A^{++}+B_2 = A^{+}+B_2^{+}$, $Q \equiv E_3+E_4-(E_1+E_2) = U_1+U_2-(U_3+U_4)$, where 1,2,3,4 refer to A^{++}, B_2, A^{+}, and B_2^{+} respectively; E is kinetic energy in laboratory system, and U is the internal energy. $E_2 = 0$, since B_2 is at rest in the laboratory system; E_4 can be determined, in terms of the measured E_1 and E_3, by linear momentum conservation, so Q can be calculated from measurements of E_1 and E_3. Q is also given by: $Q = I_2(A)-I_1(B_2)+\alpha-(\beta+\gamma)$, where $I_2(A)$ is the second ionization potential of A; $I_1(B_2)$ is the first I.P. of B_2, and α, β, and γ are the excitation energies of A^{++}, B_2^{+}, and A^{+}, above their ground states, respectively.

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[*] For Ar^{++}, N_2, both N_2^{+} and N^{+} ions of very small kinetic energies were observed.

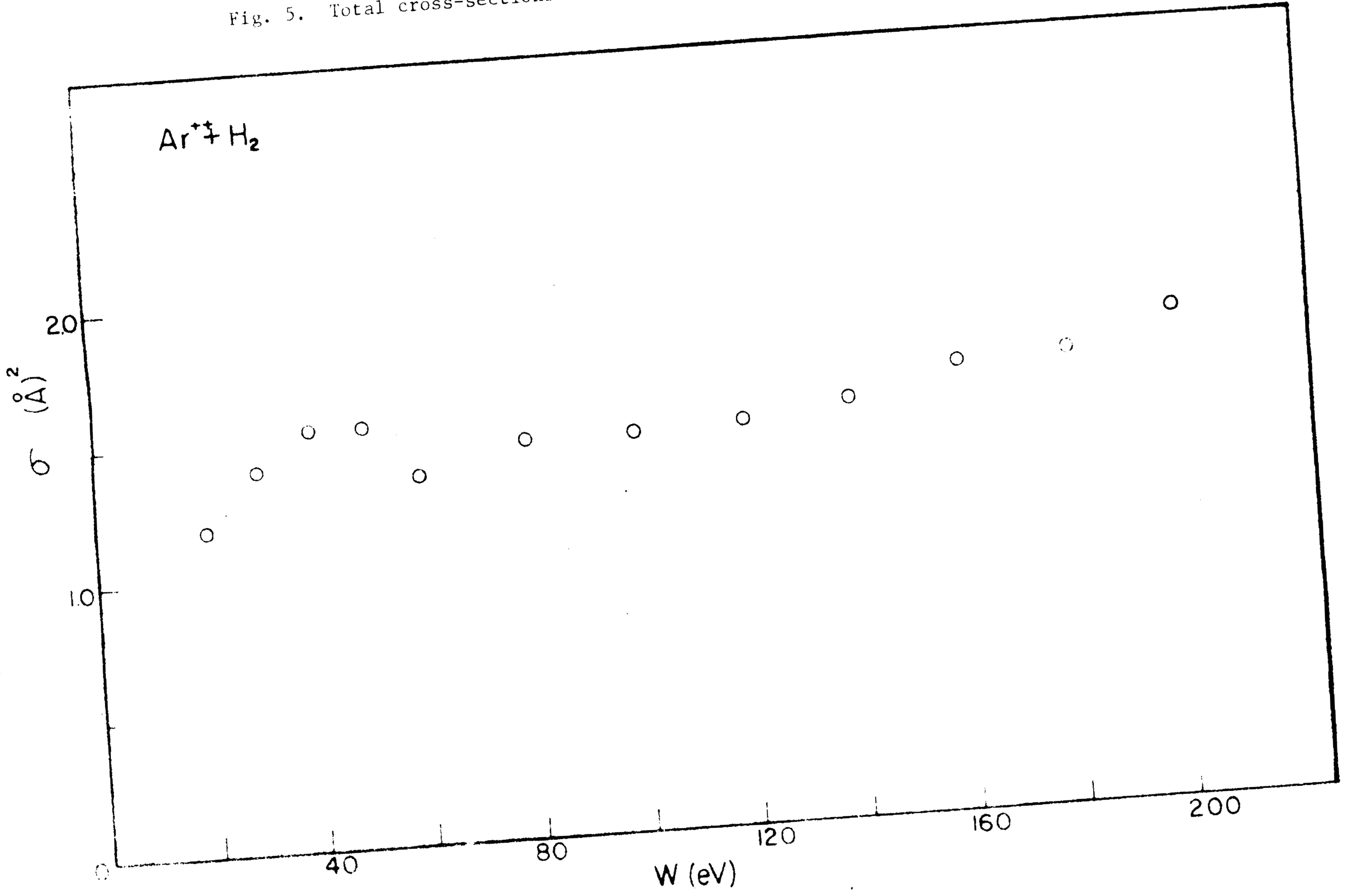
[†] $\beta \simeq 30.0$ eV implies either that $(N_2^{+})^{*}$ dissociates, or that N_2^{++} is formed.

In the Ar^{++}, N_2 studies, both N_2^+ and N^+ ions of approximately thermal energies were observed in small quantities. No H or D ion species were observed in the (Ar^{++}, H_2, D_2) experiments. This last fact is not surprising, since the total cross-section for the Ar^{++}, H_2 collisions appears to be about 1/10 that for Ar^{++}, N_2. In addition, the product ion detector system accepts only those ions which are scattered into a very small solid angle; if H_2^+ or H^+ were scattered through a broad range of angles, then the flux of these ions through the product detector could easily be below the limit of detectability. A journal article, based on the angular and energetic measurements described above, is in preparation (see item 12, Publications). A considerable amount of interpretation of these results remains to be done, but the article should be finished before the end of the current Grant term.

Total cross-sections for the production of Ar^+ in collisions of Ar^{++} with H_2 molecules, over the energy range 20 to 200 eV, have been carried out (see item 9, Publications). Currents of primary Ar^{++} and product Ar^+ ions were determined by a rather simple electrostatic separation arrangement. The results of these measurements (which are of a preliminary nature) are shown in Fig. 5. Extension of total cross-section measurements of this type to a number of collision systems is planned.

The angular and energetic studies described above are incomplete, since they give only information about the fast A^+ product of the processes $A^{++} + B_2 = A^+ + B_2^+$. Obviously, this general type of process could be much better understood if the angular and energetic distributions of the product B_2^+ ions (or B^+ ions, if B_2^+ dissociates) could be measured. Such experiments are planned, and the apparatus in which they are to be carried out is now being constructed.

Fig. 5. Total cross-sections for Ar^+ formation, in collisions of Ar^{++} with H_2.



(d) Charge Transfer Studies

The angular scattering apparatus has been used in studies of the non-resonant charge transfer processes: $He^+ + N_2 = He + (N_2^+)^*$ and $Ne^+ + N_2 = Ne + (N_2^+)^*$. For both these systems, moderately energetic N_2^+ ions were observed, and it has been possible to measure both K.E. and angular distributions of these N_2^+ ions over an appreciable range of collision energies. The results of these experiments are rather surprising, and certainly not what would be expected on the basis of simple notions of the charge transfer process. The He^+, N_2 transfer is exothermic, and appears to result in $(N_2^+)^*$ in a single internal state; i.e., this reaction proceeds with a singular value of Q. The best measure of Q, over the primary ion energy range 2 - 30 eV, is Q = +1.0 eV. The data indicate that the total transfer cross-section increases rapidly as the collision energy is decreased. In contrast to the observations, the simple adiabatic criterion of Massey predicts that the transfer cross-section should be negligibly small, for $|Q|$ appreciably different from zero, at such low collision energies. In the case of $Ne^+ + N_2 = Ne + N_2 = Ne + (N_2^+)^*$, the measurements indicate that the total cross-section is very small above primary ion energies of about 10 eV, but rises rapidly from this point, as energy is decreased; reaches a maximum at about 5.5 eV; and then drops rapidly to an apparent threshold at 3.0 eV. The apparent threshold is indicative of an endothermic process, and is in good agreement with the Q calculated for the $Ne^+ - N_2$ transfer from the K.E.'s of product N_2^+ and primary Ne^+ at collision energies above threshold. The best value of Q for the $Ne^+ - N_2$ transfer is Q = -2.5 eV. For both the $He^+ - N_2$ transfer, the energy measurements indicate that the product $(N_2^+)^*$ is in the same excited level. In addition to the above N_2^+ products of moderate kinetic energy, slow N_2^+ ions (of approximately thermal energy) have been observed.

It has not been possible to carry out reliable measurements on these "thermal" N_2^+ ions, since most of them appear to be prevented from escaping from the collision chamber by surface charge distributions. N^+ ions, presumably from dissociation of excited $(N_2^+)^*$ ions, have also been observed.

The journal article describing these results is now in preparation.

In addition to the He^+, Ne^+ in N_2 charge transfer studies, the transfer process $Ar^{++} + Ar = Ar^+ + Ar^+$ has been investigated extensively, at the primary Ar^{++} kinetic energy 200 eV. Product Ar^+ ion kinetic energy distributions measured at various scattering angles show two distinct maxima, one lying above and the other several eV below 200 eV. If the unobserved slow Ar^+ products are assumed to be in the ground state, then the observations show that the fast Ar^+ products are in highly excited states, ranging from the 3s $3p^6$ level up to the ionization limit. By varying the electron bombardment energy in the ion source it was found that the Ar^+ corresponding to the high kinetic energy maximum in the product ion kinetic energy profiles are due to exothermic (20/11) reactions which involve highly excited metastable levels of Ar^{++}, while the slower group of observed Ar^+ are due to endothermic (20/11) reactions involving only the $3s^2$ $3p^4$ configuration. The observed angular distribution for the product ions, when Ar^{++} is in the $3s^2$ $3p^4$ configuration, increases rapidly from 0° to a maximum at about 4° and decreases thereafter. The Ar^+ product ions associated with highly excited Ar^{++} primaries are found to be sharply forward collimated. A paper describing the Ar^{++}, Ar transfer studies will be presented at the 20th Annual Gaseous Electronics Conference, San Francisco, Oct. 18-20, 1967. A journal article based on this work is in preparation.

Theoretical Research

A Fortran program for computing differential ion-atom elastic scattering cross-sections, in the JWKB approximation, is in preparation, and is nearing completion. The method of calculation is similar to that of Ford and Wheeler. To the best of our knowledge, this program is the first in which the second derivative of the scattering angle with respect to impact parameter is calculated directly. Improvements over previous computational schemes have been made which should shorten the time required to compute the cross-sections at each collision energy appreciably. As it now stands, this program can be used for elastic scattering as described by a single interaction potential. Calculations for several specific collision systems will be carried out in the near future.

In order to optimize the resolution available in beam-collision experiments, an unfolding procedure has been devised which corrects analytically for the spread in kinetic energy of the projectile particles, and for other broadening factors. Such "broadening" of experimental results is described by the convolution equation:

$$h(x) = \int_{-\infty}^{+\infty} f(y)g(x-y)dy,$$

where h(x) is the observed distribution in x (where x is, for instance, kinetic energy), f(y) is the ideal distribution which would be observed in the absence of broadening, and g(z) is the resolution function which characterizes the broadening. The function g(z) may describe all, or any aspect of, the broadening. This integral equation was unfolded (or deconvoluted) to give a solution for f(y), by a method similar to those employed by Morrison, Bracewell and Roberts, and others. The g(z) was taken to be the observed distribution of the primary beam particles over the variable z (z was kinetic energy, in most cases), thus correcting for both the primary particle spread in z and the finite bandwidth in z of the detector system. Before unfolding, incompatible noise was removed from the experimental h(x) distribution by application of Morrison's iterative smoothing technique. After smoothing, f(y) was recovered using Van Cittert's iterative method. A computer program for carrying out this smoothing and unfolding has been written. Results obtained from this program have been compared with those gotten using the Fourier method of smoothing and deconvoluting.

The sample points which comprise the primary particle distribution do not generally occur in convenient positions for use in the iterative equations. For this reason, a program has been written which translates these points, with negligible end point approximation.

As has been discussed, previously application of the smoothing-unfolding technique has already resulted in significant improvement in experimental resolution. Future work along these lines is planned.

The theoretical investigations of accidental degeneracy have resulted in the publication of two journal articles (see items 1, and 2, Publications). The results of this work are most interesting, but inasmuch as they do not seem directly applicable to atomic collision phenomena, this line of research will not be continued under this Grant.

2. Participating Scientific Personnel

1. T. L. Bailey, Co-principal Investigator. Professor of Physics and Electrical Engineering.
2. B. S. Thomas, Co-principal Investigator. Assistant Professor of Physics.

3. L. D. Doverspike, Graduate Research Assistant, Ph.D. in Physics, April, 1966. P.D. Research Associate, April, 1966 to September, 1967. Present position: Assistant Professor of Physics, College of William and Mary.
4. R. L. Champion, Graduate Research Assistant, Ph.D. in Physics, April, 1966. P.D. Research Associate, April, 1966 to September, 1967. Present position: Assistant Professor of Physics, College of William and Mary.
5. G. E. Ioup, Graduate Research Assistant. Candidate for Ph.D. in Physics; expected graduation date, December, 1967. From September, 1967, Postdoctoral Fellow, Physics, University of Connecticut.
6. T. L. Budzynski, Candidate for Ph.D. in Physics. University of Florida Graduate School Predoctoral Fellow.
7. E. M. Nemeth, S.J., Postdoctoral Research Associate. To assume duties as Assistant Professor in Chemistry, University of Detroit, on about December, 1968.

3. Publications and Papers Presented at Meetings

(* denotes journal article)

*1. "Degeneracy of Cyclotron Motion," by Victor A. Dulock and Harold V. McIntosh, Journal of Mathematical Physics 7, 1401 (1966).

*2. "On the Degeneracy of the Kepler Problem," by Victor A. Dulock and Harold V. McIntosh. Pacific Jour. Math. 19, 39 (1966).

3. "Collision Induced Dissociation of D_2^+ Ions in Various Gases," by R. L. Champion, L. D. Doverspike, and T. L. Bailey, Bull. Am. Phys. Soc. 11, 532 (1966).

4. "Energetic and Angular Studies of Some Ion Molecule Reactions," by L. D. Doverspike and R. L. Champion, Bull. Am. Phys. Soc. 11, 312 (1966).

5. "Energetic Studies of Collision-Induced Dissociation of D_2^+ Ions," by R. L. Champion and L. D. Doverspike, Bull. Am. Phys. Soc. 11, 312 (1966).

*6. "Energetic and Angular Studies of ArD^+ and N_2D^+ Formation," by L. D. Doverspike, R. L. Champion, and T. L. Bailey, J. Chem. Phys. 45, 4385 (1966).

*7. "Collision Induced Dissociation of D_2^+ Ions by Argon and Nitrogen," by R. L. Champion, L. D. Doverspike, and T. L. Bailey, J. Chem. Phys. 45, 4377 (1966).

8. "Energetic Studies for Reactive Collisions for the Systems $D_2^+ + D_2$ and $D_2^+ + H_2$," by L. D. Doverspike and R. L. Champion. Paper presented at 19th Annual Gaseous Electronics Conference, October, 1966. Abstract to appear in Bull. Am. Phys. Soc.

9. "Collisions of Low-Energy Ar^{++} Ions with H_2 Molecules," Fred A. Herrero and T. L. Bailey, Bull. Am. Phys. Soc., V.11, No.6, p.826 (1966).

*10. "Experimental Investigations of Ion-Molecule Reactions of D_2^+ with D_2 and H_2," by L. D. Doverspike and R. L. Champion, J. Chem. Phys. 46, 4718 (1967).

*11. "Smoothing and Unfolding the Data of Beam Collision Experiments," by George E. Ioup and B. S. Thomas, J. Chem. Phys. 46, 3959 (1967).

*12. "Charge Transfer in Collisions of Ar^{++}, Ne^{++}, and He^{++} Ions with Diatomic Molecules." In preparation, to be submitted to J. Chem. Phys.

*13. "Angular and Energetic Studies of Charge Transfer of He^+ and Ne^+ Ions with N_2." In preparation, to be submitted to Phys. Rev.

*14. "Experimental Studies of the Charge Transfer Reaction $Ar^{++} + Ar = A_2^+ + Ar^+$." In preparation, to be submitted to Phys. Rev. or J. Chem. Phys.

4. Graduate Students Assisted by This Grant

1. L. D. Doverspike. Graduate Research Assistant, under this Grant. Ph.D. in Physics, April, 1966.
2. R. L. Champion. Graduate Research Assistant (under NASA Institutional Grant). Mr. Champion received substantial aid, in the form of equipment and research materials, from this Grant. Ph.D. in Physics, April, 1966.
3. G. E. Ioup. Graduate Research Assistant, Candidate for Ph.D. in Physics.
4. T. L. Budzynski, Candidate for Ph.D. in Physics. Suported by Fellowship stipends from University of Florida graduate school, since joining this research group. Mr. Budzynski has received aid from this Grant in the form of research equipment and materials.