

The Theory of Electron-Molecule Collisions

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(The author is currently with Shell Nederlands Raffinaderij, although the substantial part of this article was written while he was with the Science Research Council of the UK at the Daresbury Laboratory)

There are many areas of physics whose advance is dependent on the availability of data on collision processes between electrons, ions, and neutral atoms and molecules. In recent years this has been most apparent in astrophysics, atmospheric physics, laboratory plasmas (most notably in connection with the controlled thermonuclear fusion programmes), and gas lasers. In addition, the subject of atomic and molecular collisions is of great intrinsic interest, having played a leading role in the establishment of quantum theory, and includes many aspects of fundamental importance in the understanding of atomic and molecular structure.

One of the most powerful investigative tools at the disposal of the atomic and molecular physicist is the electron beam. Electrons are in many respects more versatile than their nearest "competitor", the photon, being able to induce not only all the atomic and molecular transitions possible with photons, but also those normally forbidden to photons (e.g. s-s transitions). Indeed, electron beam technology today is such that the currents and resolutions now attainable make it competitive with the best available synchrotron radiation sources. And because high energy beams can be produced at a fraction of the cost, it has been aptly dubbed by many atomic physicists as the "poor man's synchrotron".

At low energies too, i.e. below the first ionisation threshold of the target, an electron beam can reveal a wealth of information on the structure and properties of atoms and molecules. Especially in the last six to eight years, experimentalists have been able to produce, with improved techniques, a plethora of cross sectional data for low energy electron scattering from atoms and molecules, providing an accuracy and detail which are a challenge to the theorist. In many cases, the most interesting features which appear in their results, are the scattering resonances caused by the temporary formation of compound states of the incident electron and the atomic or molecular target. These resonances are particularly significant in electron-molecule collisions, as they frequently facilitate the transfer of energy from the electronic to the nuclear motion, leading to enhanced rotational and vibrational excitation cross sections and, sometimes, even to molecular dissociation.

Even in the non-resonant energy region, the determination of scattering cross sections is of interest and importance, for example as necessary data for the interpretation of many astrophysical and atmospheric processes.

Whereas the challenge presented by low energy electron-atom investigations has been, and is being, met by theorists, the situation in electron-molecule scattering has been, until recently, more an embarrassment. To be fair, the development of a rigorous and feasible theory of low energy electron-molecule scattering is a non-trivial matter, and neither the techniques nor the computers able to solve the electron-molecule equations were available. However, the incentive injected into this subject by the experimentalists' success, coupled to the increased demand for electron-molecule cross sections from other areas of science, and not least, the marked improvement in computational facilities in recent years, have encouraged theorists to look afresh at electron-molecule processes and to come up with some novel and very promising new approaches.

Theoretical Difficulties

Under normal experimental conditions, an electron beam can be well defined, in that the electrons can be assumed to possess a definite energy and momentum, they do not interact with each other, and undergo only single collisions in the scattering chamber. Under these "steady state" conditions the electron-molecule system is an eigenstate of the total energy, E , and we can write its quantum mechanical wave function as:

$$\psi(\mathbf{r}_0 \dots \mathbf{r}_N; \mathbf{R}) \exp(-iEt/\hbar) \quad (1)$$

where $\psi(\mathbf{r}_0 \dots \mathbf{r}_N; \mathbf{R})$, satisfies the time independent Schrödinger equation,

$$(H - E)\psi(\mathbf{r}_0 \dots \mathbf{r}_N; \mathbf{R}) = 0 \quad (2)$$

The Hamiltonian, H , represents both the electronic motion in the system and the nuclear motion, and for the purpose of solving the scattering problem is conveniently expressed as:

$$H = H_{\text{el}} + H_{\text{nuc}} \quad (3a)$$

where

$$H_{\text{el}} = -\hbar^2/2m_e \nabla_0^2 + V_0 + H^T \quad (3b)$$

and

$$H_{\text{nuc}} = -\hbar^2/2M \nabla_{\mathbf{R}}^2 \\ = H_{\text{vib}} + H_{\text{rot}} \quad (3c)$$

In (3b) the first two terms represent respectively, the kinetic energy of the incident electron and its coulombic interaction with the molecular electrons (i.e. $e^2/r_{01} + e^2/r_{02} + \dots$) and nuclei (i.e. $-Z_A e^2/r_{A0} - Z_B e^2/r_{B0} - \dots$). H^T is the electronic Hamiltonian for the molecule whose eigenfunctions, $\phi_n(\mathbf{r}_1 \dots \mathbf{r}_N; \mathbf{R})$ form, in principle, a complete set of discrete and continuum electronic states with eigenvalues $\epsilon_n(\mathbf{R})$. In the absence of the scattering electron, the eigenfunctions of the nuclear Hamiltonian are the molecular vibrational states, $\chi_{nv}(\mathbf{R})$, and rotational states, $\rho_{nvj}(\hat{\mathbf{R}})$.

The use of separable electronic, vibrational and rotational wave functions for the molecule is based upon the Born-Oppenheimer approximation, whose validity, in turn, is based upon the observation that the electronic motion is many times faster than that of the nuclei, due to the very large mass difference between electrons and nuclei. Consequently, no permanent transfer of energy occurs between the electronic and nuclear degrees of freedom. Similarly, when the rotational speeds (levels) are not too high, the energy difference between the vibrational and nuclear motion is a few orders of magnitude, thus permitting their independent treatment.

The choice of representation for the unknown $(N+1)$ electron wave function, $\psi(\mathbf{r}_0 \dots \mathbf{r}_N; \mathbf{R})$ is of course arbitrary, though the physics does logically favour its expansion in the complete set of target eigenstates,

$$\psi(\mathbf{r}_0 \dots \mathbf{r}_N; \mathbf{R}) = A \sum_{\alpha} (\phi_n \chi_{nv} \rho_{nvj})_{\alpha} F_{\alpha}(\mathbf{r}_0) \quad (4)$$

where the electronic, vibrational, and rotational states of the N -electron molecular target are assumed to be known. The operator A ensures the total wavefunction ψ is antisymmetric, which is a mathematical way of imposing the Pauli exclusion principle.

Equation (4) involves both a summation over the infinite set of discrete target states, and an integration over the target continuum states (α collectively represents $n, v, \text{ and } j$). In practice, most of the elec-

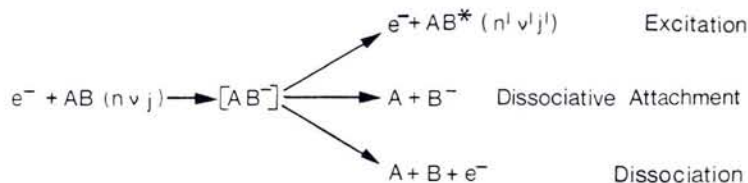


Fig. 1 — Some electron-molecule collision processes.

tronic components of the collision interaction are incorporated by the inclusion of just a small number of n terms (and/or "pseudo"- n terms, i.e. ϕ s which are not true molecular states but rather represent a large number of true states). The physics of the collision are inserted by applying the appropriate boundary conditions on the wave function (4). For example, the asymptotic form of a scattering electron's wave function $F_{\alpha'}$, represents an electron (plane wave), with energy $\hbar^2 k_{\alpha'}^2 / 2m_e$, incident upon a molecule in state α' , and having excited the final state α' , the electron scattering (spherical wave), with an energy $\hbar^2 k_{\alpha'}^2 / 2m_e$, and an angular distribution determined by a transition matrix $T_{\alpha' \alpha}$. What the experimentalist measures is the scattering cross section:

$$d\sigma_{\alpha' \alpha} / d\hat{r}_o = k_{\alpha'} / k_{\alpha} |T_{\alpha' \alpha}|^2 \quad (5)$$

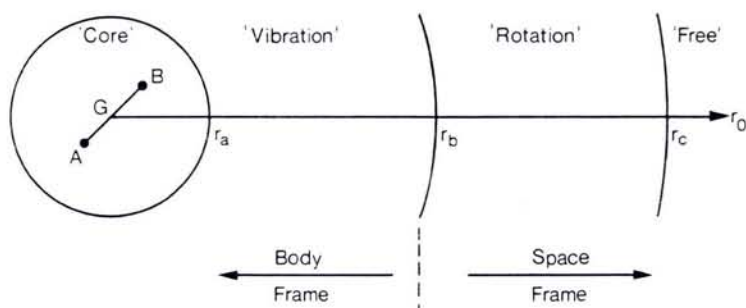
where \hat{r}_o denotes the scattering angle.

Three major difficulties confront the theorist in attempting to solve the Schrödinger equation for electron-molecule collisions. Firstly, the molecule, and therefore the electron-molecule interaction, V_o , is aspherical. This means, that if, as is standard practice, a partial wave expansion of the scattering electron's wave function, $F_{\alpha'}$, is made, i.e.

$$F_{\alpha'}(r_o) = \sum_l F_{\alpha'}(r_o) Y_{lm}(\hat{r}_o) \quad (6)$$

(where l is associated with an electron with angular momentum l) the $F_{\alpha'}$ in (6) can all couple with each other through V_o . This is in total contrast with electron-atom scattering, where the solutions for each $F_{\alpha'}$ can be determined independently in the Schrödinger equation (2). The l -coupling which occurs in electron-molecule collisions dramatically increases the size and number of the equations which need to be solved simultaneously, in order to derive the scattering cross section.

Fig. 3 — The electron-molecule interaction at various distances of the scattering electron from the molecule.



The second difficulty is the multi-centredness of molecules. If a single centre coordinate system (e.g. spherical polar, r, θ, ϕ) is adopted, the theorist must cope with potential singularities (i.e. the nuclei) displaced from the coordinate centre. Representing the scattering electron's wave function near these singularities with an expansion about the coordinate centre, is a non-trivial matter.

that an electron with energy 4 eV, say, although unlikely to excite any electronic states of the target, can cause excitation into any of the first ten vibrational levels and any of the 15 or 20 rotational states associated with each vibrational state (i.e. ~ 200 rovibrational states in all). And on top of that, it can also induce dissociative attachment via the $^2\Sigma_u^+$ resonance of H_2^- . Clearly, our approach needs to undergo a drastic simplification if a workable theory for low energy electron-molecule collisions is to be found.

Frame Transformation Approach

The theoretical analysis of bound state molecular spectra is greatly aided by the invocation of the Born-Oppenheimer approx-

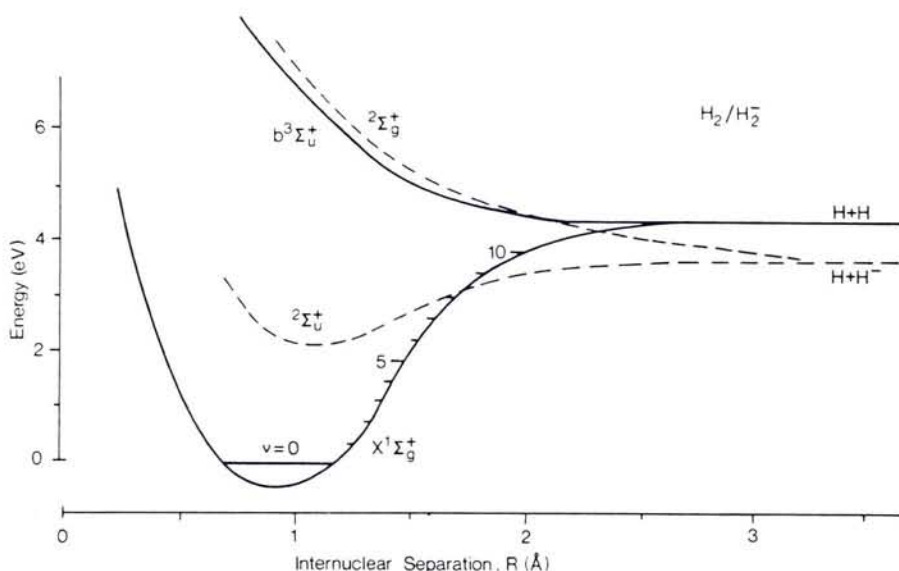


Fig. 2 — Electronic states of H_2 and H_2^- in the range 0-6 eV above the ground state.

The final and most basic difficulty (and the most challenging!) is that molecules possess nuclear as well as electronic degrees of freedom: i.e. they can rotate, vibrate, and even dissociate (see Fig. 1). It takes little effort to realise what havoc this can cause in any attempt to solve the Schrödinger equation using a target state expansion of the form (4). Taking electron scattering by molecular hydrogen to illustrate this point, it is apparent from Fig. 2

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imination which permits the separation of the electronic, vibrational, and rotational solutions of the Schrödinger equation, i.e. ϕ , χ , and ρ . It would be very useful if the Born-Oppenheimer approximation were also applicable in electron-molecule collisions. Certainly, when the scattering electron is within some distance (r_a , say, as in Fig. 3) from the molecule, it is completely indistinguishable from the other electrons, in that the strength of the coulomb interactions acting on it will be equivalent to that experienced by the bound electrons. It follows that within this "core" region, at least, a Born-Oppenheimer separation of the electronic, vibrational, and rotational solutions to the Schrödinger equation for the scattering problem can be employed. The molecular orientation (rotation) in space will be inconsequential to the scattering electron, and electronic solutions can be determined at fixed internuclear separations, using a body-fixed coordinate frame of reference.

At the other extreme, as a free electron approaches a molecule, it first experiences

a weak rotating field. The electron-molecule interaction at this stage is insufficient to effect either the vibrational or electronic motion of the target, but may cause rotational excitation. In this "rotational" region (Fig. 3), therefore, the molecule may be treated as a vibrationless charge distribution rotating in space, and the total wave function (4) needs to be expanded in terms of the target rotational states, ρ , only. The scattering equations are consequently solved in the space frame.

Finally, an intermediate "vibrational" region may exist in which the scattering electron can cause sufficient distortion of the molecular charge distribution to disturb the vibrational motion of the nuclei and induce vibrational transitions, or dissociation. If so, the electronic-nuclear interaction in this region will be non-adiabatic and the vibrational functions, χ , in (4) will have to be included.

The break-up of the scattering process into these distinct regions was first suggested by E.S. Chang and U. Fano and incorporated in their frame transformation theory of electron-molecule collisions. They suggested that the optimal representation of the solution, $\psi(\mathbf{r}_0 \dots \mathbf{r}_N; \mathbf{R})$ should be adopted for each region, and an appropriate transformation made at the dividing surfaces r_a and r_b . It may now be reasonably asked where these dividing surfaces lie.

It transpires (amazingly!) that for low energy electron-molecule collisions, the core region in Fig. 3 in general extends all the way out to the asymptotic ("free") region where a cross section can be determined. The Schrödinger equation for the scattering process may be solved for a fixed value of the internuclear separation, \mathbf{R} , (the equilibrium separation, \mathbf{R}_e , is normally chosen) and for fixed molecular orientations. The total scattering cross section is calculated by averaging over all possible orientations, whilst rotational excitation cross sections are derived by a simple mathematical transformation of the total cross section. Likewise, vibrational excitation cross sections are determined by solving the scattering equations for different values of \mathbf{R} , and averaging the resulting cross sections over the vibrational states of the target. This approach is referred to as the fixed nuclei or adiabatic theory of electron-molecule scattering. It can be appreciated in a very simple fashion when one considers that for an electron with an energy of the order of an eV, the total scattering time (i.e. the time taken to get from the free region into the core, and back out again) is only a small fraction of the vibrational or rotational period of the molecule. To all intents and purposes, the electron "sees" a stationary target.

There are two very important cases in which the adiabatic theory does not apply and where inclusion of either the

"rotation" region, or the "vibration" region is essential for an adequate theoretical description of the scattering process.

This first case, which requires the inclusion of the "rotation" region is when the target molecule possesses a permanent dipole moment (e.g. all heteronuclear diatomic molecules, H_2O , etc.). Scattering by a fixed dipole potential r_o^{-2} always leads to a divergent total cross section. If, however, the dipole is allowed to rotate it no longer behaves as r_o^{-2} since the rotational motion will average it out, and a finite cross section is obtained.

The second situation in which the adiabatic theory breaks down is at and near resonances. When the incident electron is trapped temporarily in a resonant state, the collision time is increased dramatically and it is no longer a mere fraction of the vibrational period. In such circumstances the electronic and nuclear motions will couple strongly and inclusion of the "vibration" region may be required. Furthermore, the nuclear as well as the electronic wave equations need to be solved within the core region, although, as we have already stated, this can be done separately by employing the Born-Oppenheimer approximation.

Numerical Techniques

The asphericity and multi-centredness of the molecule in any collision process will affect the scattering electron primarily at short range within the core region of Fig. 3.

A standard approach to solving any electron scattering process is to introduce an expansion of the form (4), (over electronic states only as the fixed nuclei approximation is assumed) into the Schrödinger equation and to integrate numerically the resulting coupled second order integro-differential equations to determine the scattering wave functions, F_α . In performing these integrations it is mathematically very convenient if a single centred coordinate system is used as: (a) it allows the exploitation of a number of numerical integration techniques well tested on electron-atom scattering, and (b) any electron-molecule collision is effectively single centred at asymptotic distances where the cross sections are calculated. The introduction of a single coordinate centre does mean however that the bound and continuum molecular orbitals, as well as the electron-molecule interactions, V_o , must be represented by expansions about the new centre (usually the centre-of-mass). And as the electron-nuclei interactions are singular at the nuclei it is not surprising that the expansion of the interaction near the nuclei is very slowly convergent which in turn gives rise to a slow convergence in the partial wave expansion (6) of the scattering electron's wave func-

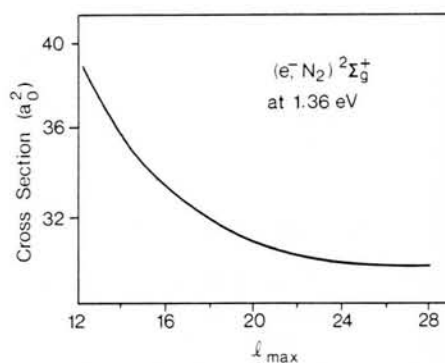


Fig. 4 — An example of the convergence of the single centre expansion of the scattering wave function (by L.A. Collins and M.A. Morrison).

tion. The upshot of all this is that a very large set of coupled (in l) equations must be integrated in order fully to solve the scattering problem. To illustrate these difficulties the slow convergence of the calculated cross section as a function of the maximum number of l -terms included in (6) is shown in Fig. 4 for the case of electron scattering by molecular nitrogen.

One might ask at this point why not use a more natural coordinate system for the scattering equations, such as for example, a spheroidal system for diatomic targets. Indeed, why not! A number of theorists have developed scattering codes using prolate spheroidal coordinates for electron scattering by diatomic targets, and have demonstrated clearly that the convergence problems met in the single centre approaches do not arise. A major drawback to this approach to the scattering equations, however, is the fact that, it is not readily applicable to triatomic or larger polyatomic molecules. Each larger molecule would require a new coordinate system, further development of the formalisms and computer codes, and the expenditure of much more manpower. The single centre formalism and codes are, on the other hand, easily applied to any molecule. Finally the marked improvement in integration techniques, and most especially in computational facilities, which have taken place in the past few years has made the implementation of the single centre approach not nearly as prohibitive as it once was.

Bound State Techniques

In molecular structure calculations the difficulties associated with the asphericity and multi-centredness of molecules are largely overcome by the employment of multi-centred expansions of analytic functions to represent the molecular wave functions. It is of interest to ask whether the bound state approach can be employed in scattering theory. The answer is, it can, and it has!

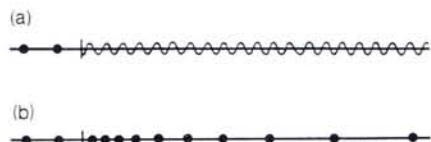
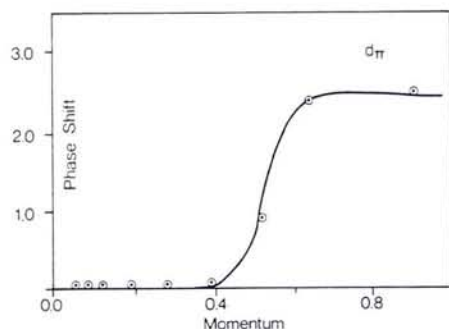


Fig. 5 — (a) The true eigenspectrum for an electron-molecule scattering system and
(b) The eigenspectrum obtained using a ten-term L^2 representation of the scattering wave function.

Bound state techniques were first employed for the continuous region of the electron-molecule eigenspectrum to determine the positions, and later the widths of resonances. When the scattering wave function is represented at distances not too far removed from the molecule by a finite analytic basis, the true eigenspectrum, Fig. 5(a) is replaced by the discrete spectrum of Fig. 5(b); i.e. the continuous spectrum above zero energy is discretized. A. Hazi and H.S. Taylor noted many years ago that some of the eigenvalues of Fig. 5(b) were remarkably stable against variations in the parameters of the basis, and were able to identify these stable roots with scattering resonances in the electron-molecule systems. Another bound state method, is based on a projection operator technique. This method however, is, strictly speaking, only valid for Feshbach resonances (resonances in which the target molecule is electronically excited and the scattering electron attaches itself at an energy below this excited state). An advantage of this technique over the stabilization method is that a single calculation can, in principle, determine the resonances, as there is no need to vary the basis. This approach has recently been further extended to determine resonance widths.

Bound state techniques can also be used to calculate scattering cross sections. We know that analytic basis sets can provide an accurate representation of the wave function at the eigenenergies, E_k of the Hamiltonian in the region where the basis is non-zero. If the Hamiltonian eigenfunctions are matched to scattering solutions

Fig. 6 — An L^2 calculation of the phaseshifts in electron-nitrogen scattering (dots) by C.W. McCurdy, T.N. Rescigno, and V. McKoy compared with a single centre calculation by the author (continuous line).



with the correct asymptotic form, then the transition matrices $T_{\alpha' \alpha}$ and therefore the scattering cross sections can be obtained. An example of how accurate this approach can be is shown for elastic electron-nitrogen scattering in Fig. 6.

There are a number of basic difficulties with these fairly simple analytic basis set approaches to electron-molecule collisions. First, they are valid only at the energies E_k . To determine scattering cross sections, for example, at all energies, either an interpolation procedure must be used or the parameters in the calculations varied to move the E_k . Further, the region over which the basis should be non-zero to produce accurate cross sections is ill-defined. Certainly, when the electron-molecule interaction is strong over a long range, such as can happen with polar molecules, the region where the basis must be non-zero will be very extended and can prove cumbersome to represent in this manner. Consequently in the last few years, interest has turned to two approaches which can avoid most of these difficulties.

The T-matrix method starts with the Lippmann-Schwinger equation (an integral form of the Schrödinger equation) for the transition matrix

$$T = 2V_0 + 2V_0 G_0^+ T \quad (12)$$

where G^+ is the free electron Green's function, the integral operator

$$[-(\hbar^2/2m_e) \nabla_0^2 - E]^{-1}.$$

By expanding the electron-molecule interaction, V_0 , (rather than the wave function ψ) in a finite basis, the integral equation (7) becomes a matrix equation for T and can be solved by standard matrix manipulation.

Although the T-matrix method has now been successfully applied to elastic scattering by many diatomic molecules, it suffers from two drawbacks. Firstly, its extension to electronically inelastic collisions is proving difficult, and secondly like the earlier L^2 -method, it becomes exceedingly cumbersome for cases with strong long range interactions. Whereas the solution to the first drawback is not yet clear, the latter difficulty can be largely overcome by writing the interaction V_0 in separable form and requiring the T-matrix (7) to satisfy the Schwinger variational principle.

An L^2 approach which attempts to bypass all the aforementioned difficulties is the R-matrix method, first introduced into nuclear collision theory by E.P. Wigner and L. Eisenbud in the late forties. Instead of employing a multi-centred expansion to represent the wavefunction over an indefinite region, it uses it only within a well-defined internal spherical region about the molecule (see Fig. 7). Within this internal region the effects of the multi-centredness of the molecule, the electron exchange and other many-body interactions dominate the collision. Furthermore because the solu-

tions to the Hamiltonian being sought are within a finite rather than an infinite region of space, the discretisation of the Hamiltonian eigenspectrum which occurs, is a real effect and not an artifact. In the external region, where only the long range components of the interaction remain, a single centre expansion is used and solutions to the Schrödinger equation calculated by the numerical techniques mentioned earlier. The scattering solutions over all space are finally determined by matching the internal and external solutions at the dividing boundary. The matrix which effects this matching is called the R-matrix.

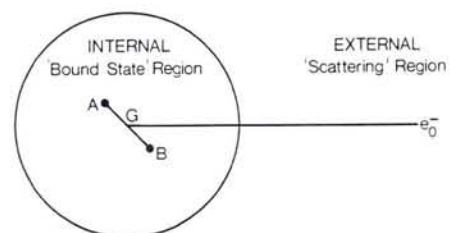
As an analytical basis set approach, the R-matrix method has at least two very obvious advantages over the other methods. First it can employ a target state expansion of the form (4) to represent the wave function in both the internal and external regions, thus avoiding any difficulties in describing inelastic scattering processes. Second, it complements the frame transformation approach in that the internal R-matrix region is essentially synonymous with the core region of the frame transformation approach. A very fine example of this is the R-matrix calculation of vibrational excitation in electron-molecular nitrogen scattering near the 2.4 eV resonance, shown in Fig. 8. It will be very interesting to see if the same approach will prove as fruitful when applied to such processes as dissociative attachment. The signs are very hopeful.

In Conclusion

A conclusion in a paper on the theory of low energy electron-molecule collisions seems somewhat inappropriate, as the situation is changing rapidly and excitingly. Computer codes using the single centre expansion method are now available which can be used for most small diatomic and triatomic molecules at non-resonant energies. These codes can determine, with an accuracy comparable with experiment, cross sections for elastic and vibrationally inelastic collisions. Also very recently, the first results for electronic excitation of H_2^+ have been reported using these codes.

The situation with respect to the "bound state method" codes (i.e. T-matrix and R-matrix) is much the same with non-resonant elastic and rotationally and vibra-

Fig. 7 — The division of configuration space in the R-Matrix approach.



tionally inelastic cross sections now readily calculable. The most exciting result, however, to appear recently, must be the *ab initio* R-matrix calculation of B.I. Schneider, M. Le Dourneuf and Vo Ky Lon on electron-nitrogen scattering near the 2.4 eV resonance. By including the electronic-nuclear interaction, they were able to reproduce faithfully all the vibrational substructure observed in the collisional cross sections near and at this resonance.

An Acknowledgement

In preparing this article, it was inevitable that a number of notable contributions to the subject of electron-molecule scattering would be omitted. For example, many significant insights into the nature of electron-molecule resonances have been afforded by the resonance theory of N. Bardsley, A. Herzenberg, F. Mandl and others, and much has been contributed by L.A. Collin, M.A. Morrison, D.W. Robb and others to the computationally difficult problem of the inclusion of exchange in the numerical approaches. Similarly, many of my colleagues have put much effort into the very daunting question of how best to represent molecular polarisation in low energy electron scattering. These unavoidable omissions, however, only further

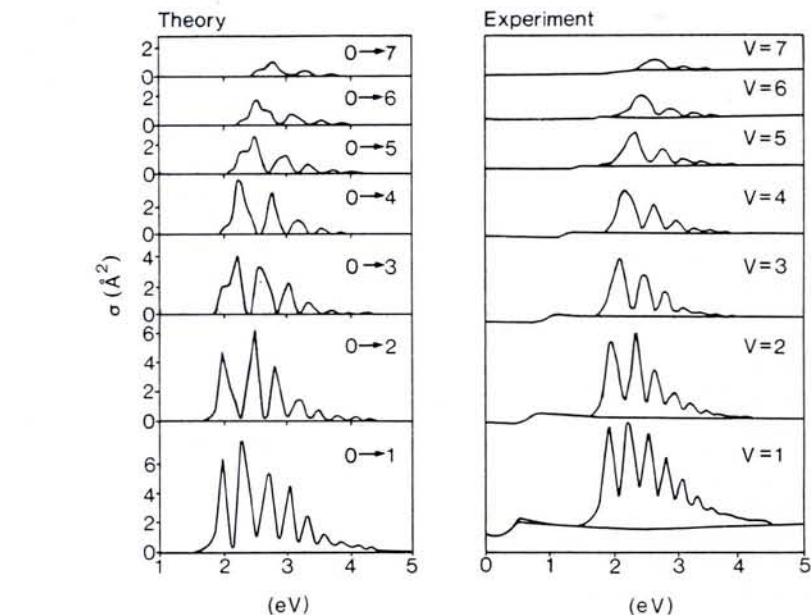


Fig. 8 — An R-Matrix calculation of the vibrational excitation cross sections in $e^- + N_2$ near the $2.4 \text{ eV } ^2\Pi_g$ resonance, (by B.I. Schneider, M. Le Dourneuf and Vo Ky Lon).

strengthen my assertion that atomic and molecular physics, and electron-molecule scattering in particular, are both important and exciting areas for a theorist to be working in today.

Further Reading

"Electron Molecule and Photon Molecule Collisions" Ed: T. Rescigno, V. McKoy, and B. Schneider. (Plenum Press, New York) 1979.

On-line Information Retrieval

Sir,

In your recent article "Searching the Literature: an enquiry by *Europhysics News*" (May 1980), you mention that *Europhysics News* knows of no single document which summarizes in any comprehensive way the services offered by the various hosts, and which include the data bases that are available and the sources from which these have been compiled.

I think you will find that HALL, J.L. *On-line Bibliographic Data bases 1979 Directory* (Aslib: London, 1979) to some extent serves as such a document. Although mainly relating to on-line bibliographic data bases, this work also lists other related on-line data bases e.g. data banks and data bases planned to go on-line in the future. This directory could be supplemented by TOMBERG, Alex *Data Bases in Europe: a directory to machine-readable data bases and data banks in Europe, 3rd. ed.* (Aslib; London, 1977). Whilst both of these works are somewhat out of date, I understand that the work by Hall will be updated some time in the future. This indeed points to one of the major problems of producing such a directory — the field is constantly changing and any directory is likely to be out of date as soon as it is in print.

I would also like to point out a major advantage of the on-line systems that was not evident from your article. This relates to the fact that the on-line database allows

one to search for the information in a fashion that is not available in the traditional abstracting or indexing journals. The traditional abstracting journals may be used in two basic ways:

(1) as a current awareness journal, i.e. the researcher turns to the relevant section of the journal and scans the entries covering his own field of interest or

(2) as a retrospective search aid, i.e. the researcher looks up the subject index for the topic he is interested in and this refers him to entries relating to that subject. The trouble with this retrospective search method is that the researcher is dependent on the indexing language used by the abs-

tracting journal and this can be slow to pick up new terminology. This, in my opinion, is where one of the advantages of the on-line search technique comes in. As well as having this "controlled index" approach available to it (in most data bases e.g. INSPEC) it also has the facility to look for "key words" in the title, abstract or indexing terminology. Thus the researcher can often pick up references that he was unable to obtain using the conventional subject index.

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