reprinted from: Sheldon Datz, AIP Conference Proceedings **205** (1990) 2–13

Keynote Lecture of ICPEAC XVI (New York 1989)

ON THE UTILITY AND UBIQUITY OF ATOMIC COLLISION PHYSICS

Sheldon Datz

Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6377, USA

This paper is divided into three parts. In the introduction, we discuss the history and makeup of ICPEAC. In the second part, we discuss the extent of applicability of atomic collision physics. In the third part, we chose one subject (dielectronic excitation) to show the interrelationship of various sub-branches of atomic collision physics

I. INTRODUCTION

From the Preface to Book of Abstracts for ICPEAC II (Boulder, Colorado, 1961):

> *"This conference is the second in a series of informal meetings organized by a group of workers in the general field of electronic and atomic collisions. The first such meeting was held at New York University in 1958, and we will probably continue to meet at irregular intervals in the future ...."*
>
> *Benjamin Bederson*
> *Conference Secretary*

This is the thirtieth anniversary, actually the thirty first, of ICPEAC. It all began in New York in 1958 with 70-80 people getting together at New York University for two days to discuss their mutual concerns. There were 47 papers, a book of abstracts, a cocktail party at the Fifth Avenue Hotel, and a good time was had by all. Since that time, the conference has grown by more than a factor of ten.

To refresh your memories, the conferences occurred as follows:

I	New York, NY	1958
II	Boulder, CO	1961
III	London, UK	1963
IV	Quebec, Canada	1965
V	Leningrad, USSR	1967
VI	Cambridge, MA	1969
VII	Amsterdam, the Netherlands	1971
VIII	Beograd, Yugoslavia	1973
IX	Seattle, WA	1975
X	Paris, France	1977
XI	Kyoto, Japan	1979
XII	Gatlinburg, TN	1981
XIII	W. Berlin, FRG	1983
XIV	Stanford, CA	1985
XV	Brighton, England	1987
XVI	New York, NY	1989

Committees can vote on policies and invited papers, but participants vote with their interest, their airplane tickets, and their contributed papers. Fig. 1 shows the growth of contributed papers *ab ovo*. The growth is almost continuous with jogs developing at *ca* 1980, because of the accelerated growth of the field in Europe. In its present form, one might expect an asymptote at ~900 – 1000 total contributed papers.

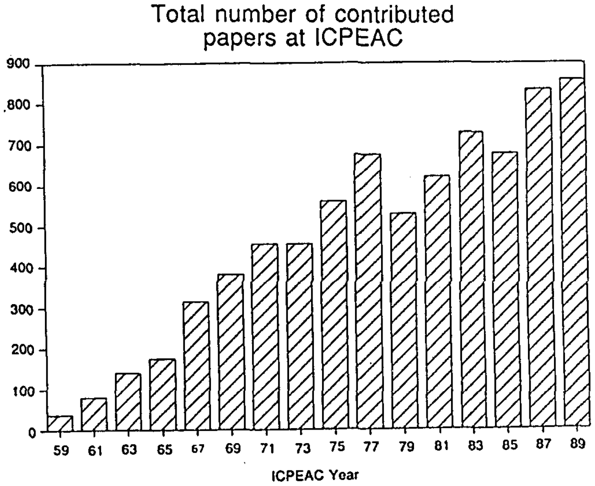

FIG. 1. Total number of contributed papers at ICPEAC.

In Fig. 2, we show the trends in subfields over the last six ICPEACs. Taking an even more detailed look at sub-disciplines and assuming no radical changes in ICPEAC policy or government funding profiles, one might safely predict for example:

- continued but declining dominance of ion-atom collisions
- steady decline in ion/atom-molecule fraction
- growth in high temperature plasma related fields, e.g., ion-ion and electron-ion collisions
- growth in collisions of "exotic" e^+, $\bar{p}$, $\mu^{\pm}$, etc. species
- possible growth in clusters and solid interactions
- continued growth in photon-atom/molecule collisions.

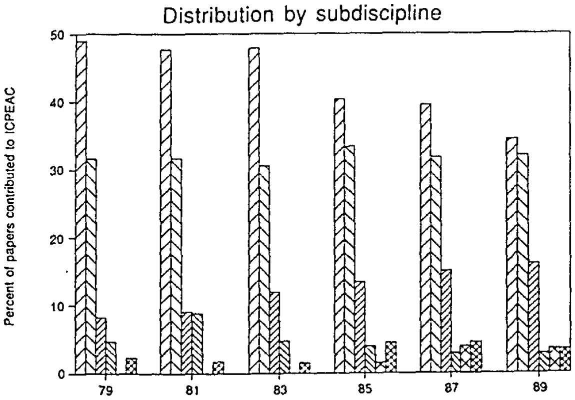

FIG. 2. Distribution of contributed papers among the sub-fields of ICPEAC over the last six conferences. ▨ ion/atom-atom/mol; ▧ e^--atom/mol.; ▨ hν-atom/mol.; ▧ Rydbergs and field assisted; ☒ exotic species; ▦ solids and clusters.

This latter point is especially worth noting. Since it's humble beginning as two contributed papers in 1965, photon interactions have grown to 130 contributions (16%) at the present meeting. This growth, shown in Fig. 2, is correlated with the development of the new tools, lasers and synchrotron light sources. It is further noteworthy that almost a third of this work involves the interaction of photons and with molecules; neither of these collision partners is mentioned in the present conference title. Evidently the practitioners in this area feel a strong identification with the community of collision physicists, rather than spectroscopists.

II. THE APPLICABILITY OF ATOMIC COLLISION PHYSICS

The need for detailed knowledge of atomic collision physics permeates many fields of science and technology. In nuclear physics, for example, there is a need for information on stopping powers and on the states of energetic ions penetrating solids and gases.[1] In this latter case, the need arises in the study of hyperfine interactions by, e.g., perturbed angular correlations.

A. Condensed Matter Physics

In condensed matter physics, the applications are very broad. They include methods of surface and near surface characterization and materials modification. A number of these are listed in Table I.

You will note that the range of energies used in the atomic probes of solids is quite broad. This breadth is a characteristic of atomic collision physics. In fact, the range exceeds that found in any other branch of science. This is illustrated in Fig. 3 where we show atomic collision physics related branches of science and technology as a function of energy; the range covers 16 orders of magnitude in energy!

Actually, if one wishes, one could include even lower energy interactions such as those involving hyperfine state changes in atomic hydrogen which occur at 1420 MHz = 6×10^{-6} eV (0.1 cal./mol.) in the interstellar medium. But, instead, I have taken, as a lower base, the mean temperature of the interstellar medium 10°K ~ 10^{-3} eV. Since the recent proposal to build THC, a heavy-ion (hadron) collider at CERN, we could extend the upper end to $\sim 10^{15}$ eV (Pb at 4 TeV/c/amu).

B. Astrophysics

The range of atomic collision energies involved in astrophysics covers the entire extent shown in Fig. 3 and, as was pointed out in Alex Dalgarno's ICPEAC XII paper,[3] *"Most of the knowledge we have about the universe resides in the form of photons. To interpret the message they bring in their journey to us, we must reconstruct the events in which they participated... The processes which produce the photons and the processes which modify them belong usually to the domain of electron, atomic, and molecular physics."*

In Fig. 4, a picture of the sun taken with radiation at 173 Å (±1 Å) is shown. The light emanates mostly from Fe IX and Fe X in the solar corona at $\sim 10^6$ degrees ($\sim 10^2$ eV).[4] Many features in the corona structure (loops, levels, etc.) are visible. It is noteworthy here that a discrepancy of a factor of two in the temperature of the solar corona as measured by the density of gradient of the corona and the Doppler widths of the spectral lines and by abundances of Na-like Fe was settled by Burgess,[5] who introduced dielectronic recom-

Table I. Some Applications of Atomic Collision Physics to Condensed Matter Science and Technology.[2]

Low Energy Ion Scattering and Atomic Diffraction (0.01 eV - 1 keV)	Top surface composition and structure.
High Energy Ion Scattering (100 keV - 10 MeV)	Atomic composition of surface and near surface layers. Lattice location of impurities in single crystals.
Ion-Induced X-Ray Emission (1 - 100 MeV)	Proton induced X-ray analysis. Heavy ion induced X-ray spectra, atomic environment at lattice site.
Secondary Ion Mass Spectrometry (100 eV - 10 keV)	Sputtered ions are analyzed; depth profiling possible.
Photoelectron and Auger Spectroscopy (50 eV - 1 keV)	Surface and near surface composition.
X-ray Fluorescence Analysis (100 eV - 100 keV)	Atomic composition in near surface region.
Material Modification; Ion-Implantation (100 keV - 10 MeV)	Modification of mechanical, chemical, and electronic properties.
Microfabrication (10 - 100 keV)	Photo-, X ray-, electron beam-, and ion beam-lithography
Radiation Biology (1 eV - 10 GeV)	Interactions of ionizing radiation and particles with biological systems (also heavy ion therapy).

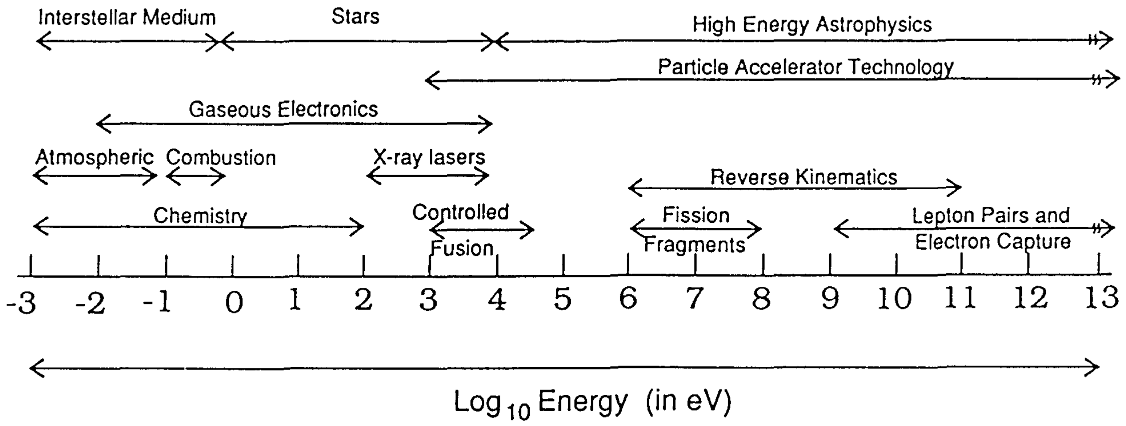

Fig. 3. Some of the sciences and technologies which require atomic collision physics input as a function of the relevant energy range.

Fig. 4. The solar corona as photographed in the emission of the resonance lines of Fe IX at 171 Å and Ge X at 174.5 Å. The dark bands visible at northern latitudes are due to overlying cool prominences. The image corresponds to coronal structures from ~0.8 x 10^6 to 1.4 x 10^6 K.

FIG. 5. The Cygnus loop photographed using its emitted soft X-ray radiation.

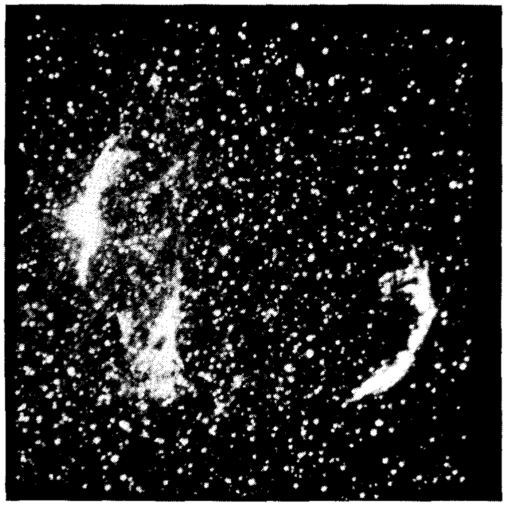

FIG. 6. The Cygnus loop photographed using its emitted green O^+ light.

bination as an additional mechanism to reduce the mean ionic charge.

A picture of the Cygnus loop,[6] taken with soft (8 — 80 Å) X rays, is shown in Fig. 5. The Cygnus loop is a supernova remnant which has expanded to the point where we can look at detailed structure. Another area is revealed in a photograph (Fig. 6) taken with visible light coming from a cooler shell. In the visible, the oxygen rich supernova remnant will look very green in a color photograph because of the large contribution from the 4959 Å and 5007 Å O III lines. Information of the sort presented in these figures is vital to all theories of Stellar evolution.

At ICPEAC XVI, we shall have two plenary talks on collision physics in relation to astrophysics. At the low energy end, a lecture on "Low Energy Molecular Collisions with Applications to Interstellar Cloud Problems" by K. Takayanagi, and a lecture covering a recent very notable higher energy event "Atomic and Molecular Processes in Supernova 1987A" by R. A. McCray.

C. Chemically Reactive Collisions

Chemically reactive collisions, and here I include ion-molecule reactions, also covers a broad range on a logarithmic scale of energies. The coldest to my knowledge being the observation of the reactions

$$\begin{aligned} He^+ + H_2 &\rightarrow He + H + H^+ \\ &\rightarrow He + H_2^+ + h\nu \end{aligned}$$

at 10°K (10^{-3} eV) in an ion trap by a group at JILA.[7] It is noteworthy that the reaction of $He^+ + H_2$ has been studied at energies up to 1 MeV, hence 9 orders of magnitude. An entire symposium on "Collisions with Cold Particles," chaired by H. Metcalf, will be presented at this conference.

The upper portion of the energy range belongs to hot atom chemistry and ion molecule reactions.

The subject of chemical kinetics was liberated from the bulb and the test tube in the mid 1950's with the successful application of molecular beam techniques.[8] Two papers on the subject appeared at ICPEAC II in 1961. One was on "Reactive Scattering of Velocity Selected K Atoms" by D. Beck, E. F. Greene, and J. Ross,[9] and the other entitled "Reactive Scattering in Crossed Molecular Beams" by G. H. Kwei, J. A. Norris, J. L. Kinsey, and D. R. Hershbach[10] discussed the reactions of CH_3I + K, Rb, and Cs. This was, in fact, the first publication from the Hershbach group.

By the mid-1970's, the scope of the technique was already permitting the investigation of state-to-state chemically reactive collisions as illustrated in Fig. 7, which is taken from a 1973 review by Hershbach.[11] It illustrates the range of reactions available for study at the time together with the possible ways of preparing specific reagent states and analysis of product states. The enormous progress that has been made since these early days is exemplified at this conference by the plenary paper of Y. T. Lee on "Molecular Beam Studies of Chemical Reactions" and the review paper by W. H. Miller on "Recent Developments in the Theory and Application of Quantum, Scattering Theory for Chemical Reactions."

D. Atmospheric Physics

Atomic collision processes control the composition of the upper atmosphere and, to a growing extent, also the lower atmosphere. One has to be totally illiterate not to be aware of the threats to the lower atmosphere by the massive production of polutants such as NO_x and O_3 and threats to the upper atmosphere by the even increasing CO_2 concentration with its attendant "Greenhouse Effect" and by the disappearance of the protective ozone layer which is being attacked by free chlorine atoms photolytically produced from chloro-fluoro carbons. The potential ozone disaster was first described by S. Rowland, a hot-atom chemist from the

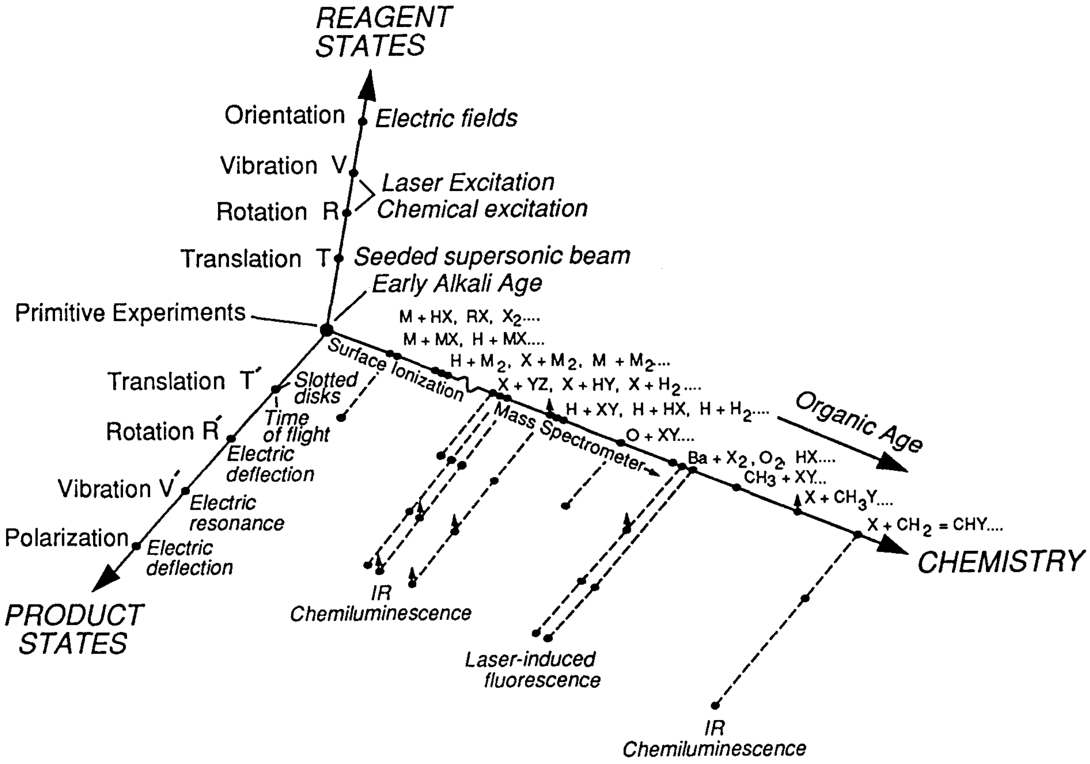

FIG. 7. Domains accessible to molecular beam chemistry, circa 1973.

University of California at Irvine almost twenty years ago. The effect is explained by a simple series of binary atom molecule collisions. To determine whether chloro-fluro carbons were truly a threat or whether competing natural processes would mitigate the effect required careful measurements of a whole series of reaction cross sections. Needless to say, the impact of these many threats on the chemical industry, the worlds economy, methods of energy generation, conservation, etc., are potentially enormous and contributions to knowledge by members of our craft may do much to help find solutions to alleviate these problems.

On a more benificent note, we can enjoy the collisional interactions of electrons exciting the oxygen red line at 6300 Å as they swirl in the earth's magnetic field[12] and create the red aurora borealis via the $2p^4\ ^1D \rightarrow 2p^4\ ^3P$ transition (Fig. 8).

Fig. 8. The red aurora.

E. X-ray Lasers

As we move up in energy, we enter the region of incompletely ionized plasmas and hence the area of gaseous electronics. This is an area of enormously broad utility ranging from such mundane things as gas discharge lighting of our streets at the low energy end to the presently exotic lasers at the higher end.

As is the case with any normal gas laser, the photons arise from the stimulation of transitions of outer shell electrons with inverted populations.[13] Since the energy levels of highly ionized species are further apart, the product photons are in the X-ray region. The population inversion needs pumping, and, because of the short radiative lifetimes involved, this creates special problems. In general, X-ray laser schemes utilize atomic collision processes to pump the inversion. The two inversion schemes presently in use are recombination to inverted states in a cooling plasma and free-electron collisional pumping. In particular, I should like to note that it was necessary to develop a dielectronic recombination theory to explain the kinetics responsible for the strong amplification in the $3p \rightarrow 3s$ ($J = 2 \rightarrow 1$) line of neon-like selenium[14] (see below). A review talk on the "Atomic Physics of Soft X-Ray Lasers" will be presented at this conference by A. V. Hazi.

F. Fission Fragments, Tracks and Stopping Powers

More complex is the understanding of the interaction of energetic heavy ions, such as fission fragments with the solids into which they recoil and, in general, the physics of heavy particle tracks. Very recent studies by Schmidt-Böcking and co-workers and by Ron Olson on the details of inelasticity and secondary electron production in such collisions now show great promise to finally understand the phenomena on an atomic basis.[15]

G. Fusion

Even a cursory discussion of the need for atomic collision data in the development of magnetically confined controlled fusion plasmas, as well as inertially confined plasmas, could easily take up this entire talk. Numerous reviews and conferences have been devoted to just this subject. Suffice it to say here that any and all information on collisional processes of electrons, hydrogen atoms, hydrogen molecules, He ions, totally and partially stripped heavy ions in the energy range of a few eV (plasma edge) to tens of keV (plasma center) are of immediate interest to this extremely important technology of the future. Immediately relevant invited papers at this conference include those by A. Bárányi, P. Hvelplund, R. Schuch, E. Salzborn, and L. Shmaenok.

H. Accelerator Technology

Particle accelerators are instruments with a much broader range of uses than is generally attributed to them (i.e., nuclear and particle physics). One need only peruse the proceedings of the latest conference on the "Application of Accelerators in Research and Industry"[16] to find in addition to 52 papers on accelerator technology; 95 papers on atomic physics and related phenomena; 20 papers on proton induced X-ray analysis (PIXE) and ion microprobes; 36 papers on materials analysis facilities, accelerator mass spectroscopy, Rutherford backscattering and channeling, nuclear reaction analysis, resonant ionization spectroscopy; and 13 papers on radiation therapy, neurosurgery with ion beams (this is only a partial list of papers).

Applications of atomic collision physics to accelerator technology actually begin with ion sources of which many are properly in the domain of gaseous electronics. Negative ion production is important for tandem Van de Graaffs[17] as is multicharged ion production for heavy particle accelerators. In this regard, a number of these multicharged ion sources, such as Electron Cyclotron Resonance Ion Sources (ECR), Electron Beam Ion Sources (EBIS), and the newly developed Electron Beam Ion Trap (EBIT) are themselves powerful tools with application to atomic collision physics.

Accelerated ions are often stripped of electrons by collisions in either gaseous or thin solid foils as in tandem electrostatic accelerators for further acceleration at higher charge states, or to achieve lower magnetic rigidity for injection into boosters. A knowledge of the electron capture and loss processes, and equilibrium charge states at the relevant energies is vital for the design parameters of these systems.[18]

Especially in synchrotrons where ions travel enormous pathlengths and especially during the acceleration phase, particles can be lost because of ionization or charge capture with background gas. Hence the requisite vacuum conditions and their associated costs are determined from a knowledge of charge-transfer cross sections.

I. Pair Production and Electron Capture

As we accelerate to even higher energies, the standard charge-changing cross sections decrease rapidly, but if we wish to take advantage of the available currents, and the kinematics of storage ring colliders, such as the proposed Relativistic Heavy Ion Collider (RHIC) at Brookhaven or the Hadron Collider at CERN, we encounter some new atomic physics phenomena namely lepton pair creation (e.g., electron-positron pairs) and negative lepton capture from the negative continuum.

To quote from a recent paper by Bottcher and Strayer[19] *"One of the most useful modern probes of hadronic matter is the associated production and decay of lepton pairs during a collision. In such collisions, lepton-hadron final state interactions are usually small, and hence the leptons carry direct information on the space-time region of creation. Historically, lepton pair production has been an important tool in collider experiments, in part, because of the special relationship between deep inelastic lepton-hadron scattering and the large mass Drell-Yan processes provide complementary information on quantum chromodynamics (QCD) in the asymptotic regime. From these experiments have arisen new ideas and phenomena: scaling, chiral and flavor symmetry, charm, and a quantitative understanding of a rich meson and baryon spectroscopy."*

The problem is that the cross section for lepton creation by non-nuclear electromagnetic (i.e., atomic physics) processes is larger than that for the desired process; hence a detailed knowledge of the cross section for their production, energy and angular distributions. The process is simply described as the formation of a virtual photon which decays by pair production. The venerable and elegant Weizaker-Williams approach to the problem is both approximate and perturbative and does not directly yield angular and energy distributions. More exact perturbative calculations have recently been carried out[19] and they, of course, differ somewhat from the Weizaker-Williams result. More disturbing, however, are the results of a non-perturbative calculation,[20] (see Fig. 9) which predicts differences of as much as factors of, e.g., 100 at RHIC energies (100 GeV/nucleon).

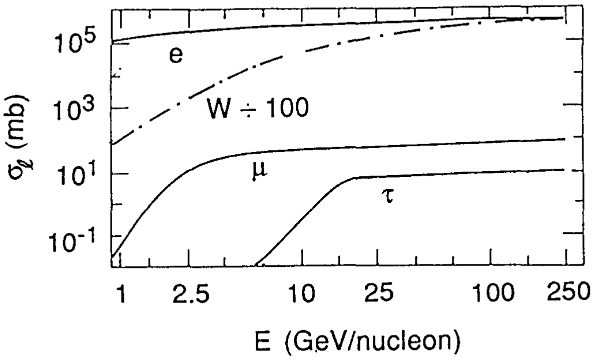

FIG. 9. Predicted cross sections (millibarns) for $e^\pm$, $\mu^\pm$, and $\tau^\pm$ pair production for $U^{92+} + U^{92+}$ collisions vs γ. For RHIC, $\gamma = 100$ for CERN SPS (200 GeV/c/amu) on a fixed target $\gamma = 10$. The solid line for $e^\pm$ from nonperturbative calculation is compared with the Weizaker-Williams calculation (W ÷ 100).

Since the pair is created in the immediate vicinity of the projectile nucleus, there is a strong posibility that the electron (negative lepton) may be captured. Hence the ionic charge changes and, if this occurs in a storage ring, the particle is lost. In fact, this process may be the limiting factor for containment times in such devices. Some detailed, but perturbative calculations have recently been carried out (Fig. 10),[21] but thus far no experiments have been performed. Clearly, this possible poison for particle physics poses a very interesting problem in atomic physics and proposals have been mounted for experiments on $e^{\pm}$ pair production and electron capture at SPS (200 GeV/amu - CERN), the AGS (20 GeV/amu - Brookhaven), and Bevelac (1 GeV/amu - Berkeley).

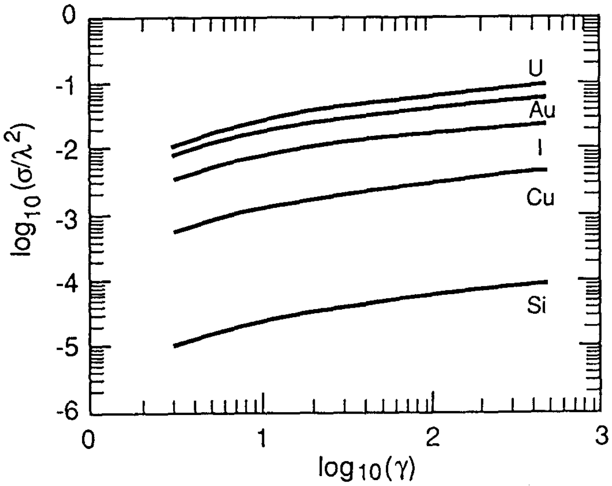

FIG. 10. Capture cross sections for symmetric $A_z + A_z$ collisions, scaled with respect to $\lambda^2 = 1.49$ Kb. Curves correspond as labeled, to the ions A(z) = Si(14), Cu(29), I(53), Au(79), and U(92), e.g., for U^{92+} at RHIC energies $\sigma_c \sim 100$ b.

J. Reverse Kinematics

The remaining bar on Fig. 3 "reverse kinematics" is not a science or a technology, but a name applied by nuclear physicists to a technique in which one uses high laboratory energy techniques to study collisions at lower center-of-mass energies; for example, an accelerated carbon ion is shot at a hydrogen target rather than a proton at a carbon target. Such kinematic tricks are in extensive use by atomic collision physicists as we shall see below.

III. DIELECTRONIC PROCESSES IN ELECTRON-ION, ION-ATOM, AND ION-SOLID COLLISIONS

Up to this point, we have been discussing the general utility of atomic collision physics in other fields of endeavor. At this point, I would like to become more specific and investigate the interaction between various and seemingly diverse branches of atomic collision physics in investigating a single problem, i.e., dielectronic excitation.

First, we will consider dielectronic recombination which occurs in collisions of ions with free electrons. This process is the dominant recombination mechanism in hot heavy-ion plasmas and, as we have indicated above is important to understand for such diverse applications as X-ray lasers and coronal temperatures. Second, we will examine resonant electron transfer and excitation (RTE) which occurs when an ion collides with an almost free electron weakly bound to an atom. Finally, we will take a look at recent studies of dielectronic excitation in crystal channels which have been shown to behave as dense Fermi electron targets.

Dielectronic recombination (DR) is initiated when a continuum electron excites a previously bound electron and in so doing loses just enough energy to be captured itself into a bound state ($n\ell$). The latter process results in a doubly excited ion (dielectronic excitation) in the next lower charge state which may either auto-ionize or emit a photon resulting in a stabilized recombination (Fig. 11). Thus, for an ion A of charge state q in initial state α, the DR process may be written:

$$A^{q+}(\alpha) + e^-(k,\ell') \rightleftarrows [A^{(q-1)+}(\beta,n\ell)]^{**} \rightarrow [A^{(q-1)+}(\alpha,n\ell)]^{*} + h\nu. \quad (1)$$

It should be noted here that the first step, i.e., the formation of the dielectronically excited state is the reverse of the Auger process. Experimental results in DR were first reported in 1983 at the Berlin ICPEAC in a "hot topic" symposium. Work has proceeded apace since then but two techniques which are giving qualitative improvements in the data have just come into fruition; these will be reported in invited talks by P. Hvelplund, R. Schuch, and A. Wolf. Both techniques utilize a merged electron-ion beam technique,[22] one in a single pass experiment[23] and the second as part of a cooled heavy-ion storage ring.[24]

The Aarhus experimental setup is described in a paper by P. Hvelplund in this volume. In the example we discuss here,[23] a beam of 20-MeV O^{6+} ions is merged with an electron beam

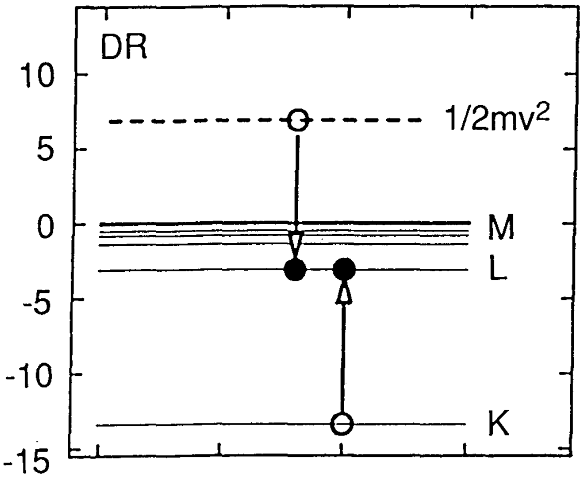

FIG. 11. Dielectronic excitation of a hydrogenic ion to a KLL state. Radiative relaxation leads to dielectronic recombination.

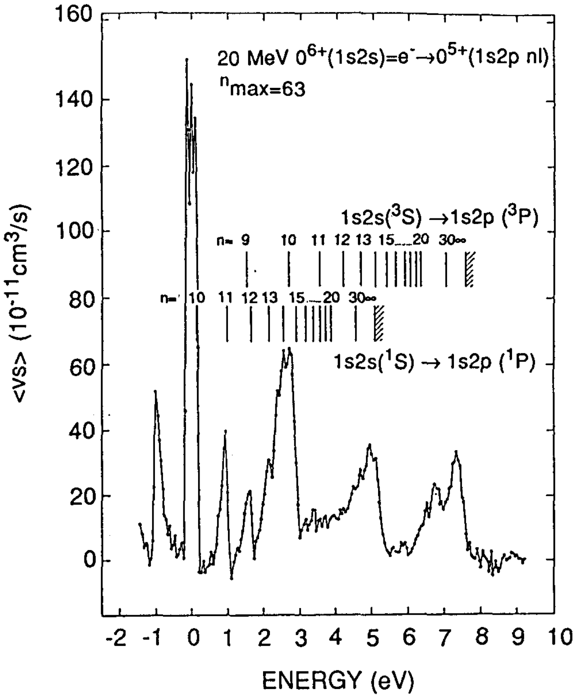

Fig. 12. Dielectronic recombination spectrum of O^{5+} (1s2s) obtained in a single pass merged electron-ion beam experiment (see Ref. 23).

whose velocity is varied to give relative velocities in the 0 — 20 eV range. The resultant recombination (to form O^{5+}) spectrum shown in Fig. 12 arises from the 1s2s metastable component of the beam via the transitions $1s2s(^1S) \rightarrow 1s2p(^1P)$ and the $1s2s(^3S) \rightarrow 1s2p(^3P)$ and (^1P) states. Note that although the ion beam energy in the laboratory is 20 MeV, the center-of-mass energy ranges from 0 — 10 eV with a resolution of ~0.15 eV.

The completion of heavy ion storage ring projects will lead to many new and dramatic advances in heavy ion atomic physics. The merged electron beam exists as an integral part of the ring where it is used for "cooling" the stored beam.[24] One advantage of the storage ring is the enormous increase in effective current and attendant luminosity obtained by circulating the same particles through the thin target at frequencies of up to a megahertz. The first results on DR obtained from the Heidelberg ring[23] (the first of the completed projects) will be discussed in invited papers by R. Schuch and by A. Wolf.

Another experiment which gives related results involves electron transfer plus excitation (TE) in ion-atom collisions. In this case, instead of a truly free electron, we use an atomic target which has weakly bound (almost free) electrons with orbital velocities $v_e \ll v_i$, where v_i is the ion velocity. This process has been dubbed "Resonant Transfer and Excitation" (RTE).[25] Here, e.g.,

$$A^{q+}(\alpha) + \mathrm{He} \rightarrow [A^{(q-1)+}(\beta,n\ell)]^{**} + \mathrm{He}^{+} \qquad (3)$$

the doubly excited state can then relax via Auger or radiative decay

$$[A^{(q-1)+}(\beta,n\ell)]^{**} \rightarrow A^{q+}(\alpha) + e_A$$

$$\rightarrow [A^{(q-1)+}(\alpha,n\ell)]^{*} + h\nu_1 \ . \qquad (4)$$

Further, the singly excited state can relax with the emission of a second X ray

$$[A^{(q-1)+}(\alpha,n\ell)]^{*} \rightarrow A^{(q-1)+}(\alpha,\alpha') + h\nu_2 \ . \qquad (5)$$

The end results are either an Auger electron which contains information on the $n\ell$ state of the originating doubly excited state, or an ion of decreased charge and two photons. Experiments have been carried out by measuring the energy dependence of the Auger electron spectra (RTEA); charge capture in coincidence with X rays (RTEX); or two X rays in coincidence (RTEXX). In all cases, the relative collision energy is scanned by varying the energy of the ion beam. RTE will be discussed in papers by Graham, Hahn, and Schuch in a symposium chaired by J. Tanis, who pioneered this technique.

As an example, consider the results of one experiment carried out at the Berkeley Super HILAC by Graham et al.[26] shown in Fig. 13. The ion used was He-like Ca^{18+} and the target was H_2. Here we can see a significant effect of RTE on the total electron capture cross section ($\sigma_{q,q-1}$). The effect is much enhanced in the measurement of a K-X ray in coincidence with the formation of Ca^{17+}. The lower energy bump, in this case, corresponds to a KLL excitation. The width of the peak is the result of a fold of the momentum distribution (Compton profile) of the bound electrons in the H_2 molecular target with the KLL resonance lines.

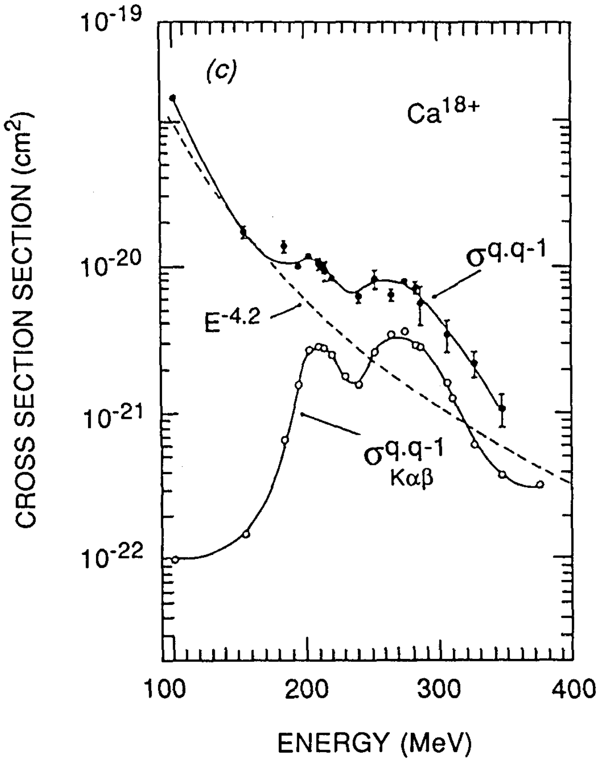

FIG. 13. Upper curve, measured capture cross section for Ca^{18+} on H_2 showing contributions from RTE. Lower curve, capture measured in coincidence with calcium K X ray (see Ref. 26).

Dielectronic excitation processes have now also been studied in crystal channels. Energetic ions traveling through crystals at small angles to low index directions may be steered to avoid small impact parameter collisions with the atomic cores of the lattice atoms ("channeling) and interact directly only with loosely bound electrons.[27] For ion velocities $v_i \gg v_f$, where v_f is the velocity of the target Fermi electrons, the penetrating ion may be viewed as being bombarded by a flux of electrons moving at velocity v_i.

Two invited papers at the present conference deal with consequences of this effect: one by J. C. Poizat on "Energy Loss and Charge Exchange Processes of High Energy Heavy Ions Channeled in Crystals" and the second by N. Claytor on the "Measurement of Electron Impact Ionization of $U^{88+} - U^{91+}$" in which ~500 MeV/amu ions are made to collide with the electrons in a crystal channel ("reverse kinematics"). If this assumption is quantitatively correct, ions traveling through this medium at velocities equivalent to the electron velocities required for sharply varying processes, such as dielectronic or direct excitation of an electron bound to the ion, should experience events similar to those in a hot dense ($\gtrsim 10^{23}$ electrons/cm^3) plasma, but with a relatively narrow electron energy distribution, i.e., a Fermi distribution as against a Maxwell-Bolzman distribution at the temperature necessary to carry out these excitation processes.

In vacuum under single collision conditions, the doubly excited state formed by dielectronic excitation would decay, as above, either by an Auger process or by radiative stabilization via two photons. The final result being the production of an ion of reduced charge state and two photons. However, if the state is created in a dense electron medium (i.e., a dense plasma or a crystal channel), secondary collisional processes leading to further excitation and ionization can come into play and may even dominate.

Take, as an example, the dielectronic excitation of a hydrogenic ion to a $[2p^2]^{**}$ KLL resonance (see e.g., Fig. 11). This state could be collisionally ionized to $[2p]^*$ or it could be excited to a $[2p3\ell]^{**}$ state. The excitation cross section from a given n state to an (n + 1) state is larger than that for direct ionization, but the ionization cross sections for high n states are so large that for n>3 in the cases under consideration,[28] the electron can be considered as removed from the ion by either excitation or ionization. The remaining 2p electron can then either radiate to 1s or undergo a similar collisional excitation or ionization. Thus, one possible path leads the ionization to form a bare nucleus at single collision energies below the first excitation potential. As an example, the results for Ca^{19+} ions (150 — 330 MeV) are shown in Fig. 14. The Ca^{19+} ion beam passed through the <110> axis of a 1.2 µm thick silicon

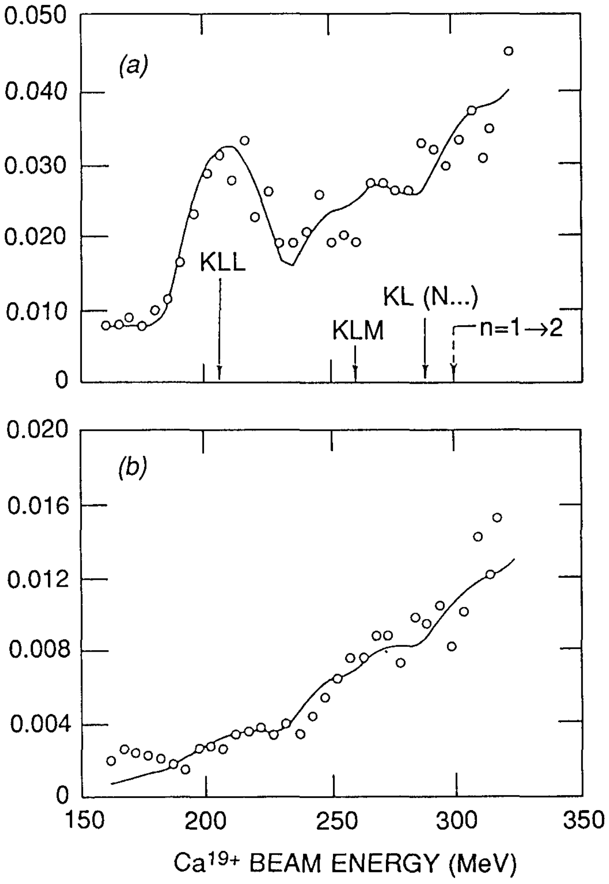

FIG. 14. (a) Yield of H-like K_α calcium X rays and (b) charge fraction of Ca^{20+} ions as a function of Ca^{19+} ion energy incident on a <100> channel in Si (1.2 μm thick) the smooth curves are calculated from the appropriate rates.

crystal. Measurements were made of (a) the emerging charge-state distributions using electrostatic deflection and a solid-state position-sensitive detector, and (b) the X-ray spectra using a Si(Li) detector which can resolve H-like K_α from the He-like K_α lines.

In Fig. 14a, the yield of H-like K_α X rays is shown as a function of ion energy. The features correspond to dielectronic excitation to KLL, KLM, KLN, etc., and at 300 MeV to direct 1s → 2p excitation. The calculated absolute magnitudes of these contributions are obtained from the appropriate rate equations containing radiative and Auger rates and collision cross sections. They are then folded with the appropriate Fermi distribution. Using the same rate coefficient as those used for the X-ray yields shown in Fig. 14a, the yield of bare Ca^{20+} ion is calculated and compared with the data in Fig. 14b. (Dielectronic excitation in channels is discussed in contributed papers 137 and 138).

IV. CODA

In this paper, I have tried to point out not only some features of the utility and ubiquity of atomic collision physics, but also the response of the ICPEAC community in meeting the challenges created by the needs of the general scientific and technological community. The great utility of atomic collision physics is, however, both a strength and a weakness; the weakness being the perception of our field as an adjunct of other disciplines toward which its results are applicable rather than as a separate discipline in and of itself.

The object of the latter part of the talk was to point out the close inter-relationship between seemingly disparate branches of our science, i.e., ion-atom, electron-ion, and ion-solid collisions. All of these are presently represented at ICPEAC. This demonstration was, in part, intended as a response to those who believe that ICPEAC is now too large and ought to be broken up into separate subdiscipline conferences .... When I was a lad growing up in New York, the New York Yankees' baseball team was by far the best in the world habitually winning the "American League Pennant" and the "World Series." Fans who favored other teams were heard to shout "Break up the Yankees!" Break up the Yankees? .... Never!

This research was sponsored by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

REFERENCES

1. See e.g., Atomic Physics in Nuclear Experimentation in Annals of the Israel Physical Society 1, B. Rosner and R. Kalish, eds., 1977.

2. Applied Atomic Collision Physics, H. S. W. Massey, E. W. McDaniel, and B. Bederson, eds., Vol. 4 Condensed Matter, S. Datz, ed., Academic Press, New York, 1983.

3. A. Dalgarno, "Applications of Atomic Collision Physics to Astrophysics" in Physics of Electronic and Atomic Collisions, S. Datz, ed., North-Holland Press (1981), pp.

4. A. B. Walker, T. W. Barbee, R. B. Hoover, and J. K. Lindblom, Science 241, 1781 (1988).

REFERENCES (contd)

5. A. Burgess, Astrophys. J. 139, 776 (1964).

6. W. P. Blair, J. C. Raymond, J. Danziger, and F. Matteucci, Astrophys. Journal 338, 812 (1989).

7. M. Schaer, S. Jefferts, S. Barlow, and G. Dunn, J. Chem. Phys. (in press).

8. E. H. Taylor and S. Datz, J. Chem. Phys. 23, 1711 (1955).

9. D. Beck, E. F. Greene, and J. Ross, Proceedings, Second Int'l Conf. on the Physics of Electronic and Atomic Collisions, **Books of Abstracts**, W. A. Benjamin and Company (1961), p. 94.

10. G. H. Kwei, T. A. Norris, I. L. Kinsey, and D. R. Herschbach, Proceedings, Second Int'l Conf. on the Physics of Electronic and Atomic Collisions, **Book of Abstracts**, W. A. Benjamin and Company (1961), p. 98.

11. D. R. Herschbach, Farad. Dis. Chem. Soc. 55, 233 (1973).

12. See e.g., D. R. Bates, "Airglow and Auroras" in Applied Atomic Collision Physics, H.S.W. Massey, E. W. McDaniel, and B. Bederson, eds., Academic Press 1, 152-200 (1982). [Photo by Al McNeal, University of Alaska]

13. See e.g., P. Jaeglé, J. Physique 48, C9 (1987).

14. B. L. Whitten, A. U. Hazi, M. H. Chen, and P. L. Hagelstein, Phys. Rev. A 33, 2171 (1986).

15. See e.g., U. Ramm, S. Schmidt, H. Schmidt-Böcking, G. Kraft, and R. E. Olson, GSI Scientific Report No. ISSN 0174-0184, p. 205 (1988).

16. Nucl. Instrum. Meth. Phys. Res. B 40/41, (1989).

17. G. D. Alton, c.f. Ref. 2, pp. 44-171.

18. H.-D. Betz, c.f. Ref. 2, pp. 2-43.

19. C. Bottcher and M. Strayer, Phys. Rev. D 39, 1330 (1989).

20. C. Bottcher and M. R. Strayer, Nucl. Instrum. Meth. Phys. Res. B 31, 122 (1988).

21. M. Rhoades-Brown, C. Bottcher, and M. R. Strayer, Phys. Rev. A (in press).

22. P. F. Dittner, Physica Scripta T22, 65 (1988).

23. L. H. Andersen, H. Knudsen, P. Hvelplund, and P. Kvistgaard, Phys. Rev. Lett. 62, 2656 (1989).

24. R. Schuch, Nucl. Instrum. Meth. Phys. Res. B 24/25, 11 (1987).

25. J. A. Tanis, E. M. Bernstein, W. G. Graham, M. Clark, S. M. Shafroth, B. M. Johnson, K. W. Jones, and M. Meron, Phys. Rev. Lett. 47, 1325 (1982).

26. W. G. Graham, E. M. Bernstein, M. W. Clark, J. A. Tanis, K. H. Berkner, P. Gohil, R. J. McDonald, A. S. Schlachter, J. W. Stearns, R. H. McFarland, T. J. Morgan, and A. Müller, Phys. Rev. A 33, 3591 (1986).

27. "Heavy Ion Channeling," S. Datz and C. D. Moak, in Heavy Ion Science, Vol. 6, D. A. Bromley, ed., Plenum Press, 1985, pp. 169-240.

28. S. Datz, C. R. Vane, P. F. Dittner, J. P. Giese, J. Gomez del Campo, N. L. Jones, H. F. Krause, P. D. Miller, M. Schulz, H. Schöne, and T. M. Rosseel, Phys. Rev. Lett. (in press).