Synopsis of the Fifth International Symposium on Polarization and Correlation in Electronic and Atomic Collisions

Electron spin polarization effects and electron–photon angular and polarization correlation studies in electronic and atomic collision processes were the major subjects discussed at the Fifth International Symposium on Polarization and Correlation in Electronic and Atomic Collisions which was held on the campus of Stevens Institute of Technology in Hoboken, NJ, August 2–4, 1989. It was the objective of the symposium to summarize and discuss developments in this field in the two years since the 1987 symposium in Belfast. In accordance with suggestions made at the previous symposium the organizers made an effort to incorporate into the program several progress reports on subjects somewhat more loosely related to the main emphasis of the symposium.

Key Words: *coherence, correlation, polarization, electronic and atomic collisions*

One of the Satellite Meetings of the 16th International Conference on the Physics of Electronic and Atomic Collisions (ICPEAC) in New York, NY, July 26–August 1, 1989 was the Fifth International Symposium on Polarization and Correlation in Electronic and Atomic Collisions which was held on the campus of Stevens Institute of Technology in Hoboken, NJ, August 2–4, 1989. Previous symposia in this series were held in Gaithersburg, MD (1981), Münster, West Germany (1983), Pasadena, CA (1985) and Belfast, United Kingdom (1987). The scope of the present symposium included topics of correlation and polarization, mainly in electron–atom collision systems, but also in simple heavy-particle atomic collision

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systems. In addition, several progress reports on subjects closely related to these topics were given. The program consisted of 23 invited talks in addition to an opening address by J. Kessler (University of Münster) and closing remarks by B. Bederson (New York University).

In his opening address, J. Kessler (University of Münster) reviewed the history of the symposium. He reminded the participants that the driving force behind this symposium is the idea of a "complete" or "perfect" scattering experiment[1,2] where all quantum numbers of the collision complex "projectile + target" are completely determined both before and after the collision. It was pointed out that subtle differences had occurred in the title of the symposium over the years, e.g., the terms "polarization" and "correlation" changed places occasionally reflecting a shift in emphasis, and the term "electron–atom collisions" was modified to "electronic and atomic collisions" at the Belfast symposium, indicating that the scope of the program was extended to include ion–atom and atom–atom collisions. The question of whether it was justified to hold such a separate symposium every two years or whether the results discussed here could just as well have been presented at ICPEAC was answered in favor of a separate symposium though with a clear distinction of the type of information that should be discussed at the symposium. While ICPEAC should be the forum for the presentation of clear-cut and established results, the symposium was the appropriate place to discuss plans for new experiments, work in progress and preliminary or controversial results. On the other hand, it was also pointed out that a positive answer in favor of the symposium should by no means be taken for granted. The group of people working in the field will have to continue to produce a sufficient number of exciting topics to justify the continued existence of this symposium.

As an example of the kind of stimulating questions discussed at previous symposia, Kessler mentioned the 1983 Münster symposium where Trajmar's group (Jet Propulsion Laboratory, Pasadena, USA) reported results from superelastic scattering experiments from laser-excited barium atoms which revealed an unexpected asymmetry which the authors found difficult to explain.[3] A broad discussion was stimulated as to whether this was a new, as yet unexplained, effect or an unresolved experimental artifact. As discussed later in this article, the solution to this question was presented at this symposium and possible implications for a variety of other similar experiments were discussed.

Another debate was opened by M. S. Lubell (City College of New York, USA) some years ago which persisted to be an active area of interest at this symposium and which might continue to play an important role for a few more years to come. The debate dealt with the inherent accuracy, or lack thereof, of electron polarimetry by Mott scattering. Major advances in the development of polarized electron sources resulted in experiments whose accuracy was solely determined by the value of the electron polarization. While different groups have claimed widely varying levels of precision in the value of the electron polarization, with errors as low as $\pm 1\%$, it was demonstrated by Fletcher, Gay and Lubell[4] that basic considerations limit the overall accuracy of Mott polarimetry to at least $\pm 5\%$.

The list of controversial problems and exciting developments discussed at the various Polarization Symposia is long. Several years ago there was the question of orbital angular momentum transfer in electron-impact excitation from the field of electron–photon coincidence experiments for which a definitive answer has now been found. At the 1985 Pasadena symposium, Andersen *et al.*[5] presented a fresh look at the interpretation of electron–photon coincidence experiments. Their approach, which looks at the shape of the excited state charge cloud, gained widespread popularity, particularly among experimentalists. Kessler noted that the very recent interest in questions concerning the role of spin-dependent effects in electron-impact excitation processes obviously shaped the program of the present symposium. Kessler concluded his opening remarks by quoting from a paper by Callaway and McDowell[6] that notwithstanding the importance of spin-flip ratios, orientation and alignment parameters, and the progress that has been made in calculating and measuring these "esoteric" quantities, one is often still puzzled by the large uncertainties in the absolute cross section for electron-impact excitation of a specific atomic energy level at a specified energy. In fact, it was pointed out[7] that in a perfect scattering experiment which yields a complete set of observables describing the collision process, it is often the absolute cross sections that are the weakest points.

U. Fano (University of Chicago, USA) opened the series of invited talks with an overview on attempts to extract dynamics from polarization measurements for the case of the "complete" experiment e + He ($1s^2$) $\rightarrow$ e′ + He (1s2p). The invariant dynamical parameters were identified as superpositions of Legendre transforms of the experimental transition amplitudes as discussed by Andersen *et al.*[5] It was shown how the convergence of the Legendre expansion can be enhanced by subtraction of the Born contribution to it.[8] The extension of this analysis to generic "complete" experiments was presented and, in addition, it was outlined how partial information on the dynamical parameters provided by less-than-complete experiments could be obtained.

One of the debates mentioned in the opening remarks which continued at this symposium is the status of electron polarimetry. The series of investigations of electron polarimetry was opened by M. A. Khakoo (University of Missouri–Rolla, USA) who reported on recent systematic investigations of Mott polarimetry using very thin gold foils. The foils used in the experiments ranged from 10 to 200 Å in thickness. The results indicated that elastic plural scattering plays a significant role, producing a lowering of the left–right electron scattering asymmetry for foils as thin as 25 Å at incident energies below 40 keV. In fact, at 20 keV it was found that 100 Å foils are effectively infinitely thick for elastic plural scattering processes and yield a polarization analyzing power which is considerably lower than that of a 10 Å foil. A. Gellrich (Universität Münster, West Germany) presented the talk of K. Jost who died very unexpectedly a few days before the symposium and will be sorely missed. Results were reported for a systematic comparison of three alternative methods of determining the analyzing power of Mott analyzers. One of the three proposed methods utilizes the circular polarization of fluorescence radiation produced by polarized electron impact excitation of helium.[9] The other two methods[10,11] make use of redundant information obtained from scattering polarized electrons from an auxiliary target which shows sufficiently distinct spin-orbit effects. It was demonstrated that the accuracy of the traditional double-scattering experiment is inferior to that potentially achievable with the proposed new experimental arrangements. J. J. McClelland (National Institute of Standards and Technology, USA) talked about recent progress made on the development of a "first-size," low-energy, diffuse-scattering electron spin detector[12] and its application in the study of spin-polarized superelastic electron scattering from sodium. The initial design of the spin detector was improved by introducing a compensation for angular and positional displacements of the incident beam and by performing detailed electron optical trajectory calculations resulting in a more efficient polarization detection. The figure-of-merit has been increased to 2.3×10^{-4} and the detector is less sensitive to beam alignment problems. Additional effort had been devoted to the study of different target materials, and it appeared that an additional factor of 2 in the figure-of-merit of a Mott analyzer could be gained by using thorium instead of gold as a scattering target.

One issue of current interest mentioned in Kessler's opening remarks was the controversial discussion of experimental evidence for the presence of spin-orbit effects in inelastic electron–atom collisions in a regime where one would not, on the basis of previous experience and physical intuition, expect such effects to play an important role. This controversy was triggered by the work of the JPL group[3] on superelastic scattering from Ba and corroborated by recent results from other groups.[13,14] P. W. Zetner (Jet Propulsion Laboratory, USA) presented an improved approach for incorporating the effects of a finite scattering volume on the parameters measured in electron–photon coincidence experiments. In particular, this more rigorous model was able finally to explain the "mysterious" asymmetry in the superelastic scattering experiments from Ba. Moreover, it was demonstrated that extreme care has to be exercised in the interpretation of all "laser-in-plane" superelastic scattering experiments and all "in-plane" electron-polarized-photon coincidence experiments, since they are particularly prone to strong geometry induced effects.

J. W. McConkey (University of Windsor, Canada) elaborated on these findings. Measurements of the coherence parameters P_4 and P_1 provide information about the parameter ρ_{00} which describes the "height" of the excited state charge cloud relative to its dimension in the scattering plane.[5] A non-zero value of ρ_{00} indicates the presence of symmetry breaking interactions, such as the spin-orbit interaction during the collision. While theoretical models and previous experience predict no significant spin-orbit effects in the regime of large impact parameters (small electron scattering angles and high impact energy), preliminary experimental evidence in Kr and Xe showed significant and unexpected nonzero values for ρ_{00}.[13] In almost all cases, this could be traced to a P_4 polarization correlation measurement (in the scattering plane) that was smaller than expected. A detailed discussion of the influence of experimental parameters such as the finite interaction volume and detector acceptance angle effects on the measured parameters and in particular on P_4 was presented along with additional experimental data for all four heavy noble gases Ne, Ar, Kr and Xe. It was concluded that the observed non-zero values of ρ_{00} in the regime of large impact parameters are most likely caused by instrumental effects due to the finite scattering volume. G. F. Hanne (Universität Münster, West Germany) presented results indicating the presence of spin-flip processes in inelastic electron–mercury collisions at small scattering angles. He also found that instrumental effects can fully account for these apparent spin flips, and consequently make it very difficult to perform reliable coincidence measurements of the parameter P_4, particularly at small electron scattering angles.

Several presentations dealt with recent theoretical and experimental results obtained from investigations which make use of polarized collision partners. K. Bartschat (Drake University, USA) compared the predictions of the Distorted Wave Born Approximation (DWBA) and the non-perturbative R-matrix (close coupling) approach for scattering processes involving polarized collision partners. Despite the feasibility of preparing almost monoenergetic beams of spin polarized projectiles as well as targets, so-called "complete" experiments are still extremely difficult to perform due to the large number of independent parameters that must be measured with high accuracy. For incomplete measurements, e.g., averaged over scattering angle, comparison between theory and experiment can be made using a "reduced" density matrix formalism or comparing "integrated" Stokes parameters.[15]

M. S. Lubell (City College of The City University of New York, USA), G. Baum (Universität Bielefeld, West Germany) and J. J. McClelland (National Institute of Standards and Technology, NIST, Gaithersburg, USA) each described complex experiments utilizing the virtue of spin-tagging of both the projectile and the target. Lubell discussed recent progress towards a precise determination of the spin asymmetry in polarized electron impact ionization of polarized atomic hydrogen at impact energies both near and substantially above threshold. Baum discussed the determination of the singlet and triplet parts of the integral ionization cross section for metastable He and for Cs atoms as well as a preliminary look at the triple differential cross section for Li atoms. Since the Coulomb three-body nature of the ionization process renders a theoretical ab initio treatment difficult, in particular for energies from near-threshold to about 10 times threshold, progress has to come primarily from experiments. It was pointed out that precision measurements at the 1% level require a detailed characterization of the polarized electron beam[16] as well as of the target beams.[17,18] J. J. McClelland reported on the recent results of superelastic scattering experiments of polarized electrons from Na at 17.9 eV. The experiment yielded information on the angular momentum transfer $L_\perp$, its triplet and singlet components, and on the ratio of triplet to singlet cross section over the angular range from 10° to 120°.

A block of presentations was devoted to progress in the field of electron–photon coincidence studies. R. E. H. Clark (Los Alamos National Laboratory, USA) introduced several recently developed computer codes for calculations of various types of atomic physics data. A set of codes is now available which are very easy to use, provide results for any atom or ion, and give substantial flexibility to the user. Codes that are relevant to the subject matter of this symposium are the CATS atomic structure code, based on Cowan's Hartree–Fock method,[19] the ACE collisional excitation code which can calculate collisional data in the distorted wave approximation (DWA) of Mann[20] or using a first-order many-body theory (FOMBT), and the TAPS code which can provide differential cross sections (DCS) and electron-impact coherence parameters (EICP). Several examples of DCS and EICP calculations using the various available approximations were presented by D. C. Cartwright (Los Alamos National Laboratory, USA). The importance of including target state correlations as well as the effect of unitarization were discussed in the cases of Mg, Ca, He, Ne and B. A detailed comparison of the theoretical calculations with experimental data indicated the need for more experiments, particularly for atoms other than He and in general for larger electron scattering angles. The dependence of the EICP's on the principal quantum number of the final state was investigated for several targets. The n-dependence was found to be generally small, similar to the wel-documented case of the He $n\ ^1P$ excitation from the ground state.[21] A complete picture for all collisional quantities for He excitation was presented within the FOMBT scheme.

A. Crowe (Queen's University of Belfast, United Kingdom) described results of correlation studies of $3\ ^{1,3}P$ and $3\ ^{1,3}D$ excitation in He by electron impact. Measurements were performed at 26.5 eV and 29.6 eV with the objective to enable an assessment of the R-matrix calculations of the theoretical group at Belfast. Data obtained at 40 eV were compared to other experimental results from the Utrecht and Stirling groups, with the DWBA calculation of Bartschat and Madison,[22] and the FOMBT calculation of Csanak and Cartwright.[23] In general, discrepancies between theory and experiment were large. On the other hand, angular correlation measurements for the excitation of the $4p^5(^2P_{3/2})5s\ ^3P_1$ state of Kr by electron impact in the angular range from 10° to 100° at incident energies of 15 eV, 30 eV and 60 eV showed surprisingly good agreement with DWBA and FOMBT calculations. P. J. O. Teubner (Flinders University, Australia) discussed orientation and alignment parameters extracted from superelastic scattering experiments from optically pumped $3\ ^2P_{3/2}$ Na. The experimental data obtained for 20 eV in the angular range from 5° to 100° enabled an assessment of the Distorted Wave Polarized Orbital calculations of Kennedy *et al.*[24] and of the coupled channels optical method of Mitroy *et al.*[25] The total reduced polarization P_{tot}, which is a measure of the coherence of the excitation process, was analyzed at 20 eV. A value of $P_{tot} = 1$ for forward angles indicated complete coherence for these conditions. However, there was a significant loss of full coherence in the angular range 50° to 60° which has been predicted to some extent by the coupled channels optical model.[25] The present results were also compared to those obtained previously from the electron–photon coincidence experiments of Riley *et al.*[26] and the merits of the two different experimental techniques were discussed.

Two presentations reported novel applications of the electron–photon coincidence technique. H. G. M. Heideman (University of Utrecht, The Netherlands) presented the first experimental observation of coherences between states that are widely separated in energy without using shifting or broadening effects such as those caused by post-collision interactions. The experiments deal with the excitation of autoionizing states of He by electron impact in the energy regime where the energies of the scattered and the ejected electrons are about equal. Overlapping between scattered- and ejected-electron energies resulting from different autoionizing states will occur in this energy domain. This provides the possibility for the different autoionizing states to decay to one final (He^+ + $e_{scattered}$ + $e_{ejected}$) state where the roles of the scattered and ejected electrons are interchanged but are indistinguishable. Interference was observed between the scattered electrons from one autoionizing state and the ejected electrons from another one and vice versa. Experimental results and the first attempt at a theory necessary for the analysis of this new type of experiment were presented. M. C. Standage (Griffith University, Australia) reported on a new type of coincidence technique in which the conventional polarized photon correlation method was modified by the addition of a laser excitation step following the initial electron impact excitation of the target atom. Coincidences are then recorded between inelastically scattered electrons and photons emitted from the stepwise excited atoms. Atomic collision parameters are determined by a measurement of coincidence rates as a function of the polarization of both the laser light and the decay photons. Several novel aspects of the technique, such as its wide range of applicability, the high optical resolution, and the role of radiation trapping, were discussed in detail. Results were presented for the stepwise excitation of mercury. The $6\ ^1S_0 \rightarrow 6\ ^1P_1$ VUV transition (185 nm) was excited by electron impact followed by a further laser excitation step via the $6\ ^1P_1 \rightarrow 6\ ^1D_2$ (579 nm) transition with subsequent fluorescence being detected from the $6\ ^1D_2 \rightarrow 6\ ^3P_1$ (313 nm) transition. A full set of atomic collision parameters was obtained for an incident energy of 16 eV and scattering angles of 10°, 20° and 30°. Evidence for substantial spin-flip cross sections and a considerable loss of coherence were found at all scattering angles.

As pointed out earlier, it was the intention of the organizing committee to continue the process started at the previous symposium and expand the scope to include contributions from the field of heavy particle collisions. The program of the Stevens symposium included three presentations devoted to atomic collision complexes. R. Hippler (Universität Bielefeld, West Germany) reported on experiments investigating alignment and orientation in some of the most simply structured atomic collision systems such as the excitation of H(2p) either by direct or charge exchange processes with H, H^+, He and He^+. The alignment parameter, A_{20}, provides detailed information about the relative populations of the $H(2p_m)$ magnetic substates and can be measured by analyzing the linear polarization of the Lyman-α radiation emitted in the decay of the excited H(2p) atoms to the H(1s) ground state. Significantly different values of A_{20} were observed for the H + H and the H + H^+ collision systems, respectively. At low collision energies, the H + H^+ system is dominated by a rotational coupling that leads to a preferential population of the $|m| = 1$ substates or a large positive value of A_{20}. This is in good agreement with theory.[27] For the H + H collision system in that energy range, on the other hand, A_{20} was found to be close to zero, similar to the case of the H^+ + He system. This indicates that the two-electron nature of H − H collision process cannot be neglected.

Two talks were devoted to the process of associative ionization in collisions between two excited alkali atoms. H. A. J. Meijer (University of Utrecht, The Netherlands and Universität Kaiserslautern, West Germany) presented a detailed experimental study of laser polarization effects on the associative ionization in Na(3p) + Na(3p) collisions. The experiment was designed to allow an independent variation of the magnetic substate population in each of the two atomic beams. The experiments were analyzed in terms of cross sections and coherence contributions for the atomic states that were prepared, as discussed by Nienhuis.[28] It was found that the electron spins play an important role and that the initial preparation of the collision partners in the $|M_J| = \frac{1}{2}$ substate is by far the most favorable with an associative ionization cross section of 4×10^{-16} cm^2, about four times larger than the cross section for any other preparation. This indicates that the $^3\Sigma$ molecular potential curve is responsible for a large part of the cross section. Additional experimental evidence, however, indicated that at least one other potential curve must contribute to some extent. A detailed comparison with existing theoretical models[29] was presented and suggested reasonably good agreement between experiment and a theoretical picture which was discussed in detail by F. Masnou-Seeuws (University of Paris–Sud, France). Masnou-Seeuws presented a comprehensive theoretical picture of the associative ionization reaction between two Na(3p) or two K(4p) atoms. The dependence of the cross section on the laser polarization was discussed in the framework of two models, an atomic picture and a molecular picture. The atomic treatment analyzes the data in a way to extract the associative ionization probability for a given preparation of the two atoms, in particular $|Jm_J\rangle$ or $|Lm_L\rangle$ substates. This picture assumes that the Na(3p) + Na(3p) manifold of states is not coupled to the neighboring Na(3s) + Na(5s) or Na(3s) + Na(4d) manifolds. The molecular treatment deals with the autoionization of the Na_2 molecule through doubly excited states correlated to Na(3p) + Na(3p) in the framework of a model potential. The conclusion is that, in such a picture, the reaction is likely to proceed via the autoionization of the $^3\Sigma_u^+$ molecular state. While such a picture is consistent with some of the experimental findings, other observations remain unexplained. This suggests that an improved atomic picture be developed which takes into account the coupling of the Na(3p) + Na(3p) channel to at least some of the neighboring channels.

A group of four presentations in areas not included in previous symposia, but which were closely related either topically or methodically to the theme of the conference, were added in an attempt to broaden the scope of the symposium. G. Stefani (University of Camerino, Italy) described correlations in (e,2e) experiments performed in asymmetric kinematics (incident energies larger than 1 keV). Both valence and core ionization processes were studied by analyzing the satellite peaks in the energy separation spectrum and the angular distributions of the ejected electrons. The ionization of C(1s) in C_2H_2 at two different ejected electron energies, 10 eV and 40 eV, produced intense recoil lobes which were much larger than the binary lobe at lower ejected energy. Neither the widths nor the relative intensities and symmetry of the lobes were reproduced by high-energy first-order interaction models. An energy shift of the C(1s) (e,2e) Auger peak position with respect to the XPS value was observed, similar to previous findings[30] in Ar. The shift of 460 meV was much larger than the 60 meV predicted by a semi-classical treatment of the Auger-ejected electron interaction. A possible explanation for the additional energy shift was given by proposing that for excess energies between 10 eV and 40 eV the C(1s) ionization proceeds through a resonant channel which accounts for as much as 30% of the total cross section. Satellite peaks in the ionization spectra of innervalence orbitals provided evidence for correlations in both the initial and the final stage of the target. .

A. J. Duncan (University of Stirling, United Kingdom) discussed the results of recent studies of the two-photon decay of metastable atomic deuterium. A measurement of the polarization correlation of the two emitted photons provided a detailed test of Bell's inequality.[31] The observed results are in good agreement with the predictions of quantum mechanics and do not support local realistic theories proposed to interpret the measurements.[32] L. Vušković (Institute of Physics, Belgrade, Yugoslavia and New York University, USA) reported results of low energy electron scattering experiments from laser-excited Na 3 $^2P_{3/2}$ atoms using the atomic recoil technique[33] in which observation is made of the atoms after collisions with an electron beam. The major advantage of this technique over conventional scattering measurements is that atomic recoil experiments more readily yield absolute cross sections. Because of the scattering kinematics, elastic scattering data could yield differential cross sections only for intermediate scattering angles, but not for small scattering angles. Superelastic scattering data, on the other hand, yielded information in the regime of small scattering angles including the forward direction. B. J. Stumpf (University of Idaho, USA) discussed interesting differences between excitation processes starting from the ground state with $L = 0$ (S-state) and the general $nL \rightarrow n'L'$ excitation process where both L and L' are nonzero. He showed that the linear polarization of radiation from an electron-impact excited state is explicitly exchange-dependent if the initial state is a pure spin state and has nonzero orbital angular momentum. Furthermore, he found a significant dependence of the linear polarization on the principal quantum number of the upper state when the lower state has a nonzero orbital angular momentum.

B. Bederson (New York University, USA) was left with the difficult task of summarizing and capturing the atmosphere of a lively, interesting, and highly stimulating symposium in his closing remarks. It was pointed out that there was not a single contribution which did not make reference to the recent review article by Andersen, Gallagher and Hertel.[5] This was attributed to the fact that, while there had been partial reviews of the field before, none had been as timely and as comprehensive as the 1988 review by Andersen *et al.* The nature of the presentations at this symposium in comparison with presentations at previous meetings was indicative of the fact that the field has enjoyed a long and productive period of growth, both in breadth and in depth. The field appears to have reached a level of maturity where experimental techniques and theoretical methods, which had traditionally been confined to the study of polarization and correlation phenomena in electron–atom collisions, are rapidly spreading into the realm of heavy-particle collisions, and are beginning to spread into other subfields of atomic and nuclear physics as well. Many complex experiments can now be performed at the 1–5% precision level, so that systematic, rather than statistical, uncertainties have become the most important accuracy limiting factors. As a consequence, the influence of experimental effects on the measured quantities has become the subject of very detailed and lively discussions. Very stringent comparisons between experiment and theory have now become feasible. On the other hand, inelastic experiments still have a long way to go towards the ultimate goal of performing a "complete" experiment in which all quantum numbers of the collision system are fully determined before and after the collision.

The stimulating atmosphere created by the lively, fruitful and in-depth discussions of the presentations was one of the most valuable assets of this symposium. At the end of a two-and-a-half-day meeting it was generally felt that the trend to expand the original scope of the symposium, a process which was begun at the Belfast meeting (1987) and continued at this meeting, should be pursued further by the organizers of the next symposium to be held in Australia in 1991.

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