Calculations by Reinhardt *et al.*[16] for positron production from the QED processes cited above are shown in Fig. 3. The general agreement of the calculated intensities and projectile energy dependences with the measured excess yields above Coulomb-excitation backgrounds suggests that the observed positrons are associated with these processes involving positron emission by the very strong time-varying electric fields present in the quasimolecular collision system, and with electrons of the pair-filling, pre-ionized, quasimolecular states and the continuum, with relative amplitudes which are presently not fully determined.

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[1]B. Müller, H. Peitz, J. Rafelski, and W. Greiner, Phys. Rev. Lett. 28, 1235 (1972).
[2]Ya. B. Zel'dovich and V. S. Popov, Usp. Fiz. Nauk 105, 403 (1971) [Sov. Phys. Usp. 14, 673 (1972)].
[3]J. Rafelski, B. Müller, and W. Greiner, Nucl. Phys. B68, 585 (1974).
[4]R. Klein and L. P. Fulcher, Phys. Rev. D 8, 2455 (1973).
[5]B. Müller, J. Rafelski, and W. Greiner, Phys. Lett. 47B, 5 (1973).
[6]V. I. Lisin, M. S. Marinov, and V. S. Popov, Phys. Lett. 69B, 141 (1977).
[7]K. Smith, H. Peitz, B. Müller, and W. Greiner, Phys. Rev. Lett. 32, 554 (1974).
[8]G. Soff, J. Reinhardt, B. Müller, and W. Greiner, Phys. Rev. Lett. 38, 592 (1977).
[9]H. Backe, E. Berdermann, H. Bokemeyer, J. S. Greenberg, E. Kankeleit, P. Kienle, Ch. Kozhuharov, L. Handschug, Y. Nakayama, L. Richter, H. Stettmeir, F. Weik, and R. Willwater, in *Proceedings of the Tenth International Conference on the Physics of Electronic and Atomic Collisions, Paris, 1977* (Commissariat à l'Energie Atomique, Paris, 1977), p. 162, and J. Phys. Soc. Jpn. Suppl. 44, 832–837 (1978).
[10]J. Bang and J. M. Hansteen, K. Dan. Vidensk. Selsk., Mat.-Fys. Medd. 31, No. 13 (1959).
[11]J. Kirsch, W. Betz, J. Reinhardt, G. Soff, B. Müller, and W. Greiner, Phys. Lett. 72B, 298 (1978).
[12]W. E. Meyerhof, R. Anholt, Y. El Masri, I. Y. Lee, D. Cline, F. S. Stephens, and R. M. Diamond, Phys. Lett. 69B, 41 (1977).
[13]A. M. R. Joye, A. M. Baxter, and M. P. Fewell, Phys. Rev. Lett. 38, 807 (1977).
[14]P. Schlüter, G. Soff, and W. Greiner, to be published.
[15]S. C. Pancholi and M. J. Martin, Nucl. Data Sheets 138, 165 (1972).
[16]J. Reinhardt, V. Oberacker, G. Soff, B. Müller, and W. Greiner, to be published.

State-Resolved Differential Cross Sections for Rotational Transitions in Na_2+Ne (He) Collisions

K. Bergmann, R. Engelhardt, U. Hefter, P. Hering, and J. Witt
Fachbereich Physik der Universität Kaiserslautern, 675 Kaiserslautern, West Germany
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We demonstrate a new technique for the measurement of state-resolved differential cross sections for elastic and inelastic collision processes involving molecules with small level spacing. Lasers are used to label a specific rovibronic level by modulation of its population via optical pumping and to probe the population of neighboring levels by laser-induced fluorescence. First results on Na_2 + Ne (He) collisions show that beyond the center-of-mass scattering angle $\theta_{c.m.} = 50°$ nearly all collision events are inelastic.

The exchange of rotational energy is an important and efficient energy transfer mechanism. Attempts to investigate these processes in molecular beams date back as far as 1964.[1] A major progress towards the ultimate goal, namely, the determination of fully state-resolved differential cross sections, has been achieved only very recently. Transitions between specified rotational quantum states have first been studied in ionic-atom–neutral-molecule collisions.[2] Mean-

while the sensitivity and energy resolution in conventional neutral-particle scattering experiments has also been pushed to a level that state-resolved differential cross sections could be measured for HD + Ne (He) collisions.[3] Data on state-resolved differential cross sections for rotational transitions will provide the most sensitive experimental information about the anisotropic part of the potential surface and may serve as a test for recently developed methods for quantum mechanical scattering calculations.[4,5] The HD + He system has prototype character since *ab initio* calculations for the potential surface are feasible. From the experimental point of view, the HD molecule has been chosen in previous work because of the large spacing of rotational levels and because selection of the initial quantum state is achieved simply by cooling of the gas. At sufficiently low temperatures only the rotational level $j = 0$ is appreciably populated. State-resolved integral cross sections in LiH + Ar collisions have recently been determined by Wilcomb and Dagdigian[6] who used a combination of state selection by a quadrupole filter and state-selective detection by laser-induced fluorescence.

The application of the experimental techniques reported so far is not limited to the investigation of collisions with HD or LiH but will remain restricted to light molecules with relatively large level spacing. As soon as a laser is available to excite molecules in a single quantum state, however, state-to-state differential cross sections in collisions of heavier molecules can also be measured. In this publication we demonstrate a novel technique to measure state-resolved differential cross sections for elastic and inelastic collision processes using lasers to label and to probe molecules in well-resolved quantum states. This technique is a molecular-beam version of optical double-resonance experiments that have been successful in cells.[7] A specific rotational-vibrational level (v_0'', j_0'') is labeled by modulation of its population via optical pumping with a laser.[8,9] A second laser beam is rotated around the scattering center and probes the population in the level $(v_0'' + \Delta v, j_0'' + \Delta j)$ by laser-induced fluorescence. Figure 1(a) shows a representative energy level diagram for a special case with $\Delta v = 0$ and $\Delta j = +2$. If the pump laser is modulated and if there is any collisional transfer between the pumped and probed level, the fluorescence induced by the probe laser will also be modulated. The angular variation of the magnitude of this modulation is proportional to the differential

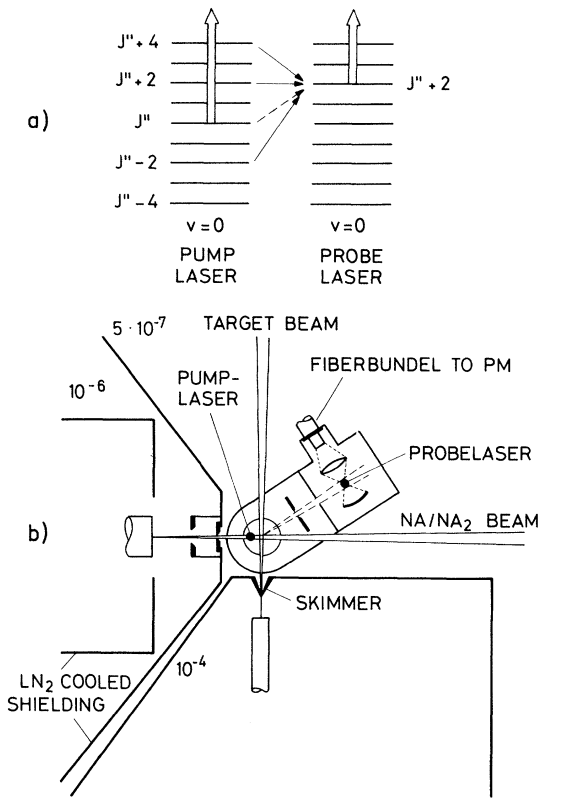

FIG. 1. (a) A schematic energy-level diagram for the optical double-resonance experiment to determine state-resolved differential cross sections. (b) Schematics of the molecular-beam apparatus with state labeling by optical pumping and state-selective detection by laser-induced fluorescence.

cross section for transitions between these two levels.

We choose to study collision processes involving the Na_2 molecule because (i) precise spectroscopic data are available,[10] (ii) several transitions can be excited with lines from an Ar^+ laser, and (iii) the cross section for inelastic collisions is quite large (100 Å^2).[2] Na_2 is a hydrogenlike molecule and pseudopotential calculations are feasible. Furthermore, scattering calculations using decoupling methods[4] are also applicable to collisions involving molecules with larger internal angular momentum j. So far these methods have been tested against experimental results only for collisions of molecules in low-j states.[11] For larger j only one trial calculation[12] in comparison with state-resolved integral-cross-section measurements in $Na_2(B\,^1\Pi_u)$ + He collisions[13] is available. State-resolved differential cross sections for Na_2 + rare-gas collisions will provide for the first time suitable data for a systematic

study of the dependence of the collision dynamics on the internal quantum states, since many rovibronic levels of the Na_2 molecule are populated in the beam.

A supersonic Na/Na_2 beam emerges through a 0.5-mm nozzle of the oven heated to 900 K. The full width at half-maximum Δu of the velocity distribution and the flow velocity u change with the internal energy.[8,9] For molecules in $v=0$ we found $\Delta u/u = 0.2$. The beam is collimated 60 mm downstream from the nozzle with a 1-mm-wide slit in the liquid-nitrogen-cooled wall that separates the oven chamber and the scattering chamber. The crossing with the rare-gas supersonic target beam lies 35 mm further downstream. The target beam emerges from a 0.05-mm nozzle (stagnation pressure 5 bars) and is collimated by a 0.5-mm-diam skimmer 20 mm downstream of the nozzle. The distance between the scattering center and the nozzle of the target beam is 100 mm.

The $\lambda = 476.5$ nm laser line was tuned to the $(0,28) \rightarrow (6,27)$ transition between the $X\,^1\Sigma_g^+$ and the $B\,^1\Pi_u$ electronic state. About 1% of all molecules are found in the (0,28) level.[9] The pump laser crosses the Na_2 beam 10 mm upstream of the scattering center [see Fig. 1(b)]. A laser power of 10 mW is sufficient to depopulate the lower level via optical pumping by 95%. No significant collisional or radiative repopulation of the pumped level occurs upstream of the crossing with the target beam. The lifetime in the upper electronic state is short (7×10^{-9} sec)[14] and no electronically excited molecules reach the scattering center. The probe laser beam is focused with a $f = 25$ mm lens into the 42-μm core of a 120-μm-diam optical fiber (Schott) which transfers the light via a vacuum feedthrough into the vacuum tank and provides a flexible link between the laser and the rotatable detector. At the exit side of the fiber the light fills a cone of 15°. The laser light is made slightly convergent with a $f = 10$ mm lens and passes through a sequence of diaphragms to reduce the stray light.

Scattered particles enter the detector through a 1-mm slit at a distance of 50 mm from the scattering center. They are detected if they cross the probe beam perpendicularly within less than 1° when the laser is tuned to the center frequency of a molecular transition. All other molecules in the probe level will be off resonance because of the Doppler shift. The fluorescence is collected with a system of lenses and focused onto a 5-mm-diam fiber bundle which transfers the light to a cooled photomultiplier (EMI 9502 SA) outside the vacuum tank. Since most of the molecular fluorescence is shifted to the red, cutoff filters are used to attenuate the residual scattered light. The background signal is about 50 counts per second and compares to 10^7 counts per second in the center of the Na/Na_2 beam. A more detailed description of the detector will be given elsewhere.

In the experiment reported here, we used the same laser line to pump and probe the level (0,28), i.e., we have $\Delta v = 0$ and $\Delta j = 0$ referring to Fig. 1(a). As a consequence, we determine the relative differential cross sections for elastic and the sum of all inelastic collisions. Transitions with $\Delta j = \pm 2$ are the dominant contributions to the latter.[15] The detector repetitively scans the range of angles that is accessible to scattered particles in increments of $\Delta\theta = 0.5°$ and 1° for collisions with He and Ne, respectively. We denote by $N_{\mathrm{off,on}}$ the count rate at a given angle θ with pump laser *off* and target beam *on* and use the corresponding notation for the other combinations. Then the following differences of the count rates,

$$\Delta N_{\mathrm{total}} = N_{\mathrm{off,on}} - N_{\mathrm{off,off}} \quad (1)$$

and

$$\Delta N_{\mathrm{elastic}} = \Delta N_{\mathrm{total}} - [N_{\mathrm{on,on}} - N_{\mathrm{on,off}}], \quad (2)$$

yield the total and elastic differential cross sections, respectively. These two curves are shown in Fig. 2 for Ne and He together with the corresponding Newton diagrams. The angular resolution in the laboratory system is 2°. At small angles S/N decreases because of the interference from the primary beam. The difference of two and four individual count rates is needed to determine the number of total and elastic processes respectively [see Eq. (1) and (2)]. Therefore S/N is smaller for the latter. The total data collection time for the set of two curves was 4 h.

No reliable potential surface for the Na_2–rare-gas system is available at present. It is likely that the surface has only a very shallow well[16] and we do expect the elastic scattering to be forward peaked. Angular momentum is more readily transferred in closer collisions, resulting in larger scattering angles. Figure 2 shows that beyond the center-of-mass angle $\theta_{\mathrm{c.m.}} = 50°$ ($\theta_{\mathrm{lab}} = 15°$ and $\theta_{\mathrm{lab}} = 5°$ for Ne and He, respectively), nearly all collision processes are inelastic. For collisions with Ne a relative maximum of the differential cross section is observed near $\theta_{\mathrm{c.m.}}$

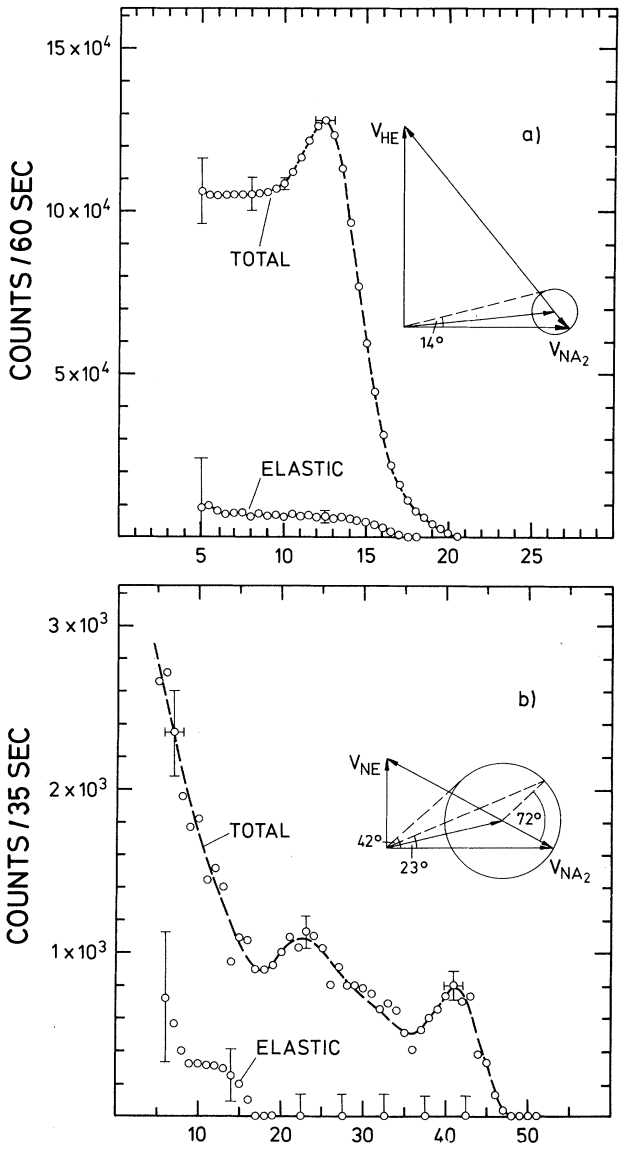

FIG. 2. Differential cross section for elastic as well as the sum of elastic and inelastic transitions terminating at the $v = 0$, $j = 28$ level of the Na_2 molecule. The collision energy for (a) Na_2 + He and (b) Na_2 + Ne was 98 and 190 meV, respectively. The energy gap between the neighboring levels $j = 26$, 28, and 30 is 2.2 meV.

= 72°. A corresponding maximum is not resolved with He as collision partner. The maximum near 42° and 14° for Ne and He, respectively, is of kinematic origin (see Newton diagrams inserted in Fig. 2).

Berbenni and McGuire[15] used a model potential energy surface to calculate state-resolved differential cross sections induced by He for collision energies up to 50 meV. They found rotational excitation out of low-j levels of the Na_2 molecule to be dominant over elastic scattering at large center-of-mass angles. The distribution shows a broad relative maximum. With increasing collision energy this maximum shifts to smaller angles and the scattering becomes more strongly peaked forward. Qualitatively the main features, namely forward peaking and a relative maximum for larger scattering angles, are reproduced by the experimental curve shown in Fig. 2(b). It should be possible to precisely probe fine details of an improved potential surface and to improve the understanding of the mechanism of rotational excitation in these systems when more data from the forthcoming systematic determination of state-resolved differential cross sections using a dye laser will be available. The angular resolution in the center-of-mass system can be considerably improved using the seeded beam technique for the Na/Na_2 beam or making use of the Doppler shift for velocity-selective optical pumping.

In conclusion, we have demonstrated that laser spectroscopic techniques in combination with molecular beams can overcome previous limitations in the molecular-beam investigation of inelastic processes. Whether differential cross sections of a given inelastic process can be measured or not is no longer limited by the magnitude of the vibrational or rotational quantum. It merely depends on the availability of a suitable laser. Since laser technology is still rapidly improving, more and more collision systems can be studied in great detail in molecular beams.

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[1]H. G. Bennewitz, K. H. Kramer, W. Paul, and J. P. Toennies, Z. Phys. 177, 84 (1964); A. R. Blythe, A. E. Grosser, and R. B. Bernstein, J. Chem. Phys. 41, 1917 (1964); J. P. Toennies, Z. Phys. 182, 257 (1965); B. Beck and H. Förster, Z. Phys. 240, 136 (1970).

[2]C. F. Giese and W. R. Gentry, Phys. Rev. A 8, 2483 (1973); R. David, M. Faubel, and J. P. Toennies, Chem. Phys. Lett. 18, 87 (1973); H. Schmidt, V. Hermann, and F. Linder, Chem. Phys. Lett. 41, 365 (1976).

[3]U. Buck, F. Huisken, J. Schleusner, and H. Pauly, Phys. Rev. Lett. 38, 680 (1977); J. M. Farrar, A. L. Burgmanns, J. M. Parson, R. B. Walker, and Y. T. Lee, in Proceedings of the Sixth International Symposium on Molecular Beams, Noordwijkerhout, The Netherlands, 1977 (unpublished), Abstracts; W. R. Giese and C. F. Gentry, J. Chem. Phys. 67, 5389

(1977).
[4]H. Klar, J. Phys. B 6, 2139 (1973); P. McGuire and D. J. Kouri, J. Chem. Phys. 60, 2488 (1974); R. T. Pack, J. Chem. Phys. 60, 633 (1974).
[5]P. McGuire, Chem. Phys. 13, 81 (1976).
[6]B. E. Wilcomb and P. J. Dagdigian, J. Chem. Phys. 67, 3829 (1977).
[7]R. E. Drullinger and R. N. Zare, J. Chem. Phys. 51, 5532 (1969), and 59, 4225 (1973); R. F. Feinberg, R. E. Teets, J. Rubbmark, and A. L. Schawlow, J. Chem. Phys. 60, 4330 (1977).
[8]T. D. Gaily, S. D. Rosner, and R. A. Holt, Rev. Sci. Instrum. 47, 143 (1976); K. Bergmann, U. Hefter, and P. Hering, J. Chem. Phys. 65, 488 (1976).
[9]K. Bergmann, U. Hefter, and P. Hering, to be published.
[10]W. Demtröder and M. Stock, J. Mol. Spectros. 55, 476 (1975).
[11]U. Buck and P. McGuire, Chem. Phys. 16, 101 (1976); P. McGuire, K. Rudolph, and J. P. Toennies, J. Chem. Phys. 65, 5522 (1977); P. McGuire, H. Schmidt, V. Hermann, and F. Linder, J. Chem. Phys. 66, 4243 (1977).
[12]H. Klar and M. Klar, J. Phys. B 8, 129 (1975).
[13]K. Bergmann and W. Demtröder, J. Phys. B 5, 1386, 2098 (1972).
[14]W. Demtröder, W. Stetzenbach, M. Stock, and J. Witt, J. Mol. Spectros. 61, 382 (1976).
[15]B. Berbenni and P. McGuire, Chem. Phys. Lett. 45, 84 (1977), and unpublished results.
[16]A. G. Visser, thesis, Rijksuniversity, Leiden, 1977 (unpublished).

Inward Transport of a Toroidally Confined Plasma Subject to Strong Radial Electric Fields

J. Reece Roth and Walter M. Krawczonek
NASA Lewis Research Center, Cleveland, Ohio 44135

and

Edward J. Powers, Jae Y. Hong, and Young C. Kim
Department of Electrical Engineering, University of Texas, Austin, Texas 78712
(Received 10 November 1977)

The NASA Lewis bumpy torus experiment confines and heats a toroidal plasma by the simultaneous application of strong dc magnetic fields *and* electric fields. Digitally implemented spectral analysis techniques were used to investigate experimentally the frequency-dependent fluctuation-induced transport across the toroidal magnetic field. It was observed that when the electric field pointed radially inward, the fluctuation-induced ion flux was inward and a significant enhancement of the plasma density resulted.

George[1] suggested that a suitable combination of magnetic and electric fields might be used to confine as well as heat a plasma of fusion interest. Theoretical papers by Kovrizhnykh[2,3] and Stix[4] have examined the effects of ambipolar electric fields on radial transport in toroidal plasmas. The purpose of the present paper is to show that the density of a toroidal plasma can be enhanced by radial electric fields far stronger than the ambipolar values, and that, if such electric fields point into the plasma, radially inward fluctuation-induced transport can result.

The steady-state plasma in the NASA Lewis bumpy torus facility is generated by a modified Penning discharge operated in a 12-coil bumpy-torus magnetic field of 1.5-m major diameter.[5] The toroidal plasma is biased to high potentials by water-cooled electrode rings which encircle the minor circumference of the plasma and are located in the midplanes of two sectors of the toroidal array. Previous investigations[5] have shown that, in common with Penning discharges and magnetronlike devices, the plasma forms rotating spokes which gyrate around the minor circumference of the plasma with velocities comparable to the spoke rotation velocity.[5] Electron kinetic temperatures are on the order of 10 eV.

Radial profiles of the floating potential of the plasma were measured with a hydraulically actuated Langmuir probe.[5,6] Some results from these measurements are as follows: (1) The entire toroidal plasma floats to potentials comparable with the electrode ring voltage; (2) the entire plasma can be biased to high potential with positive- or negative-electrode rings; (3) the electric field strength within the plasma often exceeds 1 kV/cm; (4) the radial electric fields point radially outward in the vicinity of the plasma boundary

