Scientific Activities AG Helm 2011-2013

Our research activities fall into four main topics. All experiments are done in our laboratories in Freiburg at the VF and FMF. We benefit from collaboration with groups in and outside Freiburg and are embedded in German, European and international networks.

Superposition states of atoms in tailored laser fields

The non-classical nature of superposition of two states is at the heart of modern methods of high resolution measurement. A specific class of superposition states are dark states when atoms are immune to illumination but are strongly absorbing when they are not dark. The phase of the amplitudes of the superposition is the critical parameter for darkness and we have explored its significance in the preparation of atoms and the survival of the state in presence or absence of phase-controlled light fields. For this purpose we have studied the atomic dynamics in entering the dark state condition as well as the free induction decay which is observed when the coherent superposition is illuminated by nonresonant fields. This led to the development of a phase-switching method capable of measuring the quantum phase difference of the states involved in the superposition [1, 2]. This phase can be determined in a nearly nondestructive manner provided a large sample of atoms is used. This method recently permitted a concise investigation of Berry's geometric phase which we can imprint in an atomic superposition state by rotating a laboratory magnetic field [3]. We have also explored a

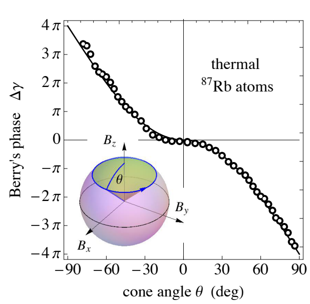

Figure 0.1: Observation of Berry's geometric phase which is imprinted in quantum superposition states of Rb-atoms by rotating the laboratory magnetic field at a cone angle θ [3].

classical analogue of the dark state in a metamaterial containing split-ring resonators [4].

Among the many applications of dark states in metrology is their entanglement with translational degrees of freedom of the atoms. The controlled darkness of vibrational transitions of an atom in a trapping potential promises a method for reaching Bose-Einstein condensation without evaporative cooling. We have pursued this topic in experiments with laser cooled trapped atoms in a far detuned optical dipole trap and prepared our understanding of this tool by numerical simulation of realistic environments [5, 6].

Nonadiabatic coupling in triatomic hydrogen

Triatomic hydrogen is a ubiquitous and frequently the predominant molecular species in hydrogen plasmas and in interstellar clouds. In its most stable form it is ionized, H_3^+. This ion controls the local electron density as it recombines with slow electrons to form H_2+H or $H+H+H$. The rate of recombination has been studied in many laboratories with greatly diverging results and has been a controversial subject for the past 30 years. Recombination involves the temporary formation of neutral triatomic hydrogen which subsequently decays. We have developed means to prepare by laser excitation these intermediate forms of neutral triatomic hydrogen and have studied their autoionization and predissociation as these represent the intimate paths involved in recombination.

Our latest studies deal with the breakup of state-selected H_3 molecules into three slow hydrogen atoms. This experiment is made possible by using time- and position sensitive wire-detectors for neutral hydrogen atoms. With 30 ps time- and 50 μm spatial resolution we succeed in the coincident detection of the three slow H(1s)-atoms released by a single molecule and measuring the momentum vectors of the three atoms. Nuclear symmetry plays a

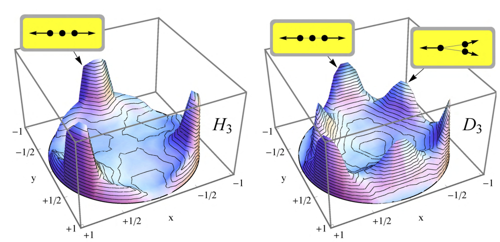

Figure 0.2: A profound isotope effect in predissociation of Rydberg states in the vicinity of the ionization thresholds of H_3 and D_3 [7].

decisive role in the selection of mechanical degrees of freedom as shown by isotope effects between D_3 and H_3 [7]. When viewed in the laboratory frame, the correlated momentum vector image is an analogue of the optical far-field of a diffracting object, in our case the intermediate H_3 molecule at the time of breakup. As the lifetime of the molecule is typically larger than the rotational and vibrational period, the image of momentum correlation represents a view of the available phase space in which nonadiabatic coupling opens a door for the molecule to enter the continuum of three separating hydrogen atoms. This is the first time that direct views of a many particle wavefunction is obtained in an experiment. The results attest to the complex forms of nonadiabatic coupling in polyatomic molecules and provide stringent tests for many-body quantum dynamics theory [8, 9].

Strong field physics

At light intensities above 1 TW/cm^2 the wavefunction and energy spectrum of atoms and molecules can be greatly distorted from the nascent form. Our pioneering development of photoelectron imaging has lead to tools (now in use in over 40 laboratories world wide) to image the distorted electronic wavefunction, as it is projected by a final photon into the continuum of free electrons. Theory has kept apace with simulating the light-field induced distortion of the atomic wavefunction using analytical models or numerical simulation of the time-dependent Schrödinger equation, even for nearly exact atomic structure, when exposed to strong light fields. By comparison the understanding of molecular structure and the structure of negative ions in strong fields is far less developed.

Recent Freiburg experiments deal with molecular hydrogen and fluorine [10, 11, 12]. They show that the commonly accepted ponderomotive shifting model can be greatly modified due to electronic coupling in bound-bound transitions. In collaboration with the Univ. Goeteborg high resolution studies of threshold photodetachment were undertaken [13, 14]. A latest highlight is the time-resolved study of strong-field ionization of a superposition of fine structure states of the neutral carbon atom ground state. The neutral atom is formed in the gas phase by fs-pulse photodetachment of C$^-$ producing the neutral C(^{3}P) atom in a coherent superposition which evolves with time manifested as oscillation of the spatial distribution of the electron density along an axis chosen by the detachment laser [15, 16].

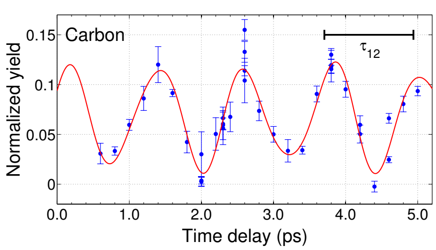

Figure 0.3: The time-resolved spatial oscillation of electron density in the carbon atom ground state is detected along a laboratory coordinate [15].

In a seemingly unrelated subject the Deutsche Wetterdienst and a local company requested measurements of the sinking velocity of airborne pollen for calibration of commercial pollen counters and simulation of pollen flight over Europe. We responded by constructing Paul traps for holding and studying single pollen over long periods of time in controlled temperature-humidity environments. We discovered that the sinking velocity controls the stability boundary of the Paul trap via the drag coefficient. The dependence of sinking velocity on the number of conglomerated pollen was determined [17].

THz radiation and applications

Our group has pioneered electro-optic detection of electromagnetic radiation fields in the THz range and has over the years concentrated on microscopic structure related vibration and relaxation of biological molecules and ionic liquids [18, 19]. Our focus has recently moved to plasmonics and metamaterials. These artificial structures are build from micro resonators and feature unusual optical properties. A latest highlight is the development of a near field microscope capable of detecting the electromagnetic field vector of an ac-field with sub-picosecond time and 5 or 25 μm spatial resolution [20, 21, 22]. This microscope has proven to be a worldwide unique tool for characterizing the near-field properties of micro resonators or surface-plasmon polaritons and for sub-wavelength resolution imaging. We visualized surface-plasmon polaritons, focused to sub-wavelength spotsize, using radially polarized light [23]. We demonstrated sub-diffraction imaging and focussing using metamaterial fibers fabricated at the Univ. Sidney [24]. The coupling between micro resonators has been studied in the near- and far-field [4, 25, 26]. In cooperation with the universities Adelaide and Southampton [27, 28] coaxial micro cavities for localized plasmons and a switchable liquid crystal based metamaterial device were developed and characterized.

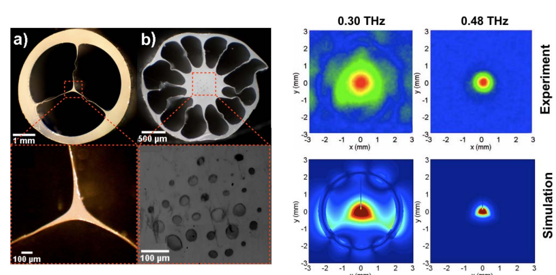

Figure 0.4: Sub-wavelength sized, solid-core fibers used for transport of electromagnetic radiation and THz near-field images at the fiber exit. [25]

Theses 2011-2013

1. Single Ionization of Molecular Hydrogen in Strong Laser Fields,
PhD thesis, Timo Wilbois 2011
2. Vibrational Cooling of a Trapped Atom: its evolution to electromagnetically induced transparency, the development of the scattered radiation field and signatures of correlation and entanglement,
PhD thesis, Maryam Roghani 2011
3. Dynamics and Structure of Negative Ions - Photoinduced double detachment on nano- and femtosecond time scales,
PhD thesis, Hannes Hultgren 2012
4. Transient Quantum Dynamics of Coherent Population Trapping Resonances,
Diploma thesis, Florian Meinert 2011
5. Zeitaufgelöste Spektroskopie an einer Dunkelresonanz von ^{87}Rb,
Diploma thesis, Alexander Lambrecht 2011
6. Untersuchung und Kontrolle der Resonatorkopplung in THz-Metamaterialien,
Diploma thesis, Faouzi Saidani 2011
7. Experimentelle Phasensteuerung eines kohärenten Überlagerungszustandes,
Diploma thesis, Reininger Katrin 2013
8. Charakterisierung elektrisch leitfähiger Mikrostrukturen im Thz-Frequenzbereich,
Diploma thesis, Christoph Testud 2013
9. Aufbau eines Interferometers zur Messung der Dispersion bei elektromagnetisch induzierter Transparenz,
Diploma thesis, Jannis Seyfried 2013
10. Entwicklung und Charakterisierung plasmonischer Linsen für radial polarisierte Strahlung im THz-Frequenzbereich,
Master thesis, Jan Hodapp 2013
11. Großflächige und frequenzselektive Terahertz Photo-Dember-Emitter,
Master thesis, Christian Grumber 2013
12. Slow Light under the Condition of Electromagnetically Induced Transparency,
Master thesis, Thomas Meyer 2013
13. Experimental and theoretical studies of Berry Phases in an EIT medium,
Master thesis, Stephan Welte 2013

Publications 2011-2013

[1] F. Meinert, C. Basler, A. Lambrecht, S. Welte, and H. Helm, “Quantitative analysis of the transient response of the refractive index to conditions of electromagnetically induced transparency," Phys. Rev. A **85** 013820 (2012)

[2] C. Basler, K. Reininger, F. Meinert, P. N. Ghosh, and H. Helm, “Phase control and diagnostic of quantum mechanical superpostition states,” Phys. Rev. A **87** 013430 (2013)

[3] S. Welte, C. Basler and H. Helm, “Studies of Berry’s phase and its sign in quantum superposition states of thermal ^{87}Rb atoms,” Phys. Rev. A (2014) →link fehlt

[4] J. Wallauer and M. Walther, “Fano line shape and phase reversal in a split-ring resonator based metamaterial,” Phys. Rev. B **88** 195118 (2013) Phys. Rev. B **88** 195118 (2013)

[5] M. Roghani, H.-P. Breuer and H. Helm, “Modeling and control of entanglement dynamics in laser cooling of trapped atoms,”
Phys. Rev. A **85** 012313 (2012)

[6] M. Roghani, H. Helm and H.-P. Breuer, “Entanglement dynamics of a strongly driven trapped atom,” Phys. Rev. Lett. **106** 040502 (2011)

[7] P. C. Fechner, K. Mozer, and H. Helm, “Profound Isotope Effect in Dissociation of Triatomic Hydrogen,” J. Phys. Chem. A **117** 9794 (2013)

[8] P. C. Fechner and H. Helm, “Imaging of spatial many-body wave functions via linear momentum measurements,” Physical Chemistry Chemical Physics - DOI: 10.1039/c3cp53300j (2013)

[9] H. Höffler, P. C. Fechner, M. Gisi, F. Baumgartner, U. Galster and H. Helm, “Momentum vector correlations in three-particle fragmentation of triatomic hydrogen,”
Phys. Rev. A **83** 042519 (2011)

[10] T. Wilbois and H. Helm, “Strong-field ionization of H_2 - from ultraviolet to near infrared wavelengths - photoelectron energy and angular identifications,”
Phys. Rev. A **84** 053407 (2011)

[11] T. Wilbois and H. Helm, “Non-ponderomotive effects in multiphoton ionization of molecular hydrogen,”
Phys. Rev. A **83** 053414 (2011)

[12] H. Hultgren and I. Yu. Kiyan, "Photodetachment dynamics of F_2^- in a strong laser field," Phys. Rev. A **84** 015401 (2011)

[13] A. O. Lindahl, J. Rohlen, H. Hultgren, I. Yu Kiyan, D. J. Pegg, C. W. Walter, and D. Hanstorp, "Threshold Photodetachment in a Repulsive Potential," Phys. Rev. Lett. **108** 033004 (2012)

[14] A. O. Lindahl, J. Rohlen, H. Hultgren, I. Yu Kiyan, D. J. Pegg, C. W. Walter, and D. Hanstorp, "Experimental studies of partial photodetachment cross sections in K^- below the K(7^2P) threshold," Phys. Rev. A **85** 033415 (2012)

[15] M. Eklund, H. Hultgren, D. Hanstorp, and I.Y. Kiyan, "Orbital alignment in atoms generated by photodetachment in a strong laser field," Phys. Rev. A **88** 023423 (2013)

[16] H. Hultgren, M. Eklund, D. Hanstorp, and I. Yu Kiyan, "Electron dynamics in the ground state of a laser-generated carbon atom," Phys. Rev. A **87** 013404 (R) (2013)

[17] F. Kohler, E. Schultz and H. Helm, "Morphological and aerodynamic characterization of airborne pollengrains captured in a Paul trap," Aerobiological Monographs, Towards a Comprehensive Vision **1** 157 (2011)

[18] D.A. Turton, J. Hunger, A. Stoppa, A. Thoman, M. Candelaresi, G. Hefter, M. Walther, R. Buchner and K. Wynne, "Rattling the cage: Micro-to-mesoscopic structure in liquids as simple as argon and as complicated as water," Journal of Molecular Liquids **159** 2 (2011)

[19] D. A. Turton, T. Sonnleitner, A. Ortner, M. Walther, G. Hefter, K. R. Seddon, S. Stana, N. V. Plechkova, R. Buchner, and K. Wynne, "Structure and dynamics in protic ionic liquids: A combined ultrafast optical Kerr-effect and dielectric relaxation spectroscopy study," Faraday Discuss. **154** 145 (2012)

[20] M. Walther and A. Bitzer, "Electromagnetic wave propagation close to microstructures studied by time and phase-resolved THz near-field imaging," Int. J. Infrared Millimeter Waves **32** 1020 (2011)

[21] J. Wallauer, A. Bitzer, S. Waselikowski and M. Walther, "Near-field signature of electromagnetic coupling in metamaterial arrays: A terahertz microscopy study," Optics Express **19** 17283 (2011)

[22] A. Bitzer, A. Ortner, H. Merbold, T. Feurer and M. Walther, "THz near-field microscopy of complementary planar metamaterials: Babinet's principle," Optics Express **19** 2537 (2011)

[23] S. Waselikowski,C. Fischer, J. Wallauer, and M. Walther, "Optimal plasmonic focusing on a metal disc under radially polarized terahertz illumination," New J. Phys. **15** 075005 (2013)

[24] A. Tuniz, K. J. Kaltenecker, B. M. Fischer, M. Walther, S. C. Fleming, A. Argyros, B. T. Kuhlmey, "Metamaterial fibres for subdiffraction imaging and focusing at terahertz frequencies over optically long distances," Nature Communication **4** 2706 (2013)

[25] B. Ung, M.Roze, A. Mazhorova, M. Walther and M. Skorobogatiy, "Suspended Core Subwavelength Plastic Fibers for THz Guidance," Optics & Photonics News **22** 41 (2011)

[26] M. Roze, B. Ung, A. Mazhorova, M. Walther, and M. Skorobogatiy, "Suspended core subwavelength fibers: practical designs for low-loss terahertz guidance," Optics Express **19** 9127 (2011)

[27] W. Withayachumnankul, C. M. Shah, C. Fumeaux, K. Kaltenecker, M. Walther, B. M. Fischer, D. Abbott, M. Bhaskaran, and S. Sriram, "Terahertz localized surface plasmon resonances in coaxial microcavities," Advanced Optical Materials **1** 412 (2013)

[28] O. Buchnev, J. Wallauer, M. Walther, M. Kaczmarek, N. I. Zheludev, and V. A. Fedotov, "Controlling Intensity and Phase of Terahertz Radiation with an Optically Thin Liquid Crystal-Loaded Metamaterial," Appl. Phys. Lett. **103** 141904 (2013)

≈≈≈≈≈≈

With deep appreciation for the heroic efforts by all members of the group. I specifically thank PD Dr. Markus Walther and PD Dr. Igor Yu Kiyan for their dedicated work.

Hanspeter Helm, November 30, 2013