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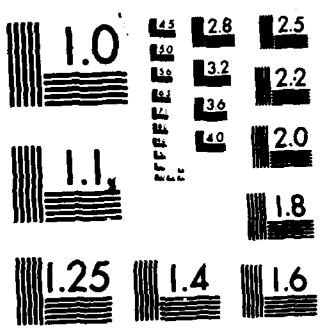
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Final Report

Contract No. N00014-76-C-0014

by

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January 1983

Contents

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II. Scientific Report

This document describes

Research was mainly in the area of laser modified atomic physics with additional work on relativistic effects in heavy atoms.

During the period of this contract I visited many Atomic Physics laboratories. The most useful resulted in strong ties with the groups at Oak Ridge (Compton and Garrett) and Amsterdam (Van der Wiel and Gavrila). This gave me close contact with experimental groups which had a strong influence on the research done here. During the last two years a post doc, Emilio Fiordilino joined our group. We hope that the fruitful collaboration started then will continue with him and his group (headed by Prof. G. Ferrante) in Palermo, Italy.

Research done during the period of the contract is grouped according to subject matter and briefly summarized below.

1. Effects of a low frequency laser on atomic processes.

In 1973 Kroll and Watson (Phys. Rev. A 8 804,, (1973)) showed that electron scattering by a potential in the presence of a low frequency laser could be described by results obtained in the absence of the laser. That is, if the cross section in the presence of the laser is expanded in powers of the laser frequency then the first two terms could be simply expressed in terms of the cross section in the absence of the laser. This derivation was extended to the next term in the series (Phys. Rev. A 19 134 (1979)) which does not have this property and some average properties of the scattering were obtained. It was extended to the situation in which a resonance in the laser-free scattering occurred (Phys. Rev. A 20 1965 (1979)) and a sum rule, different from the non-resonant one of Kroll and Watson was obtained. An attempt to include the deformation of an atomic target during the scattering was then made (Phys. Rev. A 19 99 (1979)) by considering a model atom. The program was completed by treating a real atom (Phys. Rev. A 21 79 (1980)) and it was shown that the two new effects, exchange scattering and the atomic deformation, exactly cancelled to restore the Kroll-Watson result for scattering by an atom rather than a potential.

We then turned to collisions and reactions which have Coulomb fields in the initial and/or final state. In the first of these (with J. Banerji, J. Phys. B. 14 3717 (1981)) the (e-2e) reaction in the presence of a low frequency laser was treated by with improper treatment of the Coulomb potential in the final state. This lead to a close resemblence of our result to the Kroll-Watson result which is incorrect in this case. A proper treatment was given (with J. Banerji, Phys. Rev. A 26 3706 (1982)) for Coulomb potential scattering. We first cut off the Coulomb potential beyond some large distance, R. Then we calculated the cross section and then let R approach infinity where possible. We found that this cross section had no limit for $R \to \infty$ (it oscillates) and called this "unmeasurable." The (e-2e) reaction was reexamined (J. Phys. B 16 1089 (1983)) and also found to be "unmeasurable". The reaction of photo ionization by a weak light source in the presence of a low frequency laser has a Coulomb potential in the final state. It was examined by the same techniques (with E. Fiordilino, Phys. Rev. A 28 229 (1983)) and was found to have a cross section which has a definite limit in the $R \to \infty$ limit. It is however, very different from that which would be obtained with the improper treatment of the Coulomb potential in the final state. A simple experiment is suggested here. Finally it has been shown (with L. Saez submitted to Phys. Rev. A) that the specific form of the cut off of the Coulomb potentials does not effect these results. We also gave a reason for the "unmeasurability" of some results and not others.

2. Electron-atom scattering in the presence of a resonant laser

When an atom is placed in a resonant laser the two states connected by the laser are strongly coupled. This deformed atom can act as a target for electron scattering and should produce results which are very different from the laser free results. These were investigated (with J. Gersten, Phys. Rev. A 13 123 (1976)) and alone Phys. Rev. A 14 1338 (1976)) and shown to be observable. However, it was then noted (Phys. Rev. A 16 1549 (1977)) that the usual experiment permits fluorescence by the atom before and after the scattering and this washes out all the new effects. The only observables are then cross section obtainable in principle in the absence of the laser.

The results above are obtained for a very low intensity ($I \sim 1\text{-}10\,W/cm^2$) laser. More modern tunable lasers can have much higher intensity so we extended the results above to include new effects (with E. Fiordilino, J. Phys. B 16 2205 (1983)).

One of these is the possibility of ionization by the high intensity laser. We found that new physical effects, off-shell T matrices, and interference between T matrices was observable. An experiment was suggested.

A further generalization to the case of resonance between two metastable states of the electron-atom scattering complex was considered (Phys. Rev. A 18 685 (1978)). It was found that the width of these states could be measured in such scattering experiments to the accuracy of the laser width. This is much narrower than the conventional ways of measuring these parameters.

The generalization to resonance between a meta-stable state of the electron plus atom and a negative ion state was also considered (J. Phys. B 12 1965 (1979)). It was found that this could be a very accurate means of measuring the electron affinity of the ion. An experiment by R. Compton at Oak Ridge is being done.

3. Forces on atoms in laser fields.

The theory of the force on an atom in an external (D.C.) field and a resonant, traveling wave laser field has been given (with Rubin, Callender and Gersten, Phys. Rev. A 16 583 (1977)). Further work on a standing wave laser field has been done (with E. Fiordilino, submitted to Phys. Rev. A). It agrees with previous work by Gordon and Ashkin (Phys. Rev. A 21 1606 (1980)) in the very low velocity limit but this applies only for translational energies of the atom of the order of 10^{-3} - 10^{-4} times thermal energies. The new results apply to more realistic energies. Work in this area is continuing in relation to the experimental program in this area which has just started at the City College. It is being supported by another ONR contract (N00014-83K-0654).

4. Multiphoton Ionization.

Multiphoton ionization by ultra-strong lasers was considered (Phys. Lett. 47A, 55 (1974)) and with J. Gersten Phys. Rev. A 10 24 (1974). Ultra strong means that the laser field intensity is larger than the average Coulomb field of nucleus. (10^{17} W/cm^2 for ground state hydrogen). We found the remarkable result that the high intensity regime gave a contribution to the ionzation rate which decreased with increasing intensity. This was extended to Rydberg states (with J. Gersten Phys. Rev. A 11 1103 (1975)) where the average Coulomb field is much smaller so that lower laser intensities are possible. It was found that relativistic effects became important in some cases for ultra strong laser fields and these were included (with P. Krstic, Phys. Rev. A 25 1568 (1982)). It was found that the inclusion of the relativistic effects makes the ionization rate rise (rather than fall) with increasing laser intensity.

We then started to examine the spectrum of the electrons produced in ionization (with P. Krstic, Fizika (Belgrad) 15 195 (1983)). A new theory of multiphoton ionization, based in part on a theory of rearrangement collisions, was produced to describe the spectrum of electrons which have absorbed more than the minimum number of photons required to ionize (with E. Fiordilino and P. Krstic, submitted to J. Phys. B). It concentrated on the free-free transition process which occurs here.

An associated problem concerned with the shift of the threshold energy for ionization in the presence of a laser field was discussed by Muller, Tip and Van der Wiel (J. Phys. B in press). They showed, in the context of the Berson model, (a delta function potential and a circularly polarized laser) that the ionization potential is increased by the presence of the laser by an amount which is essentially the ponderomotive potential. This was stimulated by experiments by this group. We extended the proof to the arbitrary atom with arbitrary laser polarization (Phys. Rev. A in press). Some small corrections to the results of the model problem were obtained. This can be viewed as an extension of earlier work (with J. Gersten, J. Phys. B 9 2561 (1976)) in which we attempted to calculate shifts in binding energies in various specific cases.

5. Fluorescence from atoms in resonant laser fields.

Earlier work in this field was generalized to include the effects of a D.C. magnetic field which provides Zeeman splitting of the states of the atom. This complicates the fluorescent spectrum by splitting the peaks which appear in the absence of the magnetic field (Kourlas, J. Phys. B 14 1433 (1981)).

Further work on fluorescence from an atom moving in a standing wave resonant laser field has been completed (with E. Fiordilino submitted to J. Phys. B). We found that the three peak spectrum produced by the traveling wave laser field is replaced by a much more complicated spectrum with a large number of peaks.

6. The effect of multimode operation of lasers on atomic processes.

Almost all calculations of laser-modified atomic physics are done with single mode lasers. We showed (with J. Gersten in Electron and Photon Interactions with Atoms (1976) Plenum Pub. Co. ed. H. Kleinpoppen & M.R.C. McDowell) how to take the theoretical results for single mode lasers and use a simple averaging procedure to get multi-mode laser results. This can make changes in the results which are many orders of magnitude. A knowledge of the mode structure of the laser is necessary and since this is usually not available comparison between theory and experiment is frequently not possible.

7. Atomic Charge Transfer in the presence of a laser field.

This process was investigated for the specific use of $H^{+}+H$ (Phys. Rev. A 14 586 (1976)) where it was shown that the laser introduces new dynamical processes into the scattering. It could be used to measure properties of the adiabatic curves which are not otherwise measurable.

8. Laser enhancement of β decay.

A paper on this subject (Becker, Louisell, McCullen and Scully, Phys. Rev. Lett. 47 1262 (1981)) which claimed a large effect for high intensity lasers was shown to be incomplete (with J. Gersten Phys. Rev. Lett. 48 651 (1982)) because of the omission of atomic screening. This reduces the effect by many orders of magnitude.

9. Eikonal theory for laser modified scattering.

We obtain the differential cross section for laser modified potential scattering by the eikonal method (with J. Gersten, Phys. Rev. A 12 1840 (1975)).

10. Decay of an adiabatically prepared state.

It has been known for a long time that an atom initially prepared in an excited state will decay exponentially until some large time and then switch over to a t^{-n} decay where n will depend upon the spectrum of the decay products. In many cases it can not be specified that the atom is definitely in the excited state at t=0. Instead it is excited by an adiabatic process which switches the atomic state slowly. We showed (with A. Tip, J. Phys. B in press) that the decay is then purely exponential.

11. Relativistic effects in heavy atoms

The structure of the configuration space Hamiltonian for a heavy atom was derived in a relativistic way (Phys. Rev. A <u>24</u> 1167 (1980)). Particular attention was given to the projection operators which occur. The optimum form for these was obtained. It is well known that the omission of the projection operators from the Hamiltonian produces a nonsensical Hamiltonian. Yet Hartee-Fock calculations based upon this Hamiltonian produce results which agree well with experiments. The explanation of this apparent paradox was given in the context of the optimum projection operator.

The discrepancy between K shell binding energy measurements and these calculations is of the order of 10 ev for high Z ($\sim$85). One effect omitted from the calculations is the contribution of three-body potentials. The fully relavistic form of these was used to estimate this contribution. It was found to be at least an order of magnitude too small (for all Z) to explain this discrepancy (with B. Zygelman, to be submitted to J. Phys. B).

Publications - 1975-present.

Texbook

"Introduction to the Theory of Laser-Atom Interactions", Plenum Pub. Co., N.Y. 1982

Refereed Journals

1. Eikonal theory of charged-particle scattering in the presence of a strong electromagnetic wave, with J. Gersten, Phys. Rev. A 12 1840 (1975).

2. Ionization of highly excited hydrogen atoms by intense electromagnetic fields, with J. Gersten, Phys. Rev. A 11 1103 (1975).

3. The effect of Multimode Laser Operation on Multiphoton Absorption by Atoms, with J. Gersten in "Electron and Photon Interactions with Atoms", Plenum Pub. Co., N.Y. 1976.

4. Atomic Charge Transfer in the presence of a laser field, Phys. Rev. A 14 586 (1976).

5. The shift of atomic states by laser fields, with J. Gersten, J. Phys. B 9 2561 (1976).

6. Electron Scattering from atoms in the presence of a laser field II, Phys. Rev. A 14 1338 (1976).

7. Electron Scattering from atoms in the presence of a laser field, with J. Gersten, Phys. Rev. A 13 123 (1976).

8. Electron Scattering from atoms in the presence of a laser field III, Phys. Rev. A 16 1549 (1977).

9. Deflection of laser-excited atoms by an electric field, with K. Rubin, R. Callender and J. Gersten, Phys. Rev. A 16 583 (1977).

10. Electron Scattering from atoms in the presence of a laser field IV, Phys. Rev. A 18 685 (1978).

11. Resonant Laser Induced Negative Ion Production, J. Phys. B 12 1781 (1979).

12. Resonant potential scattering in a low frequency laser field, Phys. Rev. A 20 1965 (1979).

13. Scattering of a charged particle by a model atom in the presence of a low frequency laser, Phys. Rev. A 19 99 (1979).

14. Potential Scattering of charged particles in the field of a low-frequency laser, Phys. Rev. A 19 134 (1979).

15. Electron-atom scattering in the field of a low frequency laser, Phys. Rev. A 21 79 (1980).

16. Electron-atom ionising collisions in the presence of a low frequency laser field, with J. Banerji, Phys. Rev. B 14 3717 (1981).

17. Resonant fluorescence: Zeeman and AC Stark Effects, J. Phys. B 14 1433 (1981) (by J. Kourlas).

18. Coulomb scattering in the presence of a low-frequency laser field, with J. Banerji, Phys. Rev. A 26 3706 (1982).

19. Multiphoton ionization of hydrogen in ultra strong laser fields, with P. Krstic, Phys. Rev. A 25 1568 (1982).

20. Comment on "Laser Enhancement of Nuclear β decay, with J. Gersten, Phys. Rev. Lett. 48 651 (1982).

21. Free-Free transitions in a laser field, Comm. At. Mol. Phys. 11 91 (1982).

22. Coulomb effects in e-2e collisions in the presence of a low-frequency laser field, J. Phys. B 16 1089 (1983).

23. Laser-modified electron scattering from a slowly ionising atom, with E. Fiordilino, J. Phys. B 16 2205 (1983).

24. Energy spectrum of electrons from multiphoton ionization, with P. Krstic, Fizika (Belgrad) 2 195 (1983).

25. Modification of the photoionization of hydrogen by a low frequency laser, with E. Fiordilino, Phys. Rev. A 28 229 (1983).

Papers in press or submitted

26. Resonance Fluorescence of an atom in a standing wave laser field, with E. Fiordilino.

27. Forces on Atoms in a standing wave laser field with E. Fiordilino.

28. Kinematics of multiphoton ionization in a steady laser beam.

29. Contribution of three body potentials to the binding energy of heavy atoms, with B. Zygelman.

30. Coulomb effects on atomic processes in the presence of a low frequency laser field, with L. Saez.

31. Theory of Multiphoton Ionization into Multiple Energy Continua, with E. Fiordilino and P. Krstic.

32. Decay of an adiabatically prepared state (with A. Tip).

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