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NUCLEAR EXCITATIONS AND REACTION MECHANISMS

Progress Report

by

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N O T I C E

Abstract

The main theme of this Report is the study and interpretation of the sequence of events that occur during the collisions of nuclear particles. Some of the processes discussed in parts A and B involve short range interactions; others involve interactions of long range. In most of part A one of the particles in the initial or in the final state (or in both) is a photon, which serves as a probe of the second particle, which may be a nucleus, a proton, a pion or any other hadron. The complexity of the processes taking place during the collisions makes it necessary to simplify some aspects of the physical problem. This leads to the introduction of modals which are used to describe a limited number of features in as much detail as possible. The main interest is the understanding of the hadronic excitations which result from the absorption of a photon and the determination of the fundamental structure constants of the target particle. In part B, all the particles are hadrons. The purpose here is to develop and apply optimal quantal methods appropriate for describing the interacting systems. Of particular interest are three-particle collision systems in which the final state consists of three free particles. Part B also considers the process of nuclear fusion as catalyzed by bound muons.

1. INTRODUCTION

This Progress Report describes the work of the Brown University Nuclear Theory Group for the period 1 August 1989 - 31 July 1990 under Grant DE-FG02-87ER40334. Completed and on-going research includes various theoretical and numerical studies on: virtual photons, electric polarizability, the Cabibo-Radicati sum rule, photon scattering, electron scattering, electron scattering sum rules, muon catalyzed fusion, few body collisions and breakup phenomena.

The Group consists of Profs. S. Fallieros and F.S. Levin, and two graduate students, Mr. J. Tunstall and Mr. S. Crall. In addition, research has been carried out with the following collaborators: J.L. Friar, E. Hadjimichael, Z.C. Kuruoglu, M.A. Maize and J. Shertzer.

As in the past, local computing has been carried out via time made available by Brown University, while DOE has provided time on the Crays at NERSC at Lawrence Livermore Laboratory.

A. Fallieros

SCATTERING OF PHOTONS FROM NUCLEI: NONRELATIVISTIC DESCRIPTION

The original motivation for this work was provided by photon-scattering experiments at energies above the giant-dipole-resonance region which indicated a clear departure from what is implied by the electric-dipole approximation. The latter is expected to dominate in the long-wavelength limit and is certainly valid when the photon frequencies are close to the peak energy of the dipole resonance. Mr. F. Ludecki, a graduate student at the University of Rhode Island performed some rather detailed calculations for the specific case of mass number A=40 which is small enough to make the calculations feasible and large enough to exhibit effects due to departures from the long-wavelength limit. Of particular interest to us was the consistency of the calculations since in a number of relatively recent studies we had noticed a tendency on the part of several investigators to include mutually incompatible terms in expressions used to analyze the results of experiments. One example is the simple observation that if we apply the dipole approximation using (as Siegert's theorem suggests) operators determined by the positions rather than the velocities of the particles, then the seagull (two-photon) term cannot be included in an unmodified form. Similar, but less familiar, statements become relevant when retardation effects become important. Mr. Ludecki studied first the results of the dipole approximation adding to it subsequently a properly defined seagull term. Not surprisingly, his results showed reasonable agreement with experiments at some scattering angles but the comparison became unsatisfactory at other angles. The reason why we expected such a result was that the seagull term includes scattering involving multipolarities other than the electric dipole whereas the same multipolarities had not been included in the dispersion terms which had been left unretarded. A systematic study was then made of these additional contributions (e.g., electric quadrupole). This, as expected, improved both the logical foundation of the formulations and the comparison with experiment. Mr. Ludecki has now completed his Ph.D. Thesis and has graduated from the University of Rhode Island.

PROPERTIES OF THE EXACT COMPTON AMPLITUDE FOR A SIMPLE SYSTEM

This work has been described in previous reports and we will discuss here mainly the work performed during the past year together with a summary of previously obtained results. The main idea has been to construct a model which is simple enough to permit an exact calculation of the second-order Compton amplitude and other, related, response functions and yet complex enough as to exhibit interesting features analogous to those of more realistic targets e.g., both recoil and intrinsic excitations. As described in last year's proposal our model consists of a delta-function potential in a plane with a particle in it which is bound in one dimension while moving freely in a plane perpendicular to this direction. The binding implies the presence of intrinsic excitations and the free two-dimensional motion allows the particle to recoil in the plane. Mr. John Tunstall has worked on this problem for the past few years. As we mentioned in last year's report he was forced to take a leave of absence for medical reasons and the work was interrupted. His condition has improved considerably during the past academic year and he has been making good progress toward the completion his Ph.D. thesis which we expect to be complete by the end of this coming academic year. As of now he has finished almost all the analytical work required for his thesis and he has written a first draft for most of the chapters of the thesis itself. Even though the model was simple and the exact solutions were obtained, the analytical expressions which express the results turned out to be quite lengthly. A great deal of work was performed in the past several months in an attempt to classify and clarify the results, to extract physical properties from the mathematical expressions and to verify that the solutions do indeed satisfy the basic symmetry characteristics that the theory is expected to satisfy. Work in this direction will undoubtedly continue during the next contract year. At this stage we have the nonrelativistic amplitude in a reasonably compact form and have completed and identified almost all the response functions describing most of the fundamental properties of the target.

GAUGE-INVARIANT FORMS OF THE NONRELATIVISTIC COMPTON AMPLITUDE

In the low-frequency limit, the amplitude describing the scattering of photons from any dynamical target is traditionally expanded in powers of the incident-photon frequency. The lowest term is a constant and is the well known Thomson amplitude. The term linear in frequency vanishes by crossing symmetry while the quadratic term is expressed in terms of structure-dependent constants which depend on the physical properties of the target: its size, its excitation spectrum and its excitation strength. The size-dependent term is inversely proportional to the mass of the target and represents the recoil of the finite-size target (it is equal to zero if the target is a point particle) whereas the other structure-dependent constants depend on the mass of the constituents of the target. The recoil term has motivated some debates in the recent past since it didn't appear to be physically obvious that the motion of the center of mass should lead to a purely electric-dipole effect as suggested by its angular distribution. In addition, it has been argued, such a term couldn't possibly have anything to do with absorption but if this were true, it would undoubtedly create problems with the, so-called, σ_{-2} sum which relates the total inverse-energy weighted integrated absorption cross section with the structure constants of low-energy scattering. In an attempt to clarify some of these questions we have introduced an alternative representation of the low-energy Compton amplitude. In recent work in collaboration with J.L. Friar we derived an expansion in terms of the electric and magnetic field amplitudes of the initial and the scattered photons. The new expression was shown to be completely equivalent to the traditional decomposition but, at least in some cases, provides an easier and more natural interpretation of the physical origin of the various terms. It is also helpful in illustrating how, in the special case when the target approaches the limit of a Goldstone boson, the electric polarizability and the magnetic susceptibility of a spin-zero target become opposite and tend to cancel each other. This work has already been written up and has been accepted for publication in the Physical Review.

B. Levin

MUON CATALYZED FUSION

One of the aims of this work has been to obtain not only accurate energies but also wave functions for muonic molecules such as pdμ, ddμ, dtμ and ttμ. Apart from a Monte Carlo computation, all published analyses have been variational in nature. As is well known, an error of 10^{-2n} in the variational energy means an error of 10^{-n} in the trial wave functions. Furthermore, since the trial wave functions used in variational calculations are defined over the entire domain of interest, i.e., are globally defined, these trial functions are optimized in accuracy at points where the potential is maximum. Consequently, all matrix elements which involve these trial functions, other than that of the Hamiltonian, can contain much larger errors than does the variationally-determined energy. Examples for muonic atoms are expectation values of interparticle distances and muon sticking probabilities (the probability that, e.g., $d + t\mu \rightarrow \alpha\mu + n$ rather that $d + t\mu \rightarrow \alpha + \mu + n$).

The approach we have followed to obtain improved non-energy matrix elements is that of the finite element (FE) method. In this method, the usual infinite domains of coordinate or momentum space are made finite and then discretized into smaller subdomains denoted elements. The Schrödinger equation is solved directly in each element separately. This is in contrast to the variational method, which minimizes the energy. The relevant aspect of using the FE method is that it produces energies and wave functions of comparable accuracy. Of course, as the size of the elements is decreased, the resulting energies and wave functions more closely approximate the exact ones, with the exact values being achieved in the limit.

The shortcoming to this seeming paragon of approximation methods is that its reliance on solving large matrix eigenvalue equations requires using computers with vast memories or writing complex in/out programs that access external storage. Either way, the computations are long and thus costly in CPU time. Given sufficient access to large memory supercomputers, this latter aspect is straightforwardly overcome. Such access to the Cornell supercomputer has been obtained by Prof. J. Shertzer, my collaborator in this effort, who has been responsible for computer code construction, debugging and running.

As noted in last year's Renewal Proposal, a computer program for carrying out relevant calculations for total angular momentum $J = 0$ states with vibrational quantum number $v = 0$ was then running, and a new eigenvalue code was being constructed. That construction was completed last winter and the task of determining energies and other matrix was begun.

To date, two sets of computations have been completed and an article describing them has recently been submitted for publication. The two systems reported on are the He atom and the $dd\mu^+$ muonic ion. He was included for two reasons. First, it exemplifies the generality of the computer code, constructed to treat any three-body coulomb system. Second, it provides a benchmark case for our claim that the FE method yields energies and geometries of comparable accuracy. This has been a somewhat sore point amongst those who use non-variational methods when discussing calculations with those who employ the variational approaches and belittle other methods. The He study establishes beyond doubt that the FE method lives up to its claims, in particular because this method permits direct incorporation of mass polarization effects. Results accurate to 10^{-5} have been obtained with a small grid involving less than 200 elements in this 3-D calculation. A larger grid was used in the 3-D computations for $dd\mu^+$; here 480 elements were employed with a resulting accuracy of 10^{-4}. In both calculations, 3-D plots of the wave function were obtained. In the $dd\mu^+$ case this is apparently a first (at least for the muon-catalyzed community of experimentalist).

These calculations have been very time consuming. Sticking coefficients and transition rates have not been extracted yet due to certain problems at the Cornell supercomputer, which we hope will soon be overcome, thus allowing these latter numbers and those for other muonic systems to be obtained.

THREE-PARTICLE COLLISIONS IN TWO DIMENSIONS

This study constitutes the Ph.D. thesis research of Mr. Crall. It was undertaken with two goals in mind: first, to close a gap in the exploration of the three-particle system; second, to try to shed light on the apparent problem of imposing the coordinate-space boundary condition in a numerical analysis of three-body break-up in the three dimensional case.

The gap noted above concerns the general behavior in the scattering sector of the three-particle collision system in two-dimensions. This is the only aspect of the three-particle system interacting via short-range forces which has not previously been investigated: this system has been fully analyzed for the 1-D and 3-D cases, but only its bound state and effective range properties in 2-D have so far been studied in depth.

While the lack of full understanding in the 2-D case merits further investigation, it is not a high priority item when considered in isolation. However, in the context of possibly explaining a paradox in the analysis of breakup in 3-D, this project becomes much more relevant to current research.

The paradox concerns on the one hand the apparent invalidity of a certain approximation and on the other hand its successful application in numerical calculations. The approximation in question is that of stationary phase (SP); it is derived – and assumed valid – only when the separations of the three particles forming the system are asymptotic. Even though in numerical analyses the separations are never asymptotic much less even very large, imposition of the boundary conditions based on use of the SP approximation leads to unexpected accuracy of the extracted S-matrix elements. These latter results are in contrast to estimates of Kuruoglu and Levin and of Glöckle, which suggested that large errors would be found when the stationary phase approximation is used at non-asymptotic separations. It is our hope that the breakup studies for the 2-D case will help clarify this situation.

To date, the analytical work noted in last year's Renewal Proposal has been completed: the relevant asymptotic boundary conditions have been obtained using the method of stationary phase. No other procedure has yet produced these same results. A number of numerical calculations have been undertaken and most are completed; all involve two-body systems and were designed to familiarize Mr. Crall with techniques needed for the more complex, three-particle case, programming for which will be initiated during semester I of the upcoming academic year.

TIME-DEPENDENT APPROACH TO FEW BODY COLLISIONS

It was proposed last year to perform calculations on the p-d collision system. These were to have been based on a modification of the computer code successfully used to carry out our n-d collision studies via numerical solution of the time-dependent Schödinger equation. That code had been constructed, debugged and run by my collaborator Prof. Z. C. Kuruoglu, whose responsibility it has been to carry out the modifications needed to do the p-d analyses. He returned last fall to Bilkent University in Ankara, Turkey, and has thus far encountered insurmountable problems in linking to the MFE computer facility at Lawrence Livermore Lab. Establishing this link was essential if the calculation were to have been done during this past academic year.

The absence of the link has meant that the further work on p-d and other calculations was postponed until August 1990, when Prof. Kuruoglu again visited Brown University. The majority of his visit was planned to be spent working on articles describing the earlier n-d calculations; the remaining time was to be programming the p-d computations and initiating calculations of breakup S-matrix elements for the n-d process, an undertaking that had been previously postponed.

OTHER ACTIVITIES

During the past year the efforts of Prof. D. A. Micha (University of Florida) and myself to found a new pedagogic/review book series entitled "Few Body Systems and Multiparticle Dynamics" seem to have been realized. Contract negotiations with Plenum Press are underway, with Micha and me to be joint Series and Volume Editors. Invitations to distinguished "few-body" physicists to write chapters for the first two volumes in the series have been issued and accepted.

3. PUBLICATIONS, 1 A. gust 1989 - 31 July 1990

F.S. Levin, "La Grande Illusion: Aspects of the Non-Relativistic Description of the Three-Nucleon System", in Trends in Theoretical Physics, Vol. I, ed. by P.J. Ellis and Y.C. Tang (Addison-Wesley, Redwood City, 1990), pp 1-55.

Z.C. Kuruoglu and F.S. Levin, "Wave Packet Calculation of Sharp-Energy S-Matrix Elements for a Three-Body System in the Breakup Regime", Phys. Rev. Letters **64** (1990) 1701.

J. Shertzer and F.S. Levin, "Solution of Three-Body Coulomb Problems for $J = 0$", submitted for publication.

J.L. Friar and S. Fallieros, "Gauge-Invariant Forms of the Nonrelativistic Compton Amplitude", accepted for publication in Phys. Rev.

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