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THEORETICAL NUCLEAR PHYSICS

PROGRESS REPORT

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Abstract

This report summarizes progress during the past year in the following areas of research: the role of meson exchange currents in nuclear reactions, including vector mesons in pion DCX, and K^+ -nucleus cross sections. Pion excess distributions in nuclei, and the role of nuclear correlations. Inelastic electron scattering and the Coulomb sum rule. Statistical nuclear spectroscopy, including the evaluation of static densities and expectation values.

I. Meson Exchange Currents and Nuclear Reactions

A major subject of interest in recent years has been the role of meson exchange currents (MEC) in various nuclear reactions. From the point of view of nuclear structure theory, exchange currents are many-nucleon phenomena, closely related to NN interactions and correlations in nuclei. From the point of view of nuclear reaction theory, the exchange currents are part of the substructure of the nuclear target not given by the nucleons alone. Conversely, the study of nuclear reactions is the most promising way of gaining access to subnuclear degrees of freedom in nuclei -- particularly with weakly interacting hadronic probes, or with electrons. The issue of MEC effects in reactions has therefore emerged in the last 5 to 10 years as important for mesonic and nucleonic experiments at LAMPF, BNL, IUCL, etc., and for a longer time for electron scattering in nuclei at SLAC or BATES, and soon at CEBAF.

The study of MEC in the context of mesonic reactions with nuclei has been a major effort at Rochester since 1989. This started with an attempt to straighten out a controversy in the literature about the role of MEC in the pion double charge exchange (DCX) reaction. This investigation led in turn to a study of the K^+ -nucleus reaction. By this time we found there was a general class of questions under discussion on evidence for the "pion excess" in nuclei, which is really a measure of the pion MEC. We describe our findings next.

1) Pion DCX

Our work on pion DCX has been discussed in the last few annual progress reports, and in two publications: Phys. Rev. **C42**, 2662 (1990) and Phys. Lett. **B273**, 6 (1991). The

primary result is that for low energy DCX, chiral theory limits the size of the MEC contribution to less than ($\lesssim 1/3$) that of multiple scattering. A third paper (in preparation), deals explicitly with vector meson exchange in a chiral theory, using a Lagrangian model of Wess and Zumino which includes the ρ (and the a_1 -meson – the chiral partner of the ρ -meson) as well as pions in the MEC. The result is, as expected from the second paper, that the vector meson MEC contribution is small compared to the pion MEC (which is also small!). An invited talk on this subject was presented at the International Workshop on Pions in Nuclei at Peniscola, Spain in June 1991.

Our results settle the issue of the relative importance of MEC for low energy DCX. There are, of course, many questions left open. One is what happens at higher energies, into the Δ -resonance region. It is not clear to what extent chiral symmetry constrains this region, but one does expect that chiral theories should have something to say here. For the DCX reaction itself, the outstanding issue is putting all the pieces together in a complete analysis: multiple scattering with correlations, pion absorption, and MEC.

2) K⁺-Nucleus Scattering

There has been considerable interest recently in a series of K⁺-nucleus scattering experiments at Brookhaven which have raised the possibility of anomalous behavior. The effect of interest is that experimental cross sections – most recently total cross sections – for K⁺ on ¹²C, are larger than can be explained by optical potentials based on known K⁺N amplitudes. The deviations are of order of 10% – the uncertainties in the optical theory are of similar size, but tend to be in the wrong direction to improve agreement. This difference has led to speculation in the literature about exotic effects on K⁺N scattering in a nuclear target – and to more experiments.

Our experience with MEC effects in pion-nucleus DCX scattering (see previous section) led us to investigate the possibility that MEC contributions to K⁺-nucleus scattering might be part of the answer to the anomalous cross sections. We developed a theoretical model for the process of K⁺ scattering on virtual pions exchanged within the nuclear target. Some details were given in last year's annual progress report, and the results have since been published. Our calculation for K⁺ + ¹²C (Phys. Rev. C46, 2462 (1992)) finds a positive contribution to the total cross section of about 5-7% in the range of BNL

experiments ($p_K \sim 500 - 800 \text{ MeV}/c$), which is of the right sign and magnitude to improve the disagreement between optical theory and experiment. We assign an uncertainty of $\pm 50\%$ based on the input to the calculation, so the result may be considered to be an estimate of the MEC contribution. This work has also been presented as an invited talk at a conference “Realistic Nuclear Structure” at SUNY Stony Brook in May, 1992.

Whether this process is sufficient to ‘explain’ the anomalous cross sections is not settled. One of the basic problems is that the optical results have uncertainty of their own, and must be cleaned up. Second, there may be related $K\pi$ processes which have not been included. In the $\pi\pi$ case, the chiral structure of the theory guarantees that all contributions of a given order are kept together; that is not the case here.

However, there is one interesting feature of the MEC contribution which distinguished it from a class of explanations which invoke a change in K^+ -N scattering within nuclei. The latter behaves like a change of scale (e.g. increase in the K^+ -N scattering length) which gives a change in the K^+ -nucleus total cross section for all K^+ momenta decreasing slowly with p_K . The MEC contribution, by contrast, increases with p_K from a threshold at $\sim 400 \text{ MeV}/c$, which does seem closer to the experimental trend.

The problem continues to be of interest, not only to ‘explain’ the K^+ -nucleus cross section, but also as a way of ‘seeing’ virtual pions (MEC) in nuclear targets. The existence of these is a topic of some controversy right now (see next section), and there are not many direct experimental probes. The K^+ -nucleus scattering may provide some evidence on this question, based on the relatively weak single scattering (K^+N) which provides most of the cross section. By contrast, pions do not seem to be an appropriate probe, because of the chiral suppression of the scattering.

3) Pion Excess Distribution in Nuclei

The pion excess distribution is the momentum distribution of pions exchanged among nucleons in a nucleus - that is, in excess of the pion “cloud” carried by each nucleon. Therefore, this distribution is relevant to any physical process involving MEC: for DCX, it is an isotensor distribution; for K^+ -nucleus scattering, the distribution is isoscalar.

As mentioned in the previous section, it has been known that realistic nuclear correla-

tions play an important role in calculating the excess pion distributions. We have initiated a new program to calculate these distributions for both isoscalar and isotensor cases. The effects of various correlations – central and tensor, isoscalar and isovector – on the various distributions can be separated and studied individually. We would expect to obtain similar results to those published (by Wiringa and others) for the isoscalar excess pion distribution. We shall also check the effect of correlations for isotensor MEC amplitudes – as in DCX – although the effects are expected to be less dramatic than for isoscalar.

II. Electron Scattering from Nuclei: Coulomb Sum Rule

One of the main reasons for extending the energies of excitation of nuclei into the GeV domain, as will be possible at CEBAF and RHIC, is the study of subnucleon degrees of freedom in the nuclear target. A central issue in nuclear theory is how to deal with both internal and external degrees of freedom of the constituents of nuclei : i.e. nucleons interacting with meson, fields, or nucleons as clusters of quarks, etc. A good example of this is the response of nuclei to inelastic electron scattering, including (e, e') and $(e, e'p)$ reactions. For nuclei considered as many-body systems of nucleons (generally-nonrelativistic) there exists a large theoretical technology of response and spectral functions, and sum rules for these functions (Coulomb Sum Rule, Removal Energy Sum Rule) which allow extraction of nuclear structure information (at least in principle) from inelastic scattering data. When the excitations reach energies of 0.5 - few GeV, two extensions of the response theory (at least) must be made, to include property effects of relativity, and of excitation of internal degrees of freedom (meson currents, resonances, quarks, etc.).

We have instituted a research program to deal with these questions, beginning with the study of quark models of nuclear systems using Bethe-Ansatz techniques (1986-1991). In the last year we have begun a more general study of response functions and sum rules for high energy excitations.

One of the striking issues which is well illustrated by the study of quark models is the interpretation of the Coulomb sum rule. In its standard form, in the limit of large momentum transfer, the Coulomb sum (integral of the inelastic response function over all excitation energies at fixed momentum transfer) gives a measure of the number of

independent scatterers in the target - an incoherent sum of probabilities. For a quark model this is the number of quarks (weighted by e_q^2 - the squared quark charges) while for nucleons the sum is $e^2 Z$ (in a nonrelativistic limit). This raises a number of questions about the interpretation, and indeed the existence of the Coulomb sum rule for nuclei with subnucleon degrees of freedom.

Starting last fall, we have begun a program to reanalyze systematically the theory of nuclear response and the Coulomb sum rule (among others). Our initial assumption (conjecture) is that there are modifications to the sum rule which lead to one (more likely, more than one) version which is well defined and can be interpreted in terms of nuclear structure information, in particular about two-nucleon correlation functions - in analogy to the nonrelativistic nucleon version of McVoy and VanHove. The extensions of interest should apply for excitations of up to a few GeV, where both relativity and nucleon excitation are aspects which must be incorporated in the theory.

We have made some progress on the issue of relativity, for nucleons which are treated as 'elementary', that is, not excited in electron scattering. This would be of interest for the $(e, e' p)$ reaction, in which a final proton of high momentum is detected. There is a literature going back about ten years, dealing with the Coulomb sum rule with a relativistic treatment of the nucleons, e.g. in a relativistic mean field model, often simply a Fermi gas. A number of papers have noted that (e, e') scattering is limited (by relativity) to energy transfers $\omega \leq q(c)$, where q is the momentum transfer. This means that as a practical matter, the Coulomb "sum" $S(q)$ (or energy transfer integral) is limited to $0 < \omega < q$ for fixed q . It is then not hard to show that for large q ($> 2k_F$; k_F = Fermi momentum), this $S(q)$ varies with q , and for $q \gg m$ (nucleon mass), $S \rightarrow Z/2$, as opposed to $S \rightarrow Z$ for nonrelativistic nucleons. Although theoretically extending the integration of ω to $q < \omega < \infty$ contains more strength, it also contains information about nucleon pair production irrelevant to the structure of the nucleus. The various authors have differed about how to interpret the result, and how to proceed to a sum rule from which two-nucleon correlation information about the target might be recovered.

Building on this background, but with some further development, we have succeeded in deriving a Coulomb sum rule appropriate to this relativistic nucleon situation. The

results involve some approximations for “Fermi motion” effects, but do relate a Coulomb sum $\tilde{S}(q)$ (integrated over $0 < \omega < q$) to a two-body correlation function, with limiting behavior $\tilde{S}(q) \rightarrow \sim Z$, as for the nonrelativistic case. A written account of this work is being prepared for publication.

The main issues of relativity which is dealt with in this theory are connected with the relativistic recoil of the struck proton, which give large corrections. Fermi motion in the target is less important, and is treated approximately. Explicit issues of antinucleons are not fully dealt with, and are still under investigation.

We have also begun some work on response theory which includes nucleon excitation, through their inelastic structure functions. In the process we have found some modifications to the standard approach to correcting deep inelastic (DIS) (e, e') data (e.g. EMC) for Fermi motion. These are both directions of future work.

III. Statistical Nuclear Spectroscopy

As described in recent progress reports and papers this subject divides into two parts which, broadly speaking, involve locally-energy-averaged quantities, and fluctuations about averages. The first part is treated by “fluctuation-free statistical spectroscopy” and the second by random-matrix theory whose validity has been well demonstrated by comparison of experimental and theoretical measures for spectral and strength fluctuations. Each part of the subject has its own applications. The second, considered by itself, is encountered in studying formal aspects of quantum chaos; when combined with the first it can generate, from spectra and transition strengths in complex nuclei, bounds on or measures for symmetry breaking at the nucleon-nucleon level. The first joint application gave bounds on time-reversal noninvariance in the nucleon-nucleon interaction. Recently the general structures encountered in, and the results of, these papers have been used by the TRIPLE Collaboration to derive, from neutron resonances in ^{235}U , a numerical measure for parity-breaking in the nucleon-nucleon interaction. Others, particularly the Heidelberg group, have made similar uses of our results.

Our interest in both parts of the subject continues but for the past several years we have invested most of our efforts in simplifying the treatment given earlier for fluctuation-

free statistical spectroscopy. Besides studying symmetry breaking in the nucleon-nucleon system, as discussed above, the aim is to make accessible methods for studying locally -energy averaged quantities; these include state and level densities, occupancies and expectation-values more generally, transition-strength densities, and other quantities which measure, for example the goodness of model symmetries and determine the appropriate parameters to be used in specific nuclear models as well as measures for the validity of such models.

During the last few years we have answered outstanding difficult questions connected with expectation values which may be calculated in several inequivalent ways depending on what correlations are specifically dealt with and which may be ignored. We have treated in detail single-state and multiple-state occupancies and spin-cutoff factors (which determine the angular-momentum and isospin dependence of the state densities); all of these are important for nuclear reactions and nuclear thermodynamics, to make just two applications. For state densities and for these expectation values (which derive by parametric differentiation on the densities) a complete set of computer programs have been written, tested and applied by V.K.B. Kota and R.U. Haq.

Three papers under the general title: "Fluctuation-Free Nuclear Spectroscopy" ("Elementary Principles and Applications", "State Densities and Smoothed Partition Functions" and "Expectation Values") have been written but publication has been delayed until a large set of computer programs could be tested and documented. These programs have been completed and a fourth paper is in preparation; they are designed to make calculations feasible by a person familiar with the first paper above. The first three papers will be sent soon for publication, while the fourth paper will be made available as a report.

IV. Symposium

A Symposium, "From Spectroscopy to Chaos", honoring J. Bruce French, was held at the University of Rochester on April 17, 1993. Ten invited speakers, each of whom had some research interaction with Professor French at some period in his research career, summarized his own recent research interests, which were quite diverse. The proceedings will be published by World Scientific. The program follows:

FROM SPECTROSCOPY TO CHAOS

Saturday, April 17, 1993

- 9:00 - Welcoming Remarks
W. P. Alford, Chair of Session
- 9:10 - M. MacFarlane Sum Rules in Nuclear Physics:
From Spectroscopic Factors to Condensates
- 9:40 - J. Draayer On the Complementarity of the Microscopic
and Macroscopic Pictures of Nuclear Structures
- 10:10 - Coffee Break, B&L 271
D. Cline, Chair of Session
- 10:30 - G. Mitchell Fluctuation Properties of Nuclear States:
Experimental Status
- 11:00 - R. Haq From Chaos to Spectroscopy
- 11:30 - D. Rowe Symmetry in Nuclear Physics
- 12:00 - Lunch Break
J. B. McGrory, Chair of Session
- 2:00 - S. Tomsovic Constructing Quantum Mechanics from Chaos
- 2:30 - S.S.M. Wong Solitons and Nucleons
- 3:00 - B. Altshuler Universalities in Chaotic Spectra:
Energy Levels as Fermions
- 3:30 - Coffee Break, B&L 271
G. Garvey, Chair of Session
- 4:00 - J. Ginocchio The Fractional Quantum Hall Effect
and the Spherical Shell Model
- 4:30 - O. Bohigas Quantum Spectral Fluctuations:
Towards Universalities

V. Research Publications and Reports (July 1992 - June 1993)

1. M.F. Jiang and D.S. Koltun
Meson Exchange Current Contribution to K^+ -Nucleus Scattering
Phys. Rev. **C46**, 2462 (1992).
2. M.F. Jiang, R.Machleidt and T.T.S. Kuo
Relativistic Ring-Dieagram Nuclear Matter Calculations
Phys. Rev. **C47**, 2661 (1993).
3. M.F. Jiang
Pion Meson Exchange Contribution to K^+ -Nucleus Scattering to appear in *Realistic Nuclear Structure*, proceedings of a conference in honor of T.T.S. Kuo, Stony Brook, 1992 (to be published – World Scientific).

The following papers are in preparation:

1. M.F. Jiang and D.S. Koltun
Chiral Symmetry Constraint on Meson Exchange Current Contributions to the Pion DCX Scattering
2. T.C. Ferrée and D.S. Koltun
Relativistic Coulomb Sum Rules
3. J.B. French, R.U. Haq, V.K.B. Kota and J.F. Smith
Fluctuation-Free Nuclear Spectroscopy: I. Elementary Principles and Applications
4. J.B. French, R.U. Haq, V.K.B. Kota and J.F. Smith
Fluctuation-Free Nuclear Spectroscopy: II. State Densities and Smoothed Partition Functions
5. J.B. French, R.U. Haq, V.K.B. Kota and J.F. Smith
Fluctuation-Free Nuclear Spectroscopy: III. Expectation Values

VI. Research Personnel

The work here includes, besides that of the principal investigator, research carried out by (former) Research Associate M.F. Jiang, (current) Research Associate Thomas Ferrée, and by visitors V.K.B. Kota and R.U. Haq who are involved in an ongoing collaboration together with Professor J.B. French (emeritus).

Dr. Ming-Fang Jiang ended his appointment as Research Associate in October 1992, after slightly more than three years at Rochester. He is currently Research Associate in Physics at Vanderbilt University. His collaboration with the nuclear theory group at Rochester continues.

Dr. Thomas Ferrée (Ph.D. U. Colorado, 1992) joined the research group as Research Associate in September 1992. He will continue in that position for a second year.

Two graduate students have joined the nuclear theory group in Summer 1993 as research assistants; they are Aalok Misra and Ed Turano.

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