Theoretical and Computational Studies in Intermediate Energy Nuclear Physics

Progress Report for Period

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1. Introduction

The research supported by this grant includes applications of many-body scattering theory to nuclear systems and studies of few-body systems described by effective hadronic field theories.

During the first year of the current grant from the U.S. Department of Energy considerable progress was made in bringing all first order effects into the nonrelativistic elastic nucleon-nucleus scattering in a consistent fashion. This work is directed towards completely and reliably calculating the first order term in a Watson expansion including a modification through the nuclear medium.

The research effort in few-body physics was concentrated on nucleon-nucleon (NN) scattering below pion production threshold, where recent measurements indicated that the backward angle neutron-proton (np) differential cross section may show sensitivity to the size of the pion-nucleon coupling constant.

Completed and ongoing research efforts in the two main areas mentioned above are discussed in the following two sections.

Important contributions to this work have been made by the PI's collaborators. They include C.R. Chinn and R.M. Thaler from Vanderbilt University, and J. Rapaport and A.E. Feldman from Ohio University.

2. Application of many-body Scattering Theory to Nuclear Systems.

The basis of the discussion of elastic nucleon-nucleus scattering is the Watson formulation [1] of multiple scattering theory (MST). The reason for this is that scattering of charged particles and modifications of the scattering process due to the presence of the nuclear medium can be formulated and calculated more clearly within this formalism than other formulations such as the Kerman-McManus-Thaler (KMT) [2] formalism.

Our investigation of isovector degrees of freedom in proton-nucleus elastic scattering at intermediate energies has been completed and the work has been published [3]. Isovector effects, i.e. mechanisms which distinguish neutron from proton scattering, can be treated explicitly without any difficulty in the first-order Watson multiple scattering form. In calculations based on the KMT formalism they are usually averaged out since

their inclusion is quite tedious. We tested the accuracy of the KMT averaging procedure for proton incident energies from 200 MeV to 800 MeV and found that it is very good for nuclei larger than ^4He . We then used our formalism to look at the impact of differences in the neutron density on elastic proton scattering observables. Although the proton density distribution is very well determined from electron scattering data, this is certainly not the case for the neutron distribution. Studies of ^{40}Ca and ^{208}Pb suggest that the surface neutrons may be pulled in somewhat relative to the protons. Comparisons of theoretical predictions with elastic proton scattering angular distribution data suggest, that a smaller neutron rms radius and a thinner surface are favored. A similar indication of the relative compression of surface neutrons may lie in the variational calculations of the ground state of ^{16}O by Pieper *et al.* [4], who obtain a smaller rms radius for ^{16}O than the electron scattering measurements indicate. Our studies also indicate that it remains unrealistic to expect to be able to extract detailed quantitative information about the target nucleus from elastic proton-nucleus reactions.

An important step in the proposed research project within the first-order potential for nucleon-nucleus scattering is the modification of the scattering process due to the presence of the nuclear medium. We succeeded in developing a systematic formalism as an extension to the first-order multiple scattering theory, where a mean field potential, representing the action of the residual nucleus upon the target nucleon, is used to model medium contributions. In summary, an effective NN interaction is constructed, which enters the optical potential instead of the free NN t-matrix. Consistency with multiple scattering approaches, specifically the spectator expansions [5, 6], is maintained in our formulation. Our formalism is straightforward and we performed calculations for ^{40}Ca . A paper with a detailed description of our formalism and our results for proton and neutron scattering from ^{40}Ca at energies between 48 and 200 MeV has been submitted to Physical Review C [10].

We performed our calculations with two mean field potentials taken from realistic and proven nuclear structure models [7, 8] to represent medium contributions. The full Bonn interaction [9] was used to provide the free NN t-matrix. The full spin structure of the mean field potential and the free NN t-matrix is included along with off-shell and nonlocal effects. Since only known quantities are used to represent the required physical ingredients to our calculations, it must be emphasized that there are **no** adjustable parameters present.

Our results demonstrate that the medium contributions consistently provide a significant and nonnegligible improvement in predicting observables in the case of elastic nucleon-nucleus scattering from ^{40}Ca at projectile kinetic energies between 48 and 200 MeV. Above 200 MeV medium effects are insignificant at scattering angles less than $\sim 40^\circ$.

A striking result of our calculation is the improvement of the description of the total cross section σ_{tot} for neutron scattering from ^{40}Ca (cp. Fig. 9 in Ref. [10]). While the impulse approximation with the free NN t-matrix displays an incorrect energy dependence in describing σ_{tot} between 100 and 600 MeV, our inclusion of medium contributions improves this considerably. We found, that the medium contributions mainly change the absorptive character of the optical potential, namely decrease the absorption at low energies by as much as 10% while increasing it slightly at high energies. This behavior seems to be mainly responsible for describing the energy dependence of the neutron total cross section correctly. We are in the process of analyzing this phenomenon in more detail by studying the reactive content of the optical potential by means of the optical theorem. Furthermore, we are in the process of studying the dependence of our results on different NN interactions employed and thus having a more precise estimate on the theoretical uncertainty provided by different physical ingredients to our calculations. These studies will be subject of a future publication.

3. Few-Body Systems described by Effective Hadronic Field Theories.

The PI's research effort in this area has been concentrated on studies of the sensitivity of the backward angle np differential cross section to the pion-nucleon coupling constant. This subject is at present highly controversial, since measurements by Roennqvist *et al.* [11] at 95 MeV incident neutron energy disagree with older measurements [12]. In a recent NN partial wave analysis by the Nijmegen group [13], these data have not been included, since this group believes there is some inconsistency with other data and their analysis. In a different partial wave analysis by Henneck [14], the inclusion of the Roennqvist data results in a rather high value of the ε_1 mixing parameter at 95 MeV, which is interpreted in Ref. [14] as an indication for the presence of a strong tensor force in the NN interaction. This conclusion would be inconsistent with the presently favored small value of the pion-nucleon coupling constant, since the one-pion exchange (OPE) determines the long range part of the NN tensor force.

Measurements of backward angle np differential cross sections between 65 and 250 MeV were carried out by a group at Ohio University and preliminary results were presented at the Spring APS meeting [15]. At 95 MeV those preliminary data are consistent with the Roennqvist data. The measurements of the Ohio University group are currently being repeated [16].

The size of the NN tensor force is a very important quantity in few-nucleon physics. For example, the predicted binding energy of the three-nucleon system depends almost

linearly on its size via the magnitude of the deuteron D-state probability, provided energy-independent NN potentials enter as input to the Faddeev calculations. Thus, the required magnitude of genuine three-body forces, which have to be included for a correct prediction of the three-body binding energy (among other quantities), depend indirectly on the size of the NN tensor force. Therefore, discrepancies in the extracted value of the pion-nucleon coupling constant are rather disturbing, since the pion is believed to be the most well known particle mediating the NN force, especially the long range part.

During the last two years there has been a lively discussion about the value of the pion-nucleon coupling constant. Arndt et al. [17] have redetermined the value of the charged pion-nucleon coupling constant analyzing the available $\pi^\pm p$ data below 2 GeV and find a value of $g_c^2/4\pi = 13.31 \pm 0.27$. About a decade ago, Koch and Pietarinen [18] had obtained $g_c^2/4\pi = 14.28 \pm 0.18$ in a similar analysis. The Nijmegen group has analyzed pp data below 350 MeV laboratory energy to determine the $\pi^0 pp$ coupling constant $g_0^2/4\pi$. Their analysis of 1987 yielded the value of 13.11 ± 0.11 [19]; in 1990 they obtained 13.55 ± 0.13 [20]. Both results are substantially below the value of 14.52 ± 0.4 determined by Kroll [21] in 1981, who analyzed pp -scattering data in terms of forward dispersion relations.

The PI and a student studied the sensitivity of the back angle np differential cross section to the size of $g_\pi^2/4\pi$ within the framework of One-Boson-Exchange (OBE) models [22] and the full Bonn NN interaction [9]. We preferred this approach over using the interactive DIAL-IN program SAID by R.A. Arndt, as done in Refs. [11, 14]. The reason is twofold: First, applying meson exchange models allows one to explicitly change meson couplings and thus study the effect of those changes in all partial waves. Second, the partial wave solutions provided by the program SAID display a rather disturbing dependence on the year they were carried out. We found that the rise of the backward angle np differential cross section depends on the high partial waves as well as on the 3D_2 partial wave (at 95 MeV the latter provides roughly 50% of the the contribution). Both contributions are dominated by the OPE.

We also found, that although the high partial waves do not show any cutoff dependence, they vary (within 5%) on the type of three-dimensional reduction used to cast the Bethe-Salpeter equation into Lippmann-Schwinger form. These reductions (e.g. Blankenbecler-Sugar) typically introduce factors E/M (M representing the nucleon mass, $E = \sqrt{M^2 + k^2}$), which can be interpreted as energy dependent ‘renormalization’ of the coupling constant. At the deuteron pole, these factors are irrelevant.

Our studies showed that the magnitude of the backangle np differential cross section depends almost linearly on the size of $g_\pi^2/4\pi$, provided all other couplings remain fixed. This result is independent of the NN model employed.

It is well known that the tensor force in the NN interaction results from the delicate interplay between π - and ρ -exchange. Since quark models predict a scaling of the ρ -tensor coupling, $f_\rho^2/4\pi$, with $g_\pi^2/4\pi$, we varied both couplings simultaneously. We also tested the effect of a small ratio of the ρ -vector to tensor coupling, $\kappa_\rho = f_\rho/g_\rho = 3.7$, as suggested by the vector dominance model (VDM) for the nucleon electromagnetic form factor. With the latter a satisfactory description of the deuteron properties together with a small value of $g_\pi^2/4\pi = 13.38$ has been obtained [23]. We found that the scattering data do not allow such a small value of κ_ρ and, thus, put stronger constraints on $g_\pi^2/4\pi$ and κ_ρ than the deuteron properties.

In a more sophisticated model for the NN interaction like the full Bonn model, which includes Δ -isobars and multiple meson exchanges, the situation is more complicated, since the $N\Delta\pi$ as well as the $N\Delta\rho$ coupling constants depend on the value of $g_\pi^2/4\pi$. Therefore, a change of $g_\pi^2/4\pi$ implies an overall change in the character of the nuclear force. These consequences have not been considered in the present literature. This final step is still in progress.

The above research resulted in an undergraduate thesis (advisors J. Rapaport and the PI), submitted to the Honors Tutorial College at Ohio University by B.E. Barmore. The preliminary results of this work were presented by the PI as invited talk at the 'Theory Workshop on Meson-Nucleus Dynamics at Intermediate and High Energies' at Argonne National Laboratory. A publication will follow in connection with the final experimental analysis of the Ohio University group.

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4. Student Support and Equipment Purchases

The following students were supported by the grant for one quarter each: R.A. Rice, L. Wang and S. Weppner.

The visualization software package 'PV-WAVE Point&Click', distributed by Precision Visuals, was purchased as an add-on to the already available graphics package 'PV-WAVE command language'. In addition, 12 4-megabyte SIMMS modules were purchased to upgrade the memory of the PI's SPARCstation 2 and SPARCstation IPC.

5. Publications

A. Journal Publications and Preprints

A paper entitled 'Isospin Effects in Elastic Proton-Nucleus Scattering' by C.R. Chinn, Ch. Elster and R.M. Thaler has been published by *Phys. Rev. C* **47** (1993), 2242. The following is an abstract of that paper:

Isovector effects in proton-nucleus elastic scattering at medium energies are studied. The accuracy of the KMT isospin averaging procedure is found to be very good for nuclei larger than ^4He . Studies of ^{40}Ca and ^{208}Pb suggest that the surface neutrons may be pulled in somewhat relative to the protons, although uncertainties in the detailed applicability of the present truncation of the multiple scattering treatment render firm conclusions premature.

A paper entitled 'Microscopic Formulation of Medium Contributions to the First Order Optical Potential' by C.R. Chinn, Ch. Elster and R.M. Thaler has been submitted to *Phys. Rev. C*. The following is an abstract of that paper:

A refinement of the first-order optical potential is introduced, consistent with multiple scattering theory and the spectator expansion. A systematic formalism is presented to treat medium contributions associated with the difference between the

effective NN t-matrix as required by multiple scattering theory and the free NN t-matrix. A mean field potential is used to represent the action of the residual $(A - 1)$ nucleus upon the struck target nucleon (medium effects). We calculate elastic proton and neutron scattering from ^{40}Ca , using the full Bonn interaction and two different mean field potentials taken from realistic and proven nuclear structure models. Results indicate that the medium contributions are insignificant at energies above 300 MeV and provide a significant improvement of the theoretical predictions for laboratory energies between 48 and 200 MeV.

B. Contributed Papers to Conferences and Oral Presentations at Professional Meetings

‘Backward angle n-p differential cross sections for $65 \leq E_n \leq 250$ MeV.’, by A.E. Feldman, J. Rapaport, Ch. Elster, B. Barmore, F.P. Brady, G. Fink, C.R. Howell, A. Ling, B.K. Park, J.L. Romero, D. Sorenson, W. Tornow, J. L. Ullmann, X. Yang. American Physical Society meeting, April 1993.

‘Medium Corrections within a Multiple Scattering Theory.’, by C.R. Chinn, Ch. Elster and R.M. Thaler. American Physical Society meeting, April 1993.

‘Scattering in Three Dimensions.’, by R. A. Rice and Ch. Elster, Physics Computing 1993, May 31 - June 4, 1993.

‘n-p Differential Cross Sections at Backward Angles and the πNN Coupling Constant.’ Inv. Talk at the Theory Workshop on Meson-Nucleus Dynamics at Intermediate and High Energies. Argonne. IL, August 2-6, 1993.

C. Internal Reports

‘Sensitivity of Back Angle (n,p) Scattering to the Pion-Nucleon Coupling Constant.’ by Bryan E. Barmore.

Undergraduate thesis presented to the Honors Tutorial College at Ohio University in partial fulfillment of the requirement for graduation with the degree of Bachelor of Science in Physics.

6. Appendices

*not attached,
also*

- Appendix A: Copy of the paper entiteled 'Isospin Effects in Elastic Proton-Nucleus Scattering' by C.R. Chinn, Ch. Elster and R.M. Thaler, Phys. Rev. **C47** (1993), 2242.
- Appendix B: Preprint of a paper entitled 'Microscopic Formulation of Medium Contributions to the First Order Optical Potential' by C.R. Chinn, Ch. Elster and R.M. Thaler, submitted to Phys. Rev. C.
- Appendix C: Copy of the internal report INP-93-01 of the undergraduate thesis by Bryan E. Barmore presented to the Honors Tutorial College at Ohio University, entitled 'Sensitivity of Back Angle (n,p) Scattering to the Pion-Nucleon Coupling Constant.'

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