

The Final Report to the
UNITED STATES DEPARTMENT OF ENERGY

from the

DEPARTMENT OF PHYSICS

College of Physical and Mathematical Sciences

NORTH CAROLINA STATE UNIVERSITY at Raleigh

Raleigh, North Carolina 27695-8202

for support of research entitled

NUCLEAR STRUCTURE RESEARCH

AT

THE TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

Grant No. DE-FG05-88ER40441

1 April 1988 to 4 May 1998

RECEIVED
APR 04 2000
OSTI

We have no objection from a patent
standpoint to the publication or
dissemination of this material.

MP Dunscale

3/14/00

Office of Intellectual

Property Counsel

DOE Field Office, Chicago

Date

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

OVERVIEW

Much of our research is focused on symmetries and symmetry breaking. We have emphasized the effects of the many body system on symmetry breaking – the parity violation studies. A parallel interest lies in the effects of symmetry breaking on the many body system (as manifested in the statistical distributions characterizing the system). Another major activity has involved few nucleon scattering. Our primary technical efforts are in low temperature targetry. Our service activity for the nuclear science community is Nuclear Data Evaluation.

Below we summarize the results achieved in these areas during the period of the grant. The details are given in the 10 annual progress reports, approximately 150 publications, and 10 Ph.D. dissertations.

Research Activities

1. PARITY VIOLATION WITH NEUTRONS – THE TRIPLE COLLABORATION (C. R. GOULD, D. G. HAASE, G. E. MITCHELL)

The TRIPLE Collaboration (primarily researchers from Los Alamos and TUNL, with participants from Delft, TRIUMF, KEK, Kyoto, and JINR-Dubna) was formed to study parity violation in neutron resonances in heavy nuclei at the Los Alamos Neutron Scattering Center (LANSCE). NCSU has provided a large fraction of the senior scientists and the majority of the students (three NCSU students received their Ph.D. degrees for research on this topic). The formation of the collaboration essentially coincided with the beginning of the present grant. During this period an initial experimental apparatus was used to obtain exciting preliminary results. Following these first measurements the entire system was redesigned and rebuilt. We then obtained a large body of data over a period of several years. We developed new analysis methods and wrote programs to process and analyze the data. At the end of this grant the data had not been completely analyzed, but the methods were well established. The final analysis is now being performed under a new DOE grant. This work was a major success, generating nearly 100 papers and approximately 70 invited talks during the 10 year period of the grant. An early review (J. D. Bowman, G. T. Garvey, Mikkel B. Johnson, and G. E. Mitchell, *Annu. Rev. Nucl. Part. Sci.* **43**, 829 (1993)) was based on the initial measurements. The most recent review (G. E. Mitchell, J. D. Bowman, and H. A. Weidenmüller, *Rev. Mod. Phys.* **71**, 445 (1999)) emphasized the generic nature of the enhancement of the symmetry breaking in complex systems was prepared during the period of this grant.

The TRIPLE Collaboration was formed to study the neutron-nucleus weak interaction. The nucleon-nucleon interaction consists of a parity conserving (PC) part and a parity nonconserving (PNC) part, with the strength of the weak term about 10^{-7} relative to the strong term. The weak interaction can be detected by measurement of

appropriate pseudo-scalar observables. Following the prediction by Sushkov and Flambaum, a group at JINR, Dubna, Russia, observed strong PNC effects due to mixing of compound nuclear levels with the same angular momentum and opposite parity. In heavy nuclei the enhancement of the helicity dependence of the cross section can be as large as 10^6 .

As impressive as these first results were, they were extremely limited in energy and sensitivity. At the Los Alamos Neutron Scattering Center (LANSCE) we extended the PNC measurements to several hundred eV with much improved sensitivity. Following initial positive results with an old polarizing filter, and with the first versions of the spin flipper and the neutron detector, we rebuilt and improved the entire experimental system. (We also built a γ -ray detection system that was appropriate for small isotopically enriched samples.)

With the improved system we observed over 70 statistically significant (3σ) parity violation effects. The initial attitude towards the Dubna results was that these very large enhancements were of only anecdotal interest, since analysis was clearly impossible due to lack of knowledge of the wavefunctions. However, the perceived major disadvantage of the neutron scattering data – the high degree of complexity of the nuclear resonance wave functions – can be turned into an advantage. Level statistics and strength distributions of neutron resonances are known to agree with the predictions of Random Matrix Theory. In our statistical approach, a set of PNC matrix elements obtained from the data determines the mean square matrix element and (after dividing out the level spacing) the weak spreading width. This latter quantity provides a direct measure of the strength of the effective parity violating interaction in nuclei. Thus the statistical approach yields important physical information about average quantities without the need to make any statements about the wavefunctions of individual resonances.

The price of the statistical approach is the requirement of studying a number of res-

onances per nuclide; thus the great advantage of the present work over the initial measurements. Given the longitudinal asymmetries and complete spectroscopic information the determination of the rms PNC matrix element is straightforward. However, there is rarely complete spectroscopic information available even for targets with spin zero. For targets with spin not zero, the information is never complete. We developed an analysis approach that averages over unknown quantities and that permits the inclusion of any partial spectroscopic information. This entire theoretical approach, both the generic statistical ideas and the specifics of the Bayesian analysis, was the direct contribution of the TRIPLE Collaboration.

In order to determine the longitudinal asymmetry well, one must describe the background cross section well. This requires a proper description of the multilevel cross section, which in turn requires a large amount of spectroscopic information. In addition to issues related to target composition (such as contaminant resonances and isotopic identification of resonances for those targets such as palladium, silver, and antimony, for which more than one isotope contribute significantly), there are complications related to the beam and detector. These include broadening resulting from the time structure of the neutron beam, relative motion between the neutrons and the target nuclei, and the time response of the detector system. A computer program (FITXS) was written that includes all of these considerations.

The data taking phase of the TRIPLE Collaboration work was completed in 1995. For the remaining time of this grant the focus was on analysis of the large amount of data. At times the new data make significant contributions to the spectroscopic information. For example in ^{133}Cs there was only one p -wave resonance known – we added 28 new p -wave resonances. Efforts in the mass 90 to 130 region have added significantly to the knowledge of the neutron p -wave neutron strength function in this region.

This work provides the first measurements of the effective nucleon-nucleus interaction for medium and heavy nuclei, and verifies the key elements of the theoretical

description of the enhancement of the weak interaction in the many body system.

2. PARITY VIOLATION WITH PROTONS (G. E. MITCHELL)

These experiments are intended to study parity violation in the compound nucleus in light nuclei, in order to complement the experiments described in the previous section. This research is performed at TUNL. This project was started rather late in the period being reported on and was still at the development stage at the end of this grant. Special funding for the segmented silicon strip detector and the associated electronics was provided by a DOE Capital Equipment Grant.

The neutron resonance parity violation experiments determine the effective nucleon-nucleus weak interaction. The basic questions concerning this effective interaction are its strength, energy dependence, and mass dependence. The neutron measurements determine the average strength of the effective interaction. However, they provide essentially no information concerning energy dependence (since the experiments are all at the neutron separation energy). The mass dependence issue has two facets, which may be characterized as global and local. The large number of nuclides studied in the $A = 110$ region suggest that there are local fluctuations in the strength of the effective weak interaction. However, since one has only two average values – for $A = 110$ and $A = 230$ – the overall trend is not well established. Since the purpose of the neutron parity violation experiments is the determination of the effective weak interaction, this is a serious limitation. There are very few theoretical studies on this issue and there is no consensus.

The simplest way to determine the global mass dependence of the effective weak interaction (which we characterize in a short hand notation by the weak spreading width) is to obtain information for lighter nuclei. Extending our neutron measurements to lower masses is extremely difficult in principle, and impossible in practice. Therefore we turned to charged particle parity violation experiments. The large values for the average level spacings leads to much lower parity violating asymmetries (essentially one loses the kinematic enhancement factor), but there are some compensations. First

there is available an excellent polarized proton beam at TUNL, which is a necessary requirement. In addition, for a number of s-d shell nuclei we have a large amount of spectroscopic information for proton-induced reactions on lighter nuclei from our earlier measurements at TUNL. Therefore we can (on average) decide in advance which resonances are more likely to show large parity violation effects. We considered five s-d shell nuclei and chose ^{31}P as our initial target, and also chose to study the (p,α) reaction. The details are provided in two papers which proposed this series of experiments (G. E. Mitchell and J. F. Shriner, Jr., Phys. Rev. C 54, 371 (1996) and J. F. Shriner, Jr. and G. E. Mitchell, Phys. Rev. C 49, R 616 (1994)).

We have a detector array of 64 silicon strip detectors. The data acquisition system and the associated electronics are functioning well. The experimental requirements include stability of the polarized beam energy and position, and polarization magnitude and direction. We have designed procedures for performing precision determination of these quantities. The most serious problems arises from the fact that the largest parity violation effects tend to occur for the weaker resonances. This means that the experiments involve narrow resonances, and that the beam energy stability and resolution become crucial. In addition, due to the very close geometry employed, the spatial distribution of the beam intensity and of the polarization are important.

The initial experimental efforts were performed at the close of the reporting period and were directed at the development of a reliable stable system and towards understanding and reducing the main systematic uncertainties.

3. FEW-NUCLEON SCATTERING STUDIES WITH POLARIZED BEAMS AND TARGETS (C. R. GOULD AND D. G. HAASE).

A broad-based study of few body nuclear systems with polarized beams and polarized targets has been a unique activity at TUNL for many years. Targets have included hydrogen, deuterium, and ^3He , polarized in both longitudinal as well as transverse geometries. The program is now in its concluding phase. Two students received their Ph.D. degrees for research in this area. The experimental phase of this program, involving polarized neutron beams of energies 2-18 MeV and polarized proton and deuteron targets was essentially completed during the period of the grant. Remaining efforts have focused on the analysis of the n-p data in terms of modern NN potentials and on analysis of the n-d data in terms of exact three-body calculations with and without three-body force effects.

For n-p scattering, the measurements have yielded the most accurate data to date on $\Delta\sigma_T$ and $\Delta\sigma_L$, the transverse and longitudinal differences in the total cross sections. By combining the two sets of measurements, the important phase shift parameter ϵ_1 has been deduced in a way that is almost independent of the singlet phase shift parameters. Uncertainties in these parameters have clouded earlier determinations of ϵ_1 and have made it difficult to probe small deviations from the predictions of meson exchange models of the NN interaction. A comprehensive analysis of all ϵ_1 data below 50-MeV, and comparison to predictions of NN potential models, phase shift analyses, and effective range parameterizations was undertaken after the close of this grant.

The n-d scattering data provide a new observable for testing the accuracy of 3N calculations in the continuum. While most 3N observables are well predicted by modern theory, nd analyzing power data and the binding energy of the triton continue to be problems. Via the generalized optical theorem, $\Delta\sigma_T$ and $\Delta\sigma_L$ for n-d scattering are linear in the forward scattering amplitudes and are therefore uniquely sensitive to the underlying model of the NN interaction and to the inclusion of three body force effects.

In summary these measurements have provided the best np and nd data relevant to special features of the NN interaction and to three body force effects.

4. QUANTUM CHAOS AND ISOSPIN SYMMETRY BREAKING (G. E. MITCHELL)

This is another major area of activity that has been active throughout the entire reporting period. These experiments are designed to study the effect of symmetry breaking on level statistics and on transition strength distributions. Near the beginning of the grant our studies in ^{26}Al provided the first experimental demonstration for the effect of symmetry breaking on the eigenenergies, while near the end of the grant we provided the first experimental demonstration of the effect of the symmetry breaking on the transitions. During the period of this grant we essentially completed the complete spectroscopy for another nuclide – ^{30}P . A Compton-suppression spectrometer developed for these studies was funded by a DOE Capital Equipment Grant. During this period five NCSU students received their Ph.D. degrees for research related to this project. There were a large number of publications relating to this work. The interest in this topic is demonstrated by the large number of invited talks, and by the interaction with a number of key theoretical groups – Barbosa, Guhr, Harney, and Weidenmüller of MPI Heidelberg, Hussein and Pato of the University of Sao Paulo, Ormand of Livermore National Laboratory, Horoi of Central Michigan, and Brown and Zelevinsky of Michigan State.

The study of isospin symmetry breaking in nuclei provides an ideal test case for the effect of symmetry breaking on level statistics and transition strength distributions. Since the symmetry breaking is due to the Coulomb force, it is very well understood. Our first measurements were on the effect of isospin symmetry breaking on the level statistics in ^{26}Al (G. E. Mitchell *et al.*, Phys. Rev. Lett. 61, 1473 (1988)). For this $N = Z = \text{odd}$ nuclide where the isospins $T = 0$ and 1 coexist at all energies, isospin is broken at approximately the 3% level. The observed level statistics are between those expected for one GOE sequence or for a mixture of two GOE sequences. Our experimental results were explained by Guhr and Weidenmüller. The explanation

(of the large effect caused by such a small symmetry breaking) is that the effect on the statistical observables depends on both the amount of symmetry breaking AND the level density. The particular combination of the amount of symmetry breaking and the level density led to an experimental result intermediate between one and two GOE's. This permitted extraction of the Coulomb mixing matrix element, which agrees with values obtained from other methods. Hussein and Pato later obtained the same (theoretical) result with a slightly different approach.

There is no other direct experimental test except for our measurements on ^{30}P . There are similar measurements in analog systems that mimic the effects of chaos and random matrix theory. Ellegaard's group at Copenhagen, Denmark studied the effect of breaking a two-fold symmetry in a quartz block. By breaking the symmetry in a controlled manner, they observed directly the change in the level statistics as a function of the degree of symmetry breaking. Richter's group at Darmstadt, Germany used coupled microwave cavities to model the breaking of a two-fold symmetry. Since all theoretical analyses and experiments (quantum and analog) agree, the effect of symmetry breaking on the level statistics is considered well understood.

However, for the transition distributions, the experiments were far ahead of the theory. The effect of symmetry breaking on the transition distributions is not well established. In Random Matrix Theory the independence of the off-diagonal matrix elements leads to a Gaussian distribution for the matrix elements. The distribution of the square of the matrix elements – transition strengths – is a Porter-Thomas distribution. The effect of symmetry breaking on the transition distribution had never been calculated.

We measured the electromagnetic transition strengths in ^{26}Al to test the effect of isospin breaking on the transition distribution (A. A. Adams, G. E. Mitchell, and J. F. Shriner, Jr., *Phys. Lett. B* **422**, 13 (1998)). Our results are based on about 1,000 transitions – E1 both isoscalar and isovector, M1 isovector, and E2 isoscalar – and all four groups of transitions have distributions that are significantly different

from Porter-Thomas. After the close of this reporting period, a group at Max Planck Institute Heidelberg provided an explanation of the observed results via a numerical simulation of this problem.

Thus these measurements have provided the first experimental observation of the effect of symmetry breaking on the eigenvalue and transition strength distributions. For the eigenvalues the effect had been predicted in general, and was later confirmed theoretically in detail via analytical and numerical techniques and experimentally through the study of systems that mimic the effects of chaos. For the transitions, the effect had not been predicted, and in fact was quite unexpected. Very recently there have been theoretical results consistent with our experimental observations.

5. POLARIZED TARGETS FOR NUCLEAR PHYSICS (D. G. HAASE)

NC State has a long-established program in the development of polarized targets for experiments in neutron physics. This has involved neutron transmission experiments at TUNL ($\vec{n} - \vec{p}$, $\vec{n} - \vec{d}$ and $\vec{n} - {}^3\vec{He}$), at LANL (parity violation in compound nuclear resonances), and at JINR, Dubna (neutron depolarization in ferromagnets). These devices were crucial (respectively) to the experiments described in section 3, section 1, and as a spin-off of the parity violation experiments in section 1. The NCSU group has had extensive experience in the implementation of dynamically polarized proton and deuteron targets for few body studies at TUNL.

Near the end of the grant period it became clear that a continuation of our program of target development was needed - the re-fitting of the existing TUNL spin-spin dilution refrigerator cryostat would be crucial to perform studies for the HIGS DFELL project. In general there was and is a need for new target materials and geometries. For example, the figure of merit in a neutron transmission experiment is P^2t^2 where P is the target polarization and t the target thickness. To increase the effective target thickness - and the NMR filling factor - future development efforts were planned to experiment with target material cast in the form of slabs rather than small beads.

6. NUCLEAR DATA EVALUATION FOR $A = 3-20$ (J. H. KELLEY AND D. R. TILLEY)

Near the beginning of the grant for which this is the final report, TUNL accepted the responsibility for evaluating and compiling nuclear structure and reaction data for nuclei in the mass region from $A = 3-20$. The Nuclear Data Evaluation Group at TUNL is responsible for evaluating information relevant to nuclei in the $A = 3-20$ mass range, and for maintaining a comprehensive compilation of nuclear properties, such as "Adopted Levels and Gamma-Rays" and reaction and decay information.

The effort is coordinated by the United States Nuclear Data network and is associated with the International Nuclear Structure and Data Evaluators Program. The nuclear physics interests at TUNL, a low-energy light ion-beam facility, provide a healthy environment for evaluation and review of nuclei in this mass region as much of the pertinent experimental work is performed at TUNL or at similar facilities.

Energy Levels of Light Nuclei

In 1952 T. Lauritsen and F. Ajzenberg-Selove began the evaluation and compilation effort known as "Energy Levels of Light Nuclei" with an emphasis on level and reaction information for $A = 5-20$ nuclei. These reviews, published in Nuclear Physics A, were produced by F. Ajzenberg-Selove during the years from 1974 to her retirement in 1990. At the request of the National Nuclear Data Committee (NNDC), TUNL produced reviews of $A = 3$ and $A = 4$ nuclei, and following the retirement of Fay Ajzenberg-Selove TUNL assumed the responsibility for updating reviews of $A = 3-20$ nuclei. We have produced reviews for $A = 16-19$, and the most recent update, "Energy Levels of Light Nuclei $A = 20$ ", was published in 1998 [Til98].

A review of nuclei in the $A = 5-7$ region was initiated and pre-print versions for $A = 5$ and 6 are already available for download from our web site. Preliminary evaluation of new information related to $A = 8-10$ nuclei is underway.

Evaluated Nuclear Structure Data Files (ENSDF)

TUNL is responsible for updating the $A = 2-20$ information which resides in the ENSDF data base at the NNDC. Prior to the assumption by TUNL of responsibility for this mass region, abbreviated ENSDF files in this region were prepared by M. Martin and M. Bhat and included only "adopted levels and gammas" and β -decay information. ENSDF files which include more complete level information for specific reactions have been prepared concurrently with the "Energy Levels of Light Nuclei" publications for the $A = 18-19$ and $A = 20$ publications.

Recently, ENSDF files that reflect adopted levels and reaction information for the most recent publications have been updated for $A = 2-4$, $7-10$, 16 and 17 . Updates of $A = 5-7$ ENSDF files were initiated.

World Wide Web Services

The availability of the World Wide Web access in both academic and public communities has motivated the Data Evaluation Group to emphasize this outlet as a means for dissemination. A priority activity is to provide abridged versions of the "Energy Levels of Light Nuclei" publication in PDF format for the $A = 3-20$ nuclei. The status of this project follows. The compilations by Fay Ajzenberg-Selove for $A = 5-10$, preliminary versions of TUNL's reviews for $A = 5$ and 6 , and the reviews that TUNL has produced for $A = 3$ and $A = 16-20$ are available from our web site. Production of manuscripts that are based on the evaluations of Fay Ajzenberg-Selove for $A = 11-15$ was begun.

A recent initiative is a posting of "Update List". These update lists are the result of a first-pass survey of current literature and are intended to identify and provide a brief description of recent publications that contain experimental or theoretical information on nuclear structure for each of the $A = 3-20$ nuclides. The update lists contain detailed information, such as new level information, that will be used by us in the preparation of new evaluations. We began producing update lists in preparation for our $A = 6$ review and have progressed so that now update lists are available for A

= 6-9. Beginning with $A = 8$ and above, the update lists are hyper-linked to the online Nuclear Science References (NSR) database description. Eventually, for online journals, the NSR intends to make direct links to the published articles. By making our update lists available on the web, we provide users with a summary of relevant articles that contain information that has been produced subsequent to the most recent full review in an "Energy Levels of Light Nuclei" publication.

Currently, the following information is available at our web site:

www.tunl.duke.edu/datacomp

- (a) Energy Level Diagrams for $A = 4-20$.
- (b) Abridged versions of "Energy Levels of Light Nuclei" for $A = 3$, $A = 5-10$, and $A = 16-20$. Preliminary versions of the new $A = 5$ and 6 evaluations are available.
- (c) "Update Lists" that contain detailed information from recent references for nuclei in the $A = 6-9$ region.
- (d) ENSDF files for $A = 3-20$ Nuclei.
- (e) A version of the *Table of Isotopes* that has been provided by the Berkeley Isotopes Project.
- (f) Information about the status of the evaluation project.