DOE/ER/40353-20

# PROTON RESONANCE SPECTROSCOPY

Progress Report

December 1, 1992 - February 28, 1994

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February, 1994

PREPARED FOR THE U. S. DEPARTMENT OF ENERGY

UNDER GRANT NUMBER DE-FG05-87ER40353

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## Preface

Work on chaos in low-energy nuclear systems has continued on several fronts. We have completed the preparatory stage for our experiments to establish a complete level scheme in $^{30}$P, and the first data were taken in December. As an alternative approach to chaos, we are studying suggestions that the transition strengths can be used as an appropriate signature. The first studies are using shell-model calculations for $^{22}$Na; a sufficient number of B(E1) and B(M2) values have been calculated that the statistical errors are not the primary limiting factor. We will refine our analysis techniques on this set and then analyze experimental data from $^{26}$Al. Details are given in Sects. 1 and 4.

We have also continued to study the possibilities of studying both detailed-balance violation and parity violation with charged-particle resonances. We have calculated expected enhancements for a large number of potentially interfering resonances; the results are described in Sects. 2 and 3.

We have replaced several control systems in the TUNL High Resolution Laboratory in the past year. Both the electrostatic analyzer and the analyzing magnet are now controlled via a 80486 PC running the software package LABVIEW. General operating procedures are outlined in Sect. 5.

Support by TTU and by Oak Ridge Associated Universities allowed me to spend the 1992-93 academic year at TUNL. Gloria Julian of the TTU Department of Physics has once again handled secretarial and accounting duties for this grant, and I express my gratitude for the outstanding job that she does. I also wish to thank the personnel of TUNL and the Duke Department of Physics for their hospitality and assistance during my visits.

## 1. A Complete Level Scheme for $^{30}P$

(with E. G. Bilpuch, C. R. Bybee, J. M. Drake, G. E. Mitchell, E. F. Moore, G. A. Vavrina, P. M. Wallace, and C. R. Westerfeldt

Work has continued on preparations for studying $^{29}Si(p,\gamma)$; the purpose of this experiment is to establish a complete level scheme of $^{30}P$ in order to increase our understanding of chaotic behavior at low energies in nuclei. This past year, we have installed the new target chamber and detector mounts, done final debugging on our data acquisition system, and (in December) acquired the first data with the new system. The first measurements consisted of acquiring spectra for two resonances in the $^{27}Al(p,\gamma)$ reaction for calibration purposes and for a single resonance in the $^{29}Si(p,\gamma)$ reaction. Measurements with $^{66}Ga$, $^{152}Eu$, and $^{154}Eu$ sources were also taken. One of the Compton-suppressed spectra from the $^{29}Si(p,\gamma)$ resonance at $E_p$ = 2.2381 MeV is shown in Fig. 1. Analysis of this first data and preparations for study of the remaining resonances are in progress.

## 2. A Search for Resonances Suitable for Tests of Detailed-balance Violation

(with J. M. Drake, E. G. Bilpuch, C. R. Bybee, G. E. Mitchell, and J. T. Slayton)

We have been working for several years on a search for interfering resonances which would provide an especially sensitive test of detailed-balance violation. This search was motivated by the suggestion of Bunakov and Weidenmüller [1] that large enhancements could be expected in such tests.

We examined available $(p,\alpha_0)$ resonance data for the p + $^{23}Na$ [2], p + $^{27}Al$ [3], p + $^{31}P$ [4], p + $^{35}Cl$ [5], and p + $^{39}K$ [6,7] systems. We identified 41 pairs of adjacent resonances which have the same spin/parity $J^\pi$ and which have a measured alpha

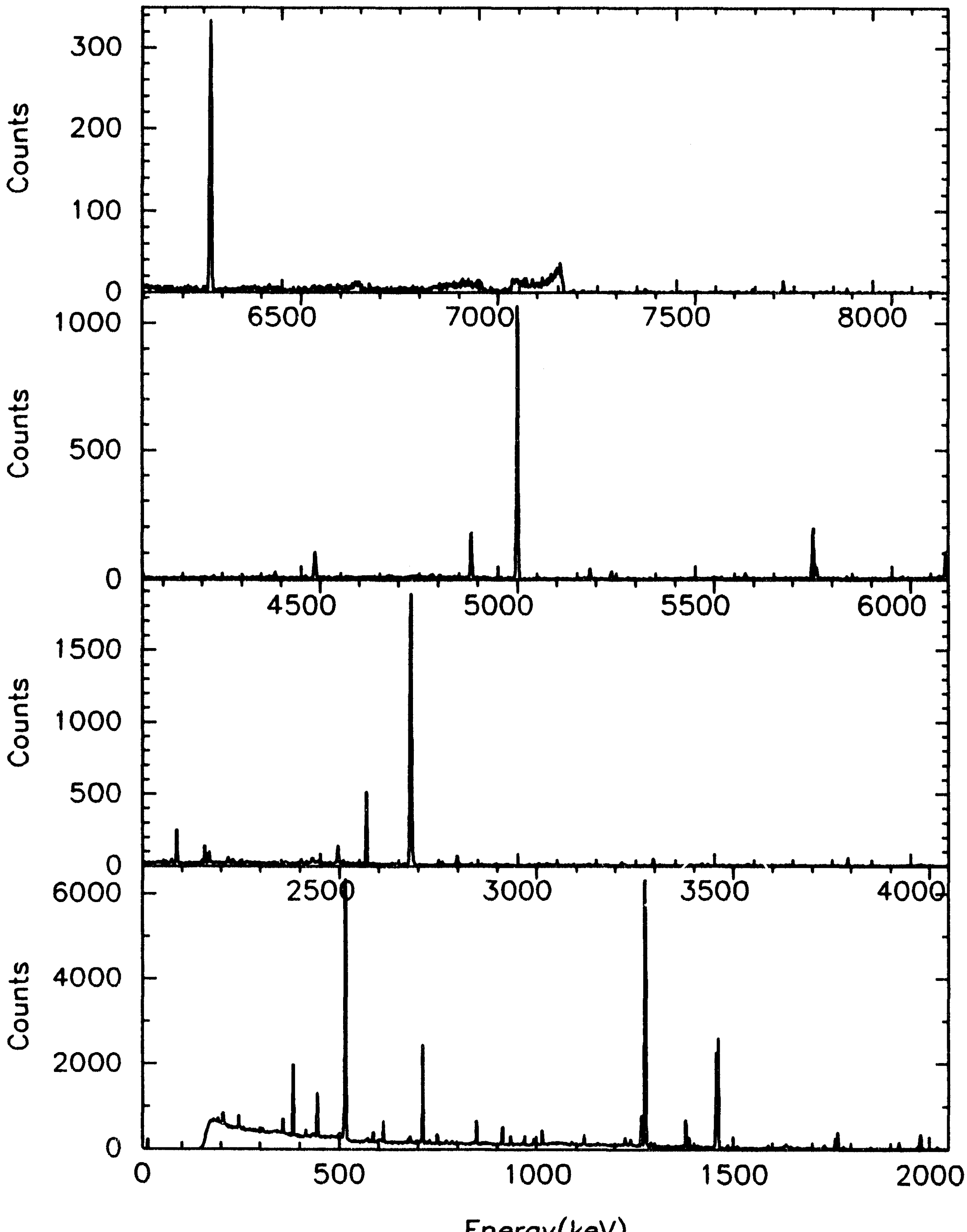


Figure 1. Gamma-ray spectrum for $^{29}Si(p,\gamma)$ at the $E_p$ = 2.2381 MeV resonance.

width for at least one of the two resonances. For each of the pairs, we calculated the quantity

$$\Delta(E,\theta) \equiv 2\,\frac{\dfrac{k_p^2}{g(p,\alpha)}\dfrac{d\sigma}{d\Omega}_{(p,\alpha)}(E,\theta) - \dfrac{k_\alpha^2}{g(\alpha,p)}\dfrac{d\sigma}{d\Omega}_{(\alpha,p)}(E,\theta)}{\dfrac{k_p^2}{g(p,\alpha)}\dfrac{d\sigma}{d\Omega}_{(p,\alpha)}(E,\theta) + \dfrac{k_\alpha^2}{g(\alpha,p)}\dfrac{d\sigma}{d\Omega}_{(\alpha,p)}(E,\theta)} \qquad (1)$$

where $k = 2\pi/\lambda$ and g is the usual statistical factor. A value of $\Delta$ differing from zero is evidence for violation of detailed balance (and thus time-reversal-invariance). To evaluate the matrix elements that appear in the differential cross-section, we followed the formalism of Moldauer [8]: A Hamiltonian of the form

$$H - H_0 + iH_{TRIV} \qquad (2)$$

has been assumed, where $H_{TRIV}$ is the time-reversal-invariance violating portion of the Hamiltonian. The matrix element of $H_{TRIV}$ is denoted by W. We have further assumed that only two states mix and that only internal mixing is important. With these assumptions, $\Delta$ is proportional to W to first order. We also identified an appropriate figure-of-merit

$$\beta_T \equiv \frac{d\sigma}{d\Omega}\left[\frac{\Delta}{W}\right]^2 \quad . \qquad (3)$$

Larger values of $\beta_T$ indicate that a certain statistical level of sensitivity to the value of W can be reached in a shorter time.

The best candidate for experimental study appears to be a pair of resonances in $^{32}S$; $\Delta/W$ is shown as a function of energy and angle in Fig. 2. A measurement in this region could lower the upper limit on the time-reversal-invariance violating spreading width by up to two orders of magnitude over the previous best detailed-balance measurements without any increase in experimental sensitivity.

Preliminary versions of these results have been published [G. E. Mitchell *et al.*, Nucl. Instrum. and Methods **B79**, 290 (1993); G. E. Mitchell *et al.*, Nucl. Phys. **A560**, 483 (1993)]. A detailed paper has been just been published in Physical Review C [J. M. Drake *et al.*, Phys. Rev. C **49**, 411 (1994)].

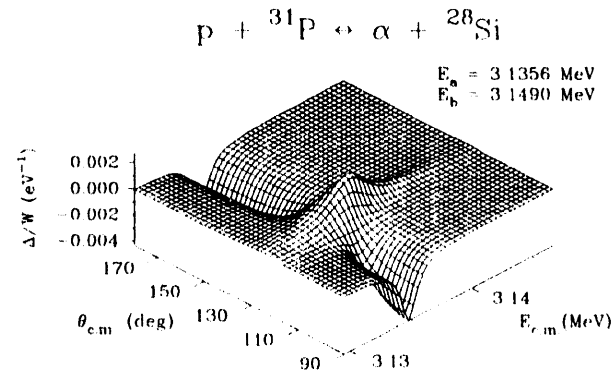


Figure 2. $\Delta/W$ for a pair of resonances in p + $^{31}P \leftrightarrow \alpha + {}^{28}Si$.

### 3. Parity Violation with Charged Particle Resonances

(with G. E. Mitchell)

In a manner similar to that described for detailed-balance violation in Sect. 2, we have also performed calculations for parity-violating observables using experimentally measured resonance parameters for the same target nuclides listed there. Our motivation was the recent observation by the TRIPLE collaboration of sign correlations in parity-violating matrix elements studied with neutron resonances [9]. While a number of explanations for this have been suggested (see the discussion in [10]), all seem to require single particle matrix elements which are much too large. Further data of this nature in a different mass region could provide new insights into this problem.

We identified 82 pairs of adjacent resonances with the same J but different $\pi$ in these five systems. For 62 of these pairs, the natural parity resonance has a measured alpha decay to the ground state. For each pair we examined the parity-violating observables $A_z(\theta)$ and $A_x(\theta)$ for both $(\vec{p},\alpha)$ and $(\vec{p},p)$; we also calculated the angle-integrated value of $A_z$ for $(\vec{p},\alpha)$. Each of these observables is proportional to the parity-violating matrix element V to first order. What we actually calculate is $A_z/V$ or $A_x/V$.

V is assumed to be a random variable. Thus we cannot estimate its value directly for any single pair of resonances. However, we employed the values of the spreading width determined in the TRIPLE measurements to estimate $V_{rms}$ for these lighter masses, and we then used $(A_z/V)\ V_{rms}$ as a measure of the expected value of $A_z$ (and also of the necesssary experimental sensitivity). For $A_z(\theta)$ in the $(\vec{p},\alpha)$ reaction, we find approximately 80% of our estimates exceed $10^{-4}$. Experiments at approximately this level of sensitivity have already been performed (see, e.g., [11,12]). Thus we conclude measurements at the $10^{-4}$ level are possible and could permit determination of $V_{rms}$ for one or more of these light nuclides.

A short paper on this topic as been accepted by Physical Review C for publication as a Rapid Communication. We are continuing to study the calculations to identify best cases, and we are investigating the possibility of making such measurements using the TUNL FN tandem and polarized ion source.

**4. Statistical Analysis of Shell Model Electromagnetic Transitions in $^{22}$Na**

(with A. A. Adams, E. G. Bilpuch, G. E. Mitchell, and W. E. Ormand)

As part of our effort to understand the role of chaos in low-energy nuclear systems, we are studying the role of electromagnetic transitions. Alhassid and Feingold [13] have suggested that the transition strengths of chaotic systems should follow a $\chi^2(\nu)$ distribution with $\nu = 1$ (the Porter-Thomas distribution) and that regular systems should follow a $\chi^2(\nu)$

with $\nu < 1$. Alhassid and Novoselsky [14] then showed that B(E2) values calculated using the interactive boson model basically followed this prediction. We wish to apply this type of approach both to experimental data for $^{26}$Al [15] and to shell model calculations for the A = 20-30 region.

We chose to start with the calculations, where limited data do not pose a problem. Shell model calculations for $^{22}$Na have been performed using the code OXBASH. The first 25 positive-parity states for spin $J \leq 5$ and isospin $T = 0, 1$, and 2 have been identified. B(M1) and B(E2) have been calculated for each pair of these states, giving a data set of $\approx$ 85,000 transition strengths. Preliminary indications are that transitions between higher energy states have $\nu = 1$ and those between lower energy states have $\nu < 1$. However, final results require a more careful treatment of the energy-dependent average strengths; that work is currently in progress. We are also cataloging and organizing the data for $^{26}$Al in preparation for analysis.

**5. Accelerator Control**

(with J. M. Drake, J. P. Quesenberry, G. A. Vavrina, and C. R. Westerfeldt)

During the past 15 months, much effort has been spent in developing new control systems for the electrostatic analyzer and the analyzing magnet in the TUNL High Resolution Laboratory. The original impetus for these changes was the failure of the PDP-11 microprocessor that had been used to control the electrostatic analyzer. We are currently using a 80486-based PC with the software package LabVIEW for Windows to handle both tasks.

The electrostatic analyzer is controlled via a PID feedback loop operating to maintain the potential difference between the two analyzer plates at a set value. The set point is determined by the desired beam energy, which has been sent from the VAXStation 3200 data acquisition computer over an RS-232 serial line. The LabVIEW program reads the potential difference, calculates the deviation from the desired value, and determines an appropriate control signal to minimize deviation. The control signal is sent to a pair of Bertan 20 kV power supplies through a pair of 16 bit DAC's; the DAC signals are scaled and summed to give 28 bits of resolution. Typical control is within 10-20 eV of the desired beam energy; if the deviation is larger than a certain value (normally chosen to be 30 eV), data acquisition is inhibited until the deviation is reduced.

The analyzing magnet is also controlled via a PID feedback loop, but this one has two different modes of operation. One sets the magnet to a requested field setting, while the other tries to center the beam on the output of the analyzer. The first mode, labeled "manual," is used to set the magnet to steer beam into the analyzer. Once beam is through the analyzer, we switch to "slit" mode, and the magnet will then automatically track changes in beam energy. The actual magnetic field is determined thru an RS-232 serial link to a digital teslameter, while the slit difference signal is processed thru an ADC. Work continues on optimizing the feedback parameters.

We have also developed a LabVIEW program to serve as a frequency analyzer. The program samples a signal for a certain length of time and then does a fast Fourier transform to generate a power spectrum. We plan to use this as a diagnostic to determine frequency components of the accelerator's terminal voltage.

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## Appendix I

## Personnel

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| G. A. Vavrina | North Carolina State University and TUNL |
| P. M. Wallace | Duke University and TUNL |
| C. R. Westerfeldt | Duke University and TUNL |

Appendix II

## PUBLISHED ARTICLES

"Detailed Balance Study of Time Reversal Invariance with Interfering Resonances," G. E. Mitchell, E. G. Bilpuch, C. R. Bybee, J. M. Drake, and J. F. Shriner, Jr., Nucl. Instrum. and Methods, **B79**, 290 (1993).

"Detailed Balance Test of Time Reversal Invariance with Interfering Resonances," G. E. Mitchell, E. G. Bilpuch, C. R. Bybee, J. M. Drake, and J. F. Shriner, Jr., Nucl. Phys. **A560**, 483 (1993).

"Detailed-balance Tests of Time-reversal Invariance with Interfering Charged-particle Resonances," J. M. Drake, E. G. Bilpuch, G. E. Mitchell, and J. F. Shriner, Jr., Phys. Rev. C **49**, 411 (1994).

## ARTICLES ACCEPTED FOR PUBLICATION

"Parity Violation in Charged Particle Nuclear Reactions," J. F. Shriner, Jr. and G. E. Mitchell, to be published in Phys. Rev. C.

## CONTRIBUTED ABSTRACTS

"Possible Charged Particle Studies of Parity Violation in Compound Nuclear Resonances," J. F. Shriner, Jr., G. E. Mitchell, and E. G. Bilpuch, B.A.P.S. **38**, 913 (1993).

"Possible Tests of Parity Violation with Charged Particle Resonances," J. F. Shriner, Jr., G. E. Mitchell, and E. G. Bilpuch, B.A.P.S. **38**, 1803 (1993).

"Possible Tests of Detailed Balance with Interfering Proton Resonances," J. M. Drake, C. R. Bybee, G. E. Mitchell, J. F. Shriner, Jr., and E. G. Bilpuch, B.A.P.S. **38**, 1804 (1993).

"Shell-Model Transition Strengths in $^{22}$Na," A. A. Adams, G. E. Mitchell, J. F. Shriner, Jr., W. E. Ormand, and E. G. Bilpuch, B.A.P.S. **38**, 2171 (1993).

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