**TENNESSEE TECH UNIVERSITY**

**Department of Physics**

# PROGRESS REPORT

## on

# RESEARCH IN NUCLEAR PHYSICS

December, 1992 - November, 1995

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Cookeville, Tennessee  38505

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# PROTON RESONANCE SPECTROSCOPY

Progress Report

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# Contents

# Preface

Work on chaos in the low-lying levels of nuclei has continued on several fronts. The major effort has been study of the $^{29}$Si(p,$\gamma$) reaction with the goal of establishing a complete level scheme for $^{30}$P and analyzing the eigenvalue fluctuations for evidence of chaos. These measurements are in progress, and the current status is described in Section 1. A related topic is the search for different signatures of chaos which do not require the extremely high degree of completeness and purity necessary for eigenvalue analyses; those efforts are discussed in Sections 2 and 3.

The possibility of studying both parity violation and time-reversal invariance violation with charged particle resonances has been explored by performing calculations using experimentally measured resonance parameters. Large enhancements are indeed available; the results are discussed in Sections 4 and 5. Preparations for an experimental study of parity violation using these techniques are ongoing.

An undergraduate project searching for experimental evidence of a parity dependence of level density is discussed in Section 6.

A number of improvements to the operation of the TUNL KN accelerator have been implemented in the past three years. These are described in Section 7.

Support by TTU and by Oak Ridge Institute for Science and Engineering allowed me to spend the 1992-93 academic year on leave at TUNL. Gloria Julian of the TTU Department of Physics has continued to handle secretarial and accounting duties for this grant admirably, 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, M. A. LaBonte, G. E. Mitchell, E. F. Moore, G. A. Vavrina, P. M. Wallace, and C. R. Westerfeldt)

One approach to chaos in quantum systems is to study eigenvalue statistics; agreement of the nearest-neighbor spacing distribution with the Gaussian orthogonal ensemble (GOE) of random matrix theory is generally accepted as a signature of chaos, while agreement with Poisson statistics is considered a signature of regular dynamics [1]. Such tests require extremely high quality data. Tests of proton and neutron resonance data [2] show good agreement with GOE. Analyses of low-energy data for $^{26}$Al [3] and $^{116}$Sn [4] show behavior between GOE and Poisson, but there are not at present sufficient high-quality data at low energies to study other nuclides. A study combining low-energy data from many nuclides has been performed [5] and suggests the dynamics move from chaotic toward regular behavior as mass increases. Studies at higher spins in deformed nuclides [6] show near-Poisson behavior. A clear pattern has yet to emerge from these various studies, and numerous questions remain which require additional data.

To obtain additional data applicable to the question of chaos at low energies in nuclei, we are measuring the $^{29}$Si(p,$\gamma$) reaction with the goal of establishing a complete level scheme for $^{30}$P. In this nuclide, states with isospin $T = 0$ and $T = 1$ exist all the way to the ground state, allowing us to study isospin breaking as well. Previous studies of $^{30}$P [7, 8] have identified 105 levels with $E_x \leq 8$ MeV. Above $E_x \approx 4$ MeV, many of the spins, parities, and/or isospins are not uniquely determined. Our measurements are designed to identify as many of the spins, parities, and isospins as possible.

## Detector Hardware and Software

A necessary step for these measurements was the design and installation of appropriate hardware for such a measurement. The $\gamma$-ray detection is accomplished primarily by a pair of 60% efficient HPGe detectors, one of which is Compton-suppressed by a BGO shield [9]. A new chamber capable of holding up to six targets was designed and built. Detector mounts which allow pivoting about the target chamber, translation toward and away from the chamber, and vertical adjustment were designed and installed. Vacuum within the chamber is provided by a turbomolecular pump. The beamline support is designed so that a table for mounting 7.62 cm $\times$ 7.62 cm NaI(Tl) detectors can easily be attached when desired. The beamline contains an electrically suppressed Faraday cup, a set of collimation slits and a beam scanner. The design and installation of this system comprised a major portion of the Ph.D. work of J. M. Drake.

It was also necessary to develop new software and set up new electronics to process the signals for these experiments. Our standard mode of operation is to use both HPGe detectors

and a single NaI(Tl) detector to detect $\gamma$-rays and a single silicon surface barrier detector to detect charged particles. The latter two detectors are used primarily to locate resonances. Appropriate electronics to process the HPGe signals and reject the signals associated with the Compton shield were purchased and installed. Software was written to allow us to store and monitor a pair of singles spectra from the two HPGe detectors as well as a pair of $\gamma - \gamma$ coincidence spectra. Some online gating of the coincidence spectra is also allowed. Routines for efficiently handling data storage for later offline analysis were also written. All the software utilizes the XSYS data acquisition package. The major hardware component of this portion of the system is an ORTEC AD413 Quad ADC. All signals are processed by a VAXStation 3200 via a CAMAC crate. Development of the software and signal-processing electronics comprised a major portion of the Ph.D. project of C. R. Bybee.

## Resonance Identification

When we began this series of measurements, several previous experiments had studied resonances in the p+$^{29}$Si system. Nelson *et al.* [10] had studied the $^{29}$Si(p,p$_0$) and $^{29}$Si(p,p$_1$) reactions in the range $E_p$ =1.29–3.31 MeV and identified 66 resonances. Reinecke *et al.* [11] had studied resonances in the $^{29}$Si(p,$\gamma$) reaction for $E_p < 2.3$ MeV. The most recent compilation [7] listed 81 resonances in the p+$^{29}$Si system.

We have restudied the $^{29}$Si(p,$\gamma$) reaction with NaI(Tl) detectors in the energy region $E_p$ =1.0–3.3 MeV to identify any previous unidentified resonances. We felt that it was important to perform these measurements at the higher energies (where capture measurements had not been performed) because the capture reaction is often much more sensitive to small resonances than are elastic and inelastic scattering and at the lower energies because our beam energy resolution is significantly better than that of Reinecke *et al.* (also allowing greater sensitivity to resonances with small widths). Thirteen previously unknown resonances were identified with $E_p > 2.0$ MeV [8] and four new resonances have been located in the range $E_p$ =1.0–2.0 MeV [8, 12].

## Fixed-detector Measurements

Our first step in identifying spin, parity, and isospin for as many states as possible has been to measure singles $\gamma$-ray spectra for each of the 47 resonances in the energy range $E_p$ =1.0–2.5 MeV. Many of these have previously been studied by Reinecke *et al.* [11], but we have remeasured them to take advantage of our improved energy resolution and higher efficiency detectors. The spectra in this first stage were taken with detectors at fixed angles: the suppressed detector was located at 55° relative to the beam and the unsuppressed detector was located at 90°. The 55° detector was used to determine intensities; since 55° is the zero of the Legendre polynomial $P_2$, angular distribution effects should be minimized. The 90° detector was used to determine $\gamma$-ray energies, since the $\gamma$-rays will not be Doppler-shifted at that angle. Energy and relative efficiency calibrations were performed using radioactive sources for low-energy $\gamma$-rays and $\gamma$-rays from a well studied $^{27}$Al(p,$\gamma$) resonance [13] for high-energy $\gamma$-rays. Targets of thicknesses 1–3 $\mu$g/cm$^2$ were used to ensure high beam energy

5

resolution. For all resonances except those with very large widths, spectra were taken both on-resonance and off-resonance. Typical accumulated charge on the Faraday cup was 100–300 mC. Spectra for each of these resonances have now been obtained, and analysis is in progress.

Our analysis of these spectra consists of fitting and identifying as many $\gamma$-rays in each spectrum as possible. Since these are singles spectra, a number of contaminant lines are present, both from room background and from other isotopes present on the targets in small amounts. For the most part, these contaminant lines have not posed a serious problem. Lines are initially assigned based on energy differences and on branching ratios previously established for the low-lying states [7]. A crucial step in the process is to check the intensity balance in/out of each level which is populated in the $\gamma$-decay. A large computer program has been written to help in suggesting such assignments (as well as numerous other aspects of the analysis).

Once $\gamma$-rays are assigned, we can begin to focus on assigning quantum numbers. If the $\gamma$-ray width of the resonance is known from the earlier resonance studies, this is combined with the measured branching ratios to determine reduced transition probabilities. Comparison of these values with recommended upper limits (RUL's) for each transition type in this mass region [14] can then be used to limit and often uniquely identify J, $\pi$, and T. At this stage, information from other experiments is often included. As an example, elastic scattering often determines the parity of the resonance uniquely but only limits J; the $\gamma$-ray measurements often have trouble distinguishing parity. The combination can yield a unique assignment that neither measurement by itself could.

As a specific example, the decay scheme for a level at $E_x = 7922$ keV is shown in Fig. 1. This level had previously been seen only as a resonance in the $^{29}$Si(p,$\gamma$) reaction at $E_p = 2.4077$ MeV [8]. No previous identification of $J^{\pi}$;T was available. Based on our measurements we were able to assign $J^{\pi}$;T $= 3^+$;0; the key transition in assigning the isospin was a 15% branch to the 4344 keV level (which has $J^{\pi}$;T $= 5^+$;0).

Approximately 80% of this phase of the analysis is now complete.

## Angular Distributions

For those states for which the fixed-detector measurements do not provide unique assignments for J, $\pi$, and T, additional measurements are necessary. Angular distributions have been a traditional method of obtaining information on both spins and mixing ratios (see e.g., [15]). In the present case, analysis of (p,$\gamma$) angular distributions is complicated by the fact that the target has non-zero spin; specifically, because $^{29}$Si has spin $\frac{1}{2}$, mixing is allowed in the entrance channel either between two different channel spins with the same value of $\ell$ (channel spin mixing) or between two different values of $\ell$ with the same channel spin ($\ell$-mixing) but not both. In addition there is often mixing in the exit channel between two different multipolarities (e.g., M1/E2).

The standard method of expressing capture angular distributions is in terms of the coefficients $a_2$ and $a_4$:
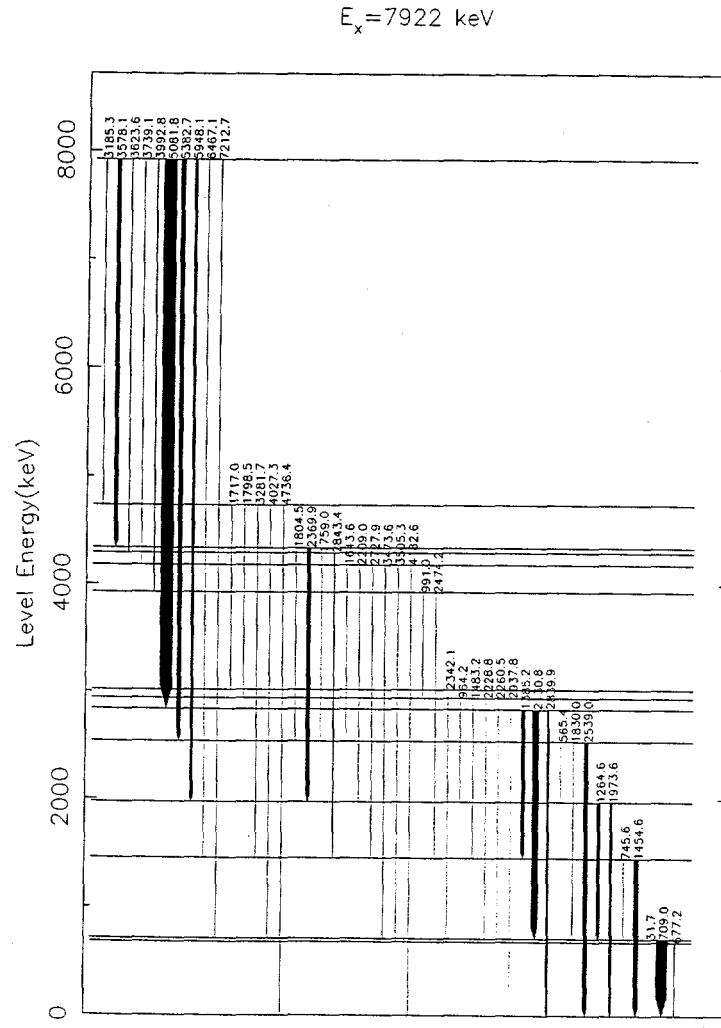
Figure 1: Decay scheme for the $E_x = 7922$ keV level; the widths of the arrows are proportional to the intensity of the $\gamma$-rays.

$$W(\theta) = A_0 \left[1 + a_2 P_2(\theta) + a_4 P_4(\theta)\right]. \tag{1}$$

Here $P_2$ and $P_4$ are Legendre polynomials, and we have assumed the highest $\gamma$-ray multipolarity allowed is L = 2. The coefficients $a_2$ and $a_4$ depend in general on both the proton mixing ratio and the $\gamma$-ray mixing ratio. Since all the primary transitions for a given resonance have a common entrance channel but independent exit channels, a complete analysis requires a simultaneous fit of all angular distributions for that resonance. Often, however, information about possible spins can be obtained even without a complete least-squares analysis. As an example, suppose that the angular distribution of a given transition had a

7

nonzero $a_4$ term; this value rules out a pure L = 1 transition. Therefore, any spin assignment for the resonance (or final state) which would require a pure L = 1 transition could be rejected.

We have calculated the theoretical expressions for $a_2$ and $a_4$ for a large number of possible initial and final state spins and parities in $^{29}$Si(p,$\gamma$). For each particular choice of initial and final states, we have established the allowed values of $a_2$ and $a_4$; experimental values lying sufficiently outside the allowed range can eliminate possible $J^\pi$ values. These allowed ranges lie within the $a_2$-$a_4$ plane and may consist of a single point, a line segment, an ellipse, or a region in the plane. In some cases, the region is discontinuous. The allowed regions are shown in Fig. 2 for four different choices of initial and final states.

Often it is necessary to know the $\gamma$-ray mixing ratios for one or more primary transitions in order to establish the isospin of either the initial or final states. For this purpose, a least-squares fitting program to fit each angular distribution to equation (1) (with appropriate expressions for $a_2$ and $a_4$ for the given initial and final states) has been written. Angular distributions have been measured for six resonances thus far. The first state analyzed was the $E_x = 7223$ keV level. This state was already known to have $J^\pi;T = 2^-;1$ and has a large yield in the capture channel; thus it is a good choice to test both the experimental and analytical techniques. Our analysis confirmed the $J^\pi;T$ assignment. It also established that the M1/E2 mixing ratio of the transition to the 4144 keV level ($J^\pi;T = 2^-;0$) has a value $\delta_\gamma = 0.06 \pm 0.02$ and that of the transition to the 4627 keV level ($J^\pi;T = 3^-;0$) has a value $\delta_\gamma = 0.00 \pm 0.02$. Analysis of the remaining measurements is in progress.

The calculations of angular distribution coefficients and the measurements of the first two $^{29}$Si(p,$\gamma$) angular distributions were performed by M. A. LaBonte as part of his M.S. thesis project.

# 2 Distribution of Reduced Transition Probabilities in Shell Model Calculations for $^{22}$Na

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

Analysis of eigenvalue statistics (see Section 1) requires data of extremely high quality. Therefore, alternative signatures of chaos applicable to nuclear data are desired. We are exploring the possibility that the distribution of reduced transition probabilities might serve this function. Alhassid and Feingold [16] suggested that the transitions of chaotic systems should follow a $\chi^2(\nu)$ distribution with $\nu = 1$ (the Porter-Thomas distribution) and that the transitions for regular systems should follow a $\chi^2(\nu)$ distribution with $\nu < 1$. Alhassid and Novoselsky [17] later showed that B(E2) values calculated with the interacting boson model basically followed this prediction. We wish to apply these ideas to experimental data.

As a starting point, we are analyzing the distributions of B(M1) and B(E2) values cal-
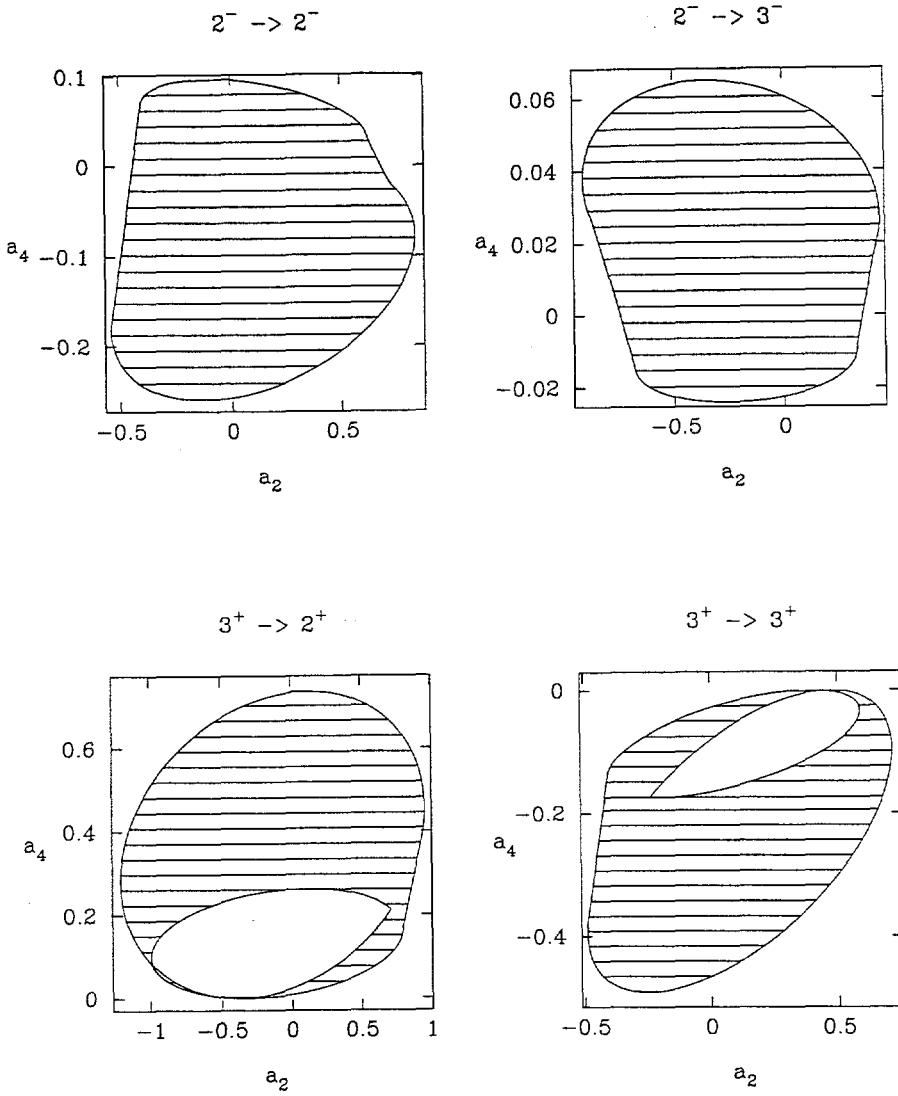
Figure 2: Allowed regions in $a_2$-$a_4$ space for four choices of initial and final states. The shaded areas are the allowed region.

culated between positive-parity states in $^{22}$Na using the shell-model code OXBASH. States with spins $J \leq 8$ and isospins $T = 0$ or 1 are included in the calculations. Using calculated values first allows us to establish a robust analysis technique without concerns about the quality of experimental data. It also allows us to examine questions such as dependence on spin, isospin, energy, or transition character which are harder to address with a more limited set of experimental data. Once the analysis techniques are finalized, we will analyze experimental reduced transition strengths from $^{26}$Al [18].

The first step in our analysis is to normalize each transition strength in a given set (consisting of all transitions with a given initial and final spin, initial and final isospin, and either M1 or E2 character) by the local average transition strength. The local average is calculated by convoluting the transition strengths with a pair of Gaussians as described in [17]. Different Gaussian widths have been tried; we find widths in the range of $1.5 - 2.5$ times the average local energy spacing to be appropriate.

Once normalized strengths are obtained, the data are histogrammed. Our bins are chosen [19] so that they would have equal probability if the distribution is $\chi^2(1)$. The histogrammed data are then fit to determine $\nu$. An error on the fit $\nu$ is calculated using standard techniques. However, the uncertainty in $\nu$ must also reflect the uncertainty in determining the local average strength. To estimate this effect, we look at the spread in $\nu$ for different choices of the Gaussian widths. We then determine the standard deviation for $\nu$ when different normalizing factors are used and combine it in quadrature with the fitting uncertainty to yield an overall uncertainty. A preliminary result is shown in Fig. 3, where the distribution and best fit for all B(E2) values in the calculation are shown. The fit corresponds to $\nu = 1.02 \pm 0.03$ and suggests chaotic behavior at all energies in this calculation.

# 3 The Fourier Transform as a Signature of Chaos in Nuclei

## (with C. R. Bybee, E. G. Bilpuch, and G. E. Mitchell)

Additional signatures of chaos which can be employed with data of lesser quality are highly desirable. In addition to studying transition strengths as a possible candidate for such a signature (see Section 2), we have studied the use of the Fourier transform of the energy spectrum. This technique has been applied successfully to atomic physics data (see, e.g., [20, 21, 22]). However, those data sets contained many more energy levels than are typically known in nuclear physics, and it was not clear that the techniques would be equally successful with smaller numbers of levels. To test this method, we have generated spectra obeying both GOE and Poisson distributions; according to the standard view, these represent chaotic and regular dynamics, respectively. What is suggested as the defining feature of chaotic behavior in this analysis is a "correlation hole" in the power spectrum $\left|\hat{S}\right|^2$ (here $\hat{S}$ denotes the Fourier transform). In Figure 4, we show the ensemble-averaged power spectrum for a collection of 500 GOE spectra and a collection of 500 Poisson spectra (all computer-generated). The hole is clearly visible near $q/\rho = 0$.

To quantify the behavior of the correlation hole, we have explored two methods: (1) a numerical evaluation of the area of the hole, and (2) fitting the power spectrum to the

10
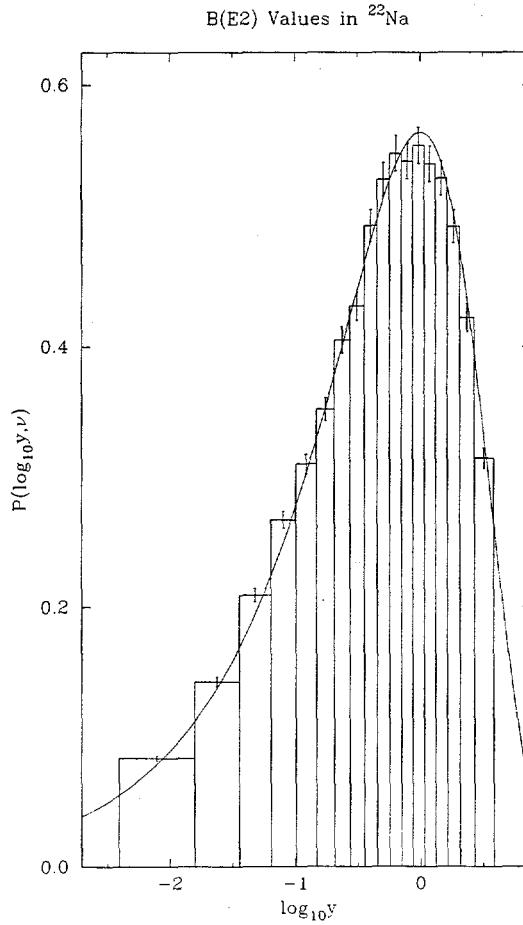
Figure 3: Distribution of B(E2) for $^{22}$Na shell model calculations. A total of 31758 values are included. The fit is a $\chi^2(\nu = 1.02)$ distribution.

empirical function

$$y\left(\frac{q}{\rho}\right) = a_3\left[a_1 \tanh\left(\frac{q/\rho}{a_2}\right) + 1\right].$$
(2)

We studied how well each of these methods succeeded at identifying the underlying nature (GOE/Poisson) of a spectrum as we varied the number of levels in the spectrum, the average spacing of those levels, and the sampling interval used in calculating the Fourier transform. We also examined the effects of missing and spurious levels on these two measures to more accurately simulate real experimental data.

Our results show that for ensemble averages, both of these methods work well, even for spectra with as few as 20 levels or with up to 50% missing or spurious levels. The ensemble average values of the area are 0.45 for pure GOE spectra and 0.00 for Poisson spectra,

11
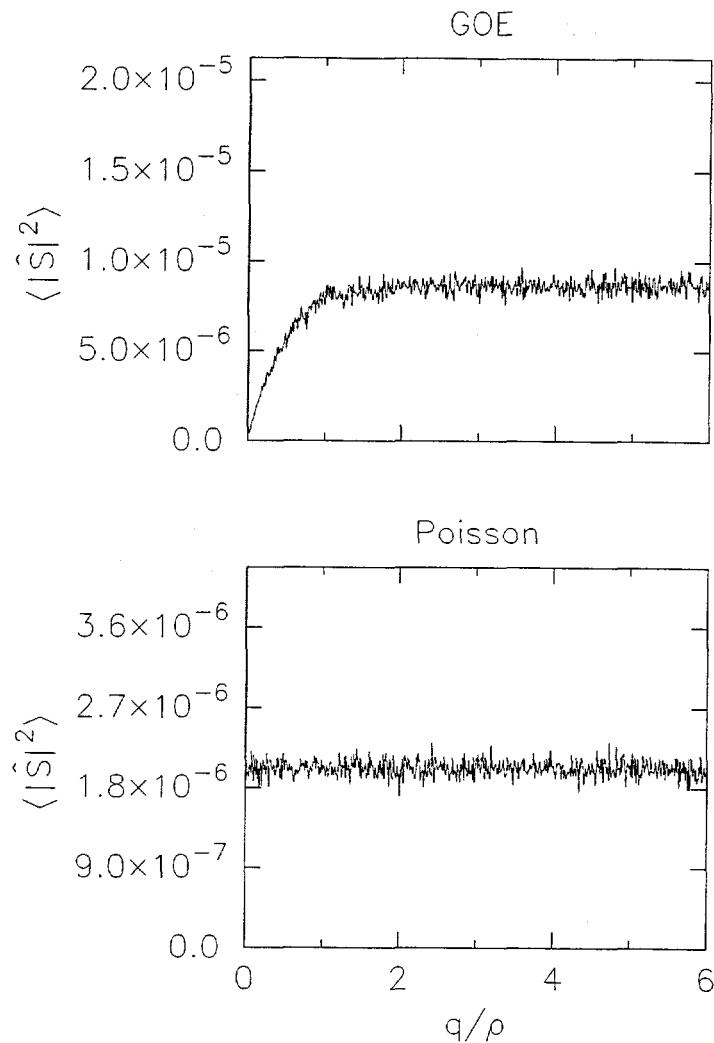
Figure 4: Ensemble-averaged power spectra for 500 GOE and Poisson spectra, each with 100 levels.

whereas $a_1$ is near zero for Poisson spectra and significantly different from zero for GOE spectra. However, the uncertainty in values for a single spectrum is the truly meaningful quantity, since a single spectrum is what one would get experimentally. For single spectra, the average and standard deviation of the correlation hole areas are listed in Table 1; these values were obtained by generating 500 spectra of each type. These results show that an area near zero almost certainly is a signature of a Poisson spectrum, but an area near 0.45 may occur even for Poisson spectra if the number of levels N is of order 100 or less. Similar results were obtained by fitting the power spectra to the form shown in equation (2). We conclude

12

Table 1: Means $\mu$ and standard deviations $\sigma$ of the correlation hole areas for ensembles of 500 spectra.

| Spectrum Type | Number of Levels | Correlation Hole Area $\mu$ | $\sigma$ |
|---|---|---|---|
| GOE | 20 | 0.41 | 0.16 |
| GOE | 50 | 0.44 | 0.10 |
| GOE | 100 | 0.45 | 0.07 |
| GOE | 150 | 0.45 | 0.06 |
| GOE | 300 | 0.46 | 0.04 |
| Poisson | 20 | 0.00 | 0.41 |
| Poisson | 50 | 0.00 | 0.24 |
| Poisson | 100 | 0.00 | 0.18 |
| Poisson | 150 | 0.00 | 0.14 |
| Poisson | 300 | 0.00 | 0.10 |

that the Fourier transform is indeed a good signature of chaos even for data with many missing or spurious levels as long as there are sufficient levels. Its applicability to nuclear physics, however, seems limited, since most sets of data do not contain enough levels.

This work comprised a major portion of the Ph.D. dissertation of C. R. Bybee.

# 4    Parity Violation with Charged-particle Resonances

## (With G. E. Mitchell, N. R. Roberson, and W. S. Wilburn)

A number of experiments have now shown that parity-violating observables can be significantly enhanced in the neighborhood of close-lying resonances. Alfimenkov *et al.* [23] studied the helicity dependence of neutron total cross sections and found significant evidence of parity violation for single resonances in several different nuclides. More recent measurements by the TRIPLE collaboration of neutron scattering from $^{232}$Th [24] and $^{238}$U [25] have focused on a statistical interpretation by measuring parity-violating (PV) observables for several resonances in the same nuclide and determining the rms PV matrix element $V_{rms}$. They obtain values of $V_{rms} \approx 1$ meV in the A $\approx$ 230 region.

One question which arises from these results is whether $V_{rms}$ has a mass dependence. Several measurements exist for parity doublets in light nuclei [26, 27]; the values for $V$ are typically of order 1 eV, although large uncertainties generally remain; however these are values for a single pair of states and do not necessarily represent the statistical average. Neutron resonance measurements near A = 100 have been performed and are being analyzed [28], but measurements with neutrons at significantly lighter masses appear less feasible. We have performed calculations to determine the feasibility of studying parity violation with

13

charged particle resonances in the A = 20–40 region.

The calculations employ experimentally measured resonance parameters for the (p,p) and (p,$\alpha$) reactions on the five targets $^{23}$Na[29], $^{27}$Al[30, 31], $^{31}$P[32], $^{35}$Cl[33], and $^{39}$K [34]. For each pair of resonances with the same spin but opposite parity and whose energies are within ten times the sum of the two resonance widths, we have calculated the longitudinal analyzing power

$$A_z(\theta) \equiv \frac{\frac{d\sigma}{d\Omega}(\rightarrow) - \frac{d\sigma}{d\Omega}(\leftarrow)}{\frac{d\sigma}{d\Omega}(\rightarrow) + \frac{d\sigma}{d\Omega}(\leftarrow)}; \tag{3}$$

here $\rightarrow$ ($\leftarrow$) represents a beam polarization in the direction of (opposite to) the beam momentum. The parity violation is included via two-level mixing with a PV matrix element $V$ and first-order perturbation theory. The denominator in equation (3) is just twice the unpolarized cross section; a full multilevel calculation is performed for that quantity. Under these assumptions, $A_z$ is proportional to $V$ to first order, and thus $A_z/V$ can be used as a measure of the relative enhancement.

Calculations of $A_x$, which is also proportional to $V$, have also been performed. The results are similar in nature to those for $A_z$. Since $A_z$ seems more amenable to experimental measurement, we shall discuss only those calculations further.

We find that $A_z/V$ varies strongly with energy, with angle, and with resonance pair. Some aspects of these effects are shown in Fig. 5, where $A_z/V$ is plotted as a function of both energy and angle for four resonance pairs in the p + $^{31}$P system. These results show that proper choice of both energy and angle is crucial for a measurement, since an improper choice could accidentally result in a measured value of zero for $A_z$, irregardless of the value of $V$.

Of course, the quantity to be measured is $A_z$, not $A_z/V$; thus an estimate for $V$ is desirable. These systems are generally believed to be chaotic at these energies, and statistical descriptions are most appropriate. In this view, $V$ is a random variable; thus a prediction of $V$ for any pair of resonances is not possible. Instead we have estimated $V_{rms}$ by employing the spreading width

$$\Gamma^{PV} \equiv 2\pi \frac{V_{rms}^2}{D}. \tag{4}$$

Here $D$ is the average level spacing. For isospin violation, the spreading width is known to be approximately independent of mass [35]. We assume that is also true for parity violation and use the value of the spreading width from the A = 230 region to estimate that $V_{rms} \approx$ 100 meV in these lighter systems. We then estimate

$$A_z \approx \frac{A_z}{V} V_{rms}. \tag{5}$$

For the $^{31}$P($\overrightarrow{p}$,$\alpha_0$) reaction, a significant number of estimates of $A_z$ are $\geq 10^{-4}$, comparable to what has been measured in previous experiments of this nature [27, 36, 37, 38, 39]. Therefore, from this perspective, these experiments appear feasible.

14

$^{31}P(p,\alpha_0)$

$E_n = 1.6433$ MeV
$E_u = 1.5875$ MeV



$^{31}P(p,\alpha_0)$

$E_n = 2.8545$ MeV
$E_u = 2.8484$ MeV



$^{31}P(p,\alpha_0)$

$E_n = 3.0356$ MeV
$E_u = 3.0341$ MeV



$^{31}P(p,\alpha_0)$

$E_n = 3.3963$ MeV
$E_u = 3.3941$ MeV
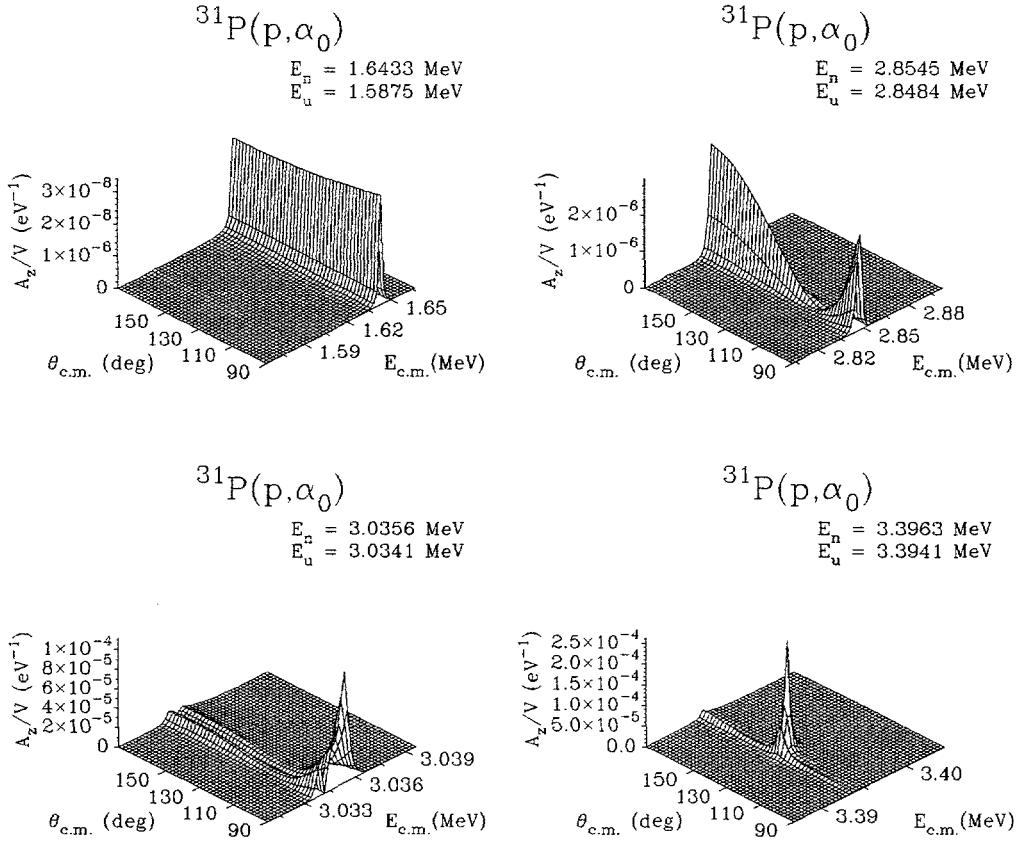


Figure 5: Values of $A_z/V$ for four resonance pairs in the p + $^{31}$P system as a function of both energy and angle. A beam energy resolution of 500 eV FWHM has been assumed.

Next, we explored the issue of counting times. Since $A_z$ can be large solely because the cross section is small (which of course leads to large counting times), we determined a figure-of-merit which combines the values of $A_z/V$ and $\sigma(\theta)$ to indicate optimal conditions. The figure-of-merit for a single detector is

$$\beta_P = \left(\frac{A_z}{V}\right)^2 \sigma(\theta);$$

(6)

this quantity is inversely proportional to the time necessary to reach a given level of statistical significance for $V$. Just as they did for $A_z/V$, values of $\beta_P$ vary widely from one pair to another and as a function of energy and angle.

15

The counting times estimated using calculated values of $\beta_P$ are sufficiently long that detectors with large solid angles are clearly desirable. However, because of the angular variation in $A_z$, we need to ensure that a single large detector does not "wash out" a measurable effect. Therefore, we explored the desirability of segmented detectors, each portion of which covers a finite range in $\theta$. The appropriate figure-of-merit in this case is

$$\beta_P = \sum_{i=1}^{N} \frac{\left[\int_{\theta_i}^{\theta_{i+1}} \left(A_z\left(\theta\right)/V\right)\sigma\left(\theta\right)\sin\theta\,d\theta\right]^2}{\int_{\theta_i}^{\theta_{i+1}} \sigma\left(\theta\right)\sin\theta\,d\theta}, \tag{7}$$

where $N$ is the total number of segments and the integration limits correspond to the edges of each segment. The calculations show that 4-6 segments seem optimal in the sense that fewer segments often require a significantly longer time to reach the same level of statistical significance for $V$ and a greater number of segments does not generally produce a significant additional reduction in counting time. Design of such a detector is currently in progress.

Another issue we have studied is that of multi-level effects. The TRIPLE analysis assumed that a single p-wave resonance interfered with several s-wave resonances and that each s-p pair could be treated independently of the others. We have explicitly performed 3-level mixing calculations and verified that this assumption is valid for their data. However, the quantity $\Gamma/D$ is on average much larger for these charged particle resonances, and therefore interference effects are generally greater. For some of our charged particle resonances, it appears that considering the interference pairwise may not be satisfactory. We are continuing to explore this issue.

A Rapid Communication describing some of our calculations of $A_z$ has been published in Physical Review C [J. F. Shriner, Jr. and G. E. Mitchell, Phys. Rev. C **49**, R616 (1994)].

# 5  Enhancement of Detailed Balance Violation with Interfering Resonances

## (with J. M. Drake, E. G. Bilpuch, and G. E. Mitchell)

It is well known that parity violating observables can be enhanced in the neighborhood of interfering resonances (see Section 4), and there have been numerous suggestions that similar enhancements should exist for tests of time-reversal-invariance (TRI) involving resonance measurements (see, e.g., [40]). One specific suggestion is that of Bunakov and Weidenmüller [41], who considered possible enhancements in detailed-balance violation due to interfering resonances. They proposed that enhancements of $10^3$–$10^4$ might be obtained under favorable conditions. We examined this scenario in more detail by performing calculations using experimentally measured (p,p) and (p,$\alpha$) resonance parameters for the compound systems $^{24}$Mg [29], $^{28}$Si [30, 31], $^{32}$S [32], $^{36}$Ar [33], and $^{40}$Ca [34]. We assumed a Hamiltonian of the form $H = H_0 + iH_{TRIV}$, where $H_0$ is the TRI portion of $H$ and $H_{TRIV}$ is the (small)

TRI-violating portion. A convenient measure of detailed-balance violation is the quantity $\Delta$, defined by

$$\Delta \equiv 2 \frac{\frac{k_p^2}{g_{(p,\alpha)}} \frac{d\sigma}{d\Omega}(p,\alpha) - \frac{k_\alpha^2}{g_{(\alpha,p)}} \frac{d\sigma}{d\Omega}(\alpha,p)}{\frac{k_p^2}{g_{(p,\alpha)}} \frac{d\sigma}{d\Omega}(p,\alpha) + \frac{k_\alpha^2}{g_{(\alpha,p)}} \frac{d\sigma}{d\Omega}(\alpha,p)}. \tag{8}$$

A nonzero value of $\Delta$ is evidence of detailed-balance violation. To first order, $\Delta$ is proportional to W, the matrix element of $H_{TRIV}$.

We have calculated $\Delta$ for 41 pairs of resonances in these five compound nuclei; the criteria for choosing these particular pairs were that the two resonances in the pair were adjacent (no other resonances between them in energy) with the same $J^\pi$ and that at least one of the pair must have a measured width in the $\alpha$ channel. Our results can be summarized as follows: (1) significant enhancements are indeed present in some cases; (2) the magnitude of the enhancement varies strongly from one pair to another; (3) the enhancement generally has a strong dependence on both energy and angle. The relevant figure-of-merit for such measurements (assuming a point detector) is

$$\beta_T = \left(\frac{\Delta}{W}\right)^2 \sigma(\theta); \tag{9}$$

this quantity also shows large enhancements and variations with energy and angle. Some sample behavior for the quantity $\Delta$/W is shown in Figure 6.

Of fundamental interest is the value of the spreading width

$$\Gamma_{TRIV} = \frac{2\pi \langle W^2 \rangle}{D}, \tag{10}$$

where D is the average spacing. In practice, it seems likely that one would obtain only an upper limit on $\Delta$ and therefore for W and $\Gamma_{TRIV}$. A crude estimate for the resonance pair with the best figure-of-merit suggests that one might obtain $\Gamma_{TRIV} \leq 5.5 \times 10^{-4}$ eV if one has the same experimental sensitivity as previous measurements [42, 43]. This is two orders of magnitude better than the present limit on detailed-balance violation [44]. Of course, several pairs would have to be measured to actually estimate $\langle W^2 \rangle$.

This work formed a major portion of the Ph.D. thesis of J. M. Drake. A paper describing further details of this work has been published in Physical Review C [J. M. Drake *et al.*, Phys. Rev. C **49**, 411 (1994).]

# 6  Parity Dependence of Level Densities in $^{49}$V

## (with J. P. Quesenberry)

The study of level densities in nuclei dates back to the work of Bethe in 1936-37 [45, 46]. He treated the nucleus as a Fermi gas and obtained the following expression for the level

$$p + {}^{31}P \leftrightarrow \alpha + {}^{28}Si$$

$E_a = 2.8148$ MeV
$E_b = 2.8567$ MeV

$$p + {}^{31}P \leftrightarrow \alpha + {}^{28}Si$$

$E_a = 3.3200$ MeV
$E_b = 3.3306$ MeV

$$p + {}^{27}Al \leftrightarrow \alpha + {}^{24}Mg$$

$E_a = 2.6625$ MeV
$E_b = 2.7087$ MeV

$$p + {}^{39}K \leftrightarrow \alpha + {}^{36}Ar$$

$E_a = 3.3180$ MeV
$E_b = 3.3219$ MeV
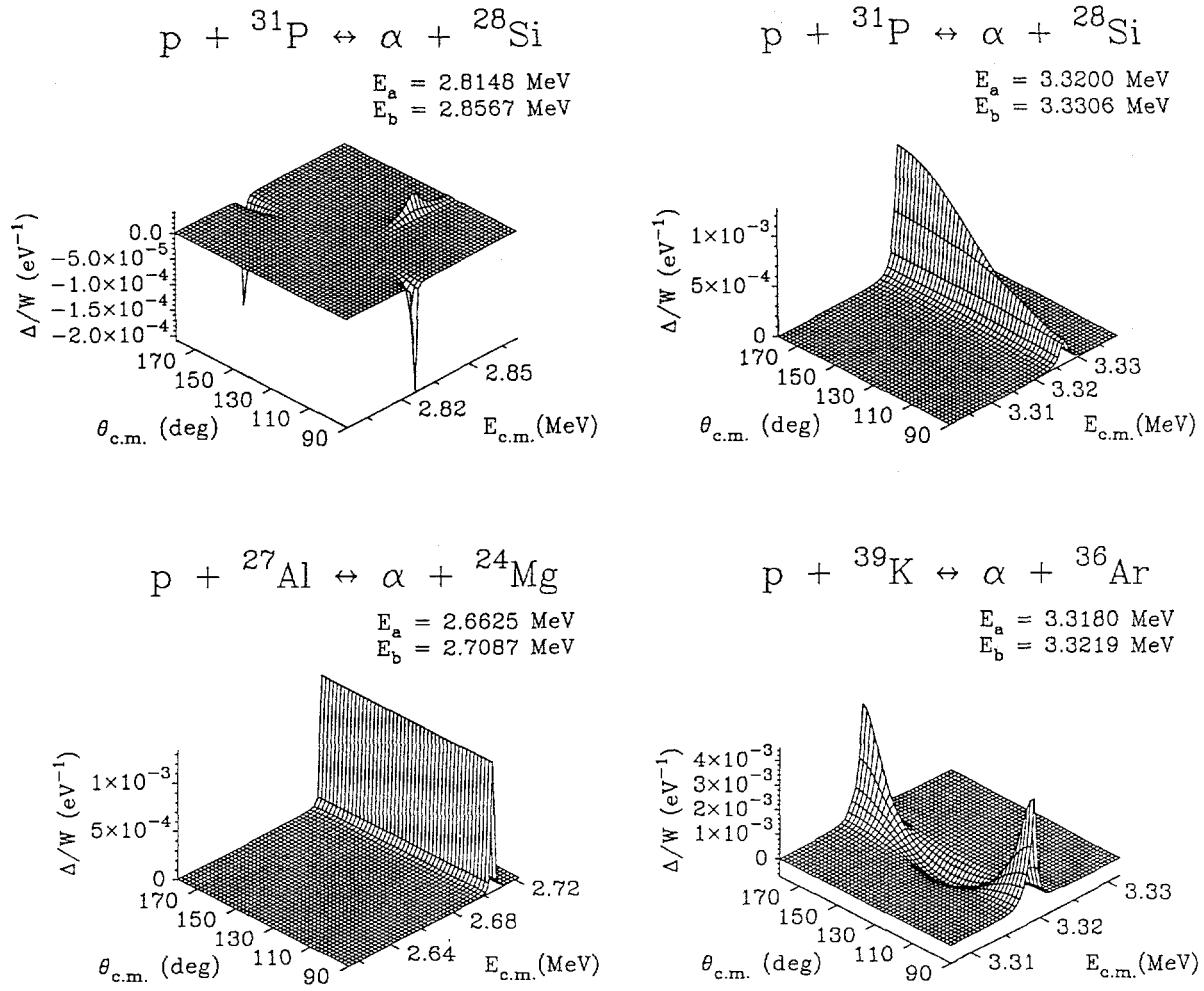
Figure 6: $\Delta/W$ as a function of energy and angle for four pairs of compound nuclear resonances.

density:

$$\rho(U, J) = \frac{\sqrt{\pi}}{12} \frac{\exp\left(2\sqrt{aU}\right)}{a^{1/4}U^{5/4}} \left(\frac{2J+1}{2\sqrt{2\pi\sigma^3}}\right) \exp\left[-\left(J+\frac{1}{2}\right)^2 / (2\sigma)^2\right]. \tag{11}$$

Here $\rho$ is the level density of states with spin J in units of states per MeV, U is the excitation energy in MeV, $a$ is known as the level density parameter, and $\sigma$ is called the spin cutoff parameter. The parameters $a$ and $\sigma$ can be determined empirically by comparison with experimental data.

Since Bethe's work, a number of refinements have taken place. Gilbert and Cameron [47] modified the low energy form of $\rho$ and included some effects from the nuclear shell

model. More recently, phenomenological expressions have been developed by Ignatyuk *et al.* [48] and Kataria *et al.* [49]. Both these models give results similar to Bethe's but with additional correction terms. A common factor in all these models is a dependence on J, the spin of the levels. An interesting question is whether the level density at a given excitation energy depends on parity as well as spin. The standard argument has been that by the time the concept of level density is truly meaningful, the energy is high enough and the states sufficiently complicated that parity should not matter. However, data for directly testing this hypothesis is scarce. To study this question, we performed an experiment to determine the number of $J^\pi = 1/2^-$ levels in the nucleus $^{49}$V. A previous measurement by Li *et al.* [50] of $^{48}$Ti(p,$p_0$) and $^{48}$Ti(p,$p_1$) in the range of proton energies $E_p = 3.08 - 3.86$ MeV had determined the number of $J^\pi = 1/2^+$ states in $^{49}$V in this energy region and had established the existence of 270 $\ell = 1$ resonances . These $\ell = 1$ resonances can have either $J^\pi = 1/2^-$ or $J^\pi = 3/2^-$, but Li's measurements could often not distinguish the two probabilities. We studied the angular distributions of $^{48}$Ti(p,$p_1$) and $^{48}$Ti(p,$p_1\gamma$) for each $\ell = 1$ resonance in the energy range $E_p = 3.08 - 3.43$ MeV. If the spin of the resonance is J=1/2, then both these angular distributions must be isotropic; if the spin is 3/2, then at least one of the two distributions must be anisotropic. Unfortunately, the level density was so high that most of the angular distributions showed the effects of interference with a nearby neighbor. Only 17 unambiguous spin assignments could be made for the 109 p-wave resonances in this region; 13 were assigned $J^\pi = 3/2^-$ and the remaining 4 were assigned $J^\pi = 1/2^-$. Assuming that this ratio of $3/2^-$ to $1/2^-$ states is indicative of the entire energy region, we estimate that there are $32 \pm 5$ states with $J^\pi = 1/2^-$ in this energy region. We estimate based on Li's analysis that there are $39 \pm 4$ states with $J^\pi = 1/2^+$ in this same region. These data are therefore consistent with the assumption that level density does not depend on parity. This work was the project of John Quesenberry, an undergraduate student at TTU. A talk on this work was presented at the Ninth National Conference on Undergraduate Research, and a paper describing the work appears in the Proceedings of that conference.

# 7  Accelerator Control Systems Development

## (with C. A. Grossmann, L. K. McLean, J. P. Quesenberry, J. M. Drake, G. A. Vavrina, and C. R. Westerfeldt)

New control systems have been developed and implemented during the current contract period for two of the major pieces of hardware in the TUNL High Resolution Laboratory. The electrostatic analyzer and its associated electronics are the primary system responsible for the ultrahigh beam energy resolution available in this laboratory. The analyzing magnet also forms an integral part of the high resolution feedback loops. Both instruments must operate stably and reproducibly if the resolution is to be adequate for the experiments designed here. Failure of the PDP-11 microprocessor which had been used to control the electrostatic

analyzer in the period $\approx$ 1985 - 1991 prompted us to consider alternate methods of control. We decided to use an 80486 PC and the software package LabVIEW for Windows as the basis for new control systems in the laboratory. Both the electrostatic analyzer and the analyzing magnet are now controlled from this PC. 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 via 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 via a digital I/O line 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 through an RS-232 serial link to a digital teslameter, while the slit difference signal is processed through an ADC. We are currently adding to this LabVIEW program the capability to turn on/off both the magnet power supply and the water flow to the magnet (these now must be done manually); this will be done by setting a digital I/O line to set the state of a relay.

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# Appendix I

## Personnel 1993-95

### Faculty
J. F. Shriner, Jr.

### Undergraduate Research Assistants
| | |
|---|---|
| L. M. Fittje | 1995 |
| J. A. Hutchins | 1995 |
| J. P. Quesenberry | 1993-94 |
| J. T. Slayton | 1993 |

### Collaborators
| | |
|---|---|
| A. A. Adams | North Carolina State University and Triangle Universities Nuclear Laboratory |
| E. G. Bilpuch | Duke University and TUNL |
| C. R. Bybee | North Carolina State University and TUNL |
| J. M. Drake | North Carolina State University and TUNL |
| C. A. Grossmann | North Carolina State University and TUNL |
| S. H. Hurth | North Carolina State University and TUNL |
| M. A. LaBonte | North Carolina State University and TUNL |
| L. K. McLean | North Carolina State University and TUNL |
| G. E. Mitchell | North Carolina State University and TUNL |
| E. F. Moore | North Carolina State University and TUNL |
| N. R. Roberson | Duke University and TUNL |
| W. E. Ormand | University of Tennessee and Oak Ridge National Laboratory |
| G. A. Vavrina | North Carolina State University and TUNL |
| P. M. Wallace | Duke University and TUNL |
| C. R. Westerfeldt | Duke University and TUNL |
| W. S. Wilburn | Duke University and TUNL |

# Appendix II

## Dissertations and Theses Supervised

Joann Marie Drake, "Resonance Tests of Detailed Balance and Design of Compton Suppression Spectrometer," Ph.D. degree, North Carolina State University, 1994. Supervisors – G. E. Mitchell and J. F. Shriner, Jr.

Charles Randall Bybee, "Fourier Transform as Signature of Chaos in Nuclei and Data Acquisition for Compton-Suppressed Spectrometer," Ph.D. degree, North Carolina State University, 1995. Supervisors – G. E. Mitchell and J. F. Shriner, Jr.

Matthew Alyn LaBonte, "Angular Distribution Study of the $^{29}$Si(p,$\gamma$) Reaction," M.S. degree, North Carolina State University, 1995. Supervisors – G. E. Mitchell and J. F. Shriner, Jr.

## 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).

"Tests of Time Reversal Invariance and Parity with Charged Particles," G. E. Mitchell, C. R. Bybee, J. M. Drake, E. G. Bilpuch, and J. F. Shriner, Jr., in *Time Reversal Invariance and Parity Violation in Neutron Reactions*, ed. by C. R. Gould, J. D. Bowman, and Yu. P. Popov, World Scientific (Singapore), 1994, p. 167.

"Parity Violation in Charged Particle Nuclear Reactions," J. F. Shriner, Jr. and G. E. Mitchell, Phys. Rev. C **49**, R616 (1994).

"Fluctuation Properties of Nuclear States: Experimental Status," G. E. Mitchell and J F. Shriner, Jr., in *From Spectroscopy to Chaos*, ed. by Daniel Koltun and Ashok Das, World Scientific (Singapore), 1995, p. 77.

"Parity violation in charged particle resonances," G. E. Mitchell and J. F. Shriner, Jr., Nucl. Instrum. and Methods **B99**, 305 (1995).

"A Compton-suppressed spectrometer for studies of chaos in nuclei," J. F. Shriner, Jr., E. G. Bilpuch, C. R. Bybee, G. E. Mitchell, E. F. Moore, J. D. Shriner, and C. R. Westerfeldt, Nucl. Instrum. and Methods **B99**, 641 (1995).

## Invited Talks

"A Compton-suppressed Spectrometer for Studies of Chaos in Nuclei," J. F. Shriner, Jr., Thirteenth International Conference on the Application of Accelerators in Research and Industry, Denton, TX, 1994.

## Abstracts

"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).

"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. **39**, 1824 (1994).

"A Compton-Suppressed Spectrometer for the Study of $^{29}$Si(p,$\gamma$)," G. A. Vavrina, C. R. Bybee, J. M. Drake, G. E. Mitchell, E. F. Moore , J. F. Shriner, Jr., E. G. Bilpuch, P. M. Wallace, and C. R. Westerfeldt, B.A.P.S. **39**, 1825 (1994).

"A High Resolution Study of $^{29}$Si(p,$\gamma$)," P. M. Wallace, E. G. Bilpuch, C. R. Westerfeldt, C. R. Bybee, J. M. Drake, M. A. LaBonte, G. E. Mitchell, E. F. Moore, G. A. Vavrina, and J. F. Shriner, Jr., B.A.P.S. **39**, 1825 (1994).

"Possible Tests of Parity Violation with Charged Particle Resonances," J. F. Shriner, Jr. and G. E. Mitchell, B.A.P.S. **40**, 1634 (1995).

## Technical Report

"The TUNL High Resolution Laboratory System and Operating Procedure," C. R. Westerfeldt, J. F. Shriner, Jr., and G. A. Vavrina.

## Seminars Presented

"Search for Chaos in $^{30}$P," Tennessee Technological University, 1994.

"Search for Chaos in $^{30}$P," University of the South, 1994.

## Undergraduate Publications

"Parity Dependence in Level Density of $^{48}$Ti," J. P. Quesenberry, in *Proceedings of the National Conference on Undergraduate Research*, Vol. II, University of North Carolina Asheville (Asheville), 1995, p. 799.