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December 1, 1990 - November 30, 1991

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PROTON RESONANCE SPECTROSCOPY

Progress Report

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PREFACE

This report summarizes the progress on Grant No. DE-FG05-87ER40353 during the period December 1, 1990 to November 30, 1991. The primary focus of the research during this period has been on establishing a complete level scheme for ^{30}P in the hopes of gaining greater understanding of the role of chaotic behavior in the nucleus. In Sections 1A and 1B, the measurements and analysis performed thus far are described; in Section 1C the design and current status of a new spectrometer system necessary for these measurements is discussed. A description of a search for pairs of resonances which might be particularly suitable for tests of detailed-balance violation is given in Section 2. In Section 3, we describe one possible alternative method for identifying chaotic behavior in nuclei, the Fourier transform, and our plans for exploring it. Section 4 summarizes our work over the past several years measuring entrance channel amplitudes and correlations in p + ^{27}Al resonances. A study of resonance levels in p + ^{48}Ti with the goal of ultimately studying the parity dependence of level densities is under way and is discussed in Section 5. Section 6 describes a computer program written to assist in the evaluation of angular distributions and correlations.

One of the important aspects of the research supported by this grant is the involvement of undergraduate students. This year three Tennessee Technological University undergraduates have worked on the project. Brent York (currently in graduate school in Aeronautical Engineering at Virginia Tech) had the major responsibility for the work on level densities in ^{49}V (discussed in Sect. 5). Erin Moore (a junior) spent much of the summer deciphering the computer code OPTIC and using it to study possible beam lines for the new detector system (Section 1C.4). Travis Slayton (a sophomore) worked on the final phases of the p + ^{27}Al analysis (Section 4) and also assisted with the detailed-balance calculations (Section 2). Both of these latter students spent the summer at TUNL, where they were also involved in the maintenance of the laboratory and the general day-to-day activities of the High Resolution Group there.

The secretarial and accounting duties for this grant have been performed by Gloria Julian of the TTU Department of Physics, and I once again wish to express my appreciation. I also wish to thank the personnel at TUNL and in the Duke Department of Physics for their hospitality and assistance during my visits.

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

Over the past several years, interest in "quantum chaos" has been high. While the term chaos has a well-defined meaning in classical physics, there is no clear consensus at present on even a definition in situations which require quantum-mechanical descriptions. One conjecture, originally proposed by Bohigas et al. [1], was that quantum systems which are time-reversal-invariant and whose classical analogs are chaotic show fluctuations described by the Gaussian orthogonal ensemble (GOE) of random matrix theory [2]. Further studies have generally supported this conjecture, and examining the fluctuation behavior of the system has become a generally accepted test for quantum chaos; GOE behavior is believed to be evidence for a chaotic system, while Poisson statistics suggest an integrable system (see [3-5] for some recent applications to nuclear energy levels). One problem with such analyses is the need for extremely high-quality data, since missing or misassigned levels can severely affect the analysis [6]. Thus, alternative signatures for quantum chaos would be most helpful.

A number of other approaches to quantum chaos have been suggested. The dissipation of shell effects in nuclear physics [7] has been proposed as a signature. Several studies, within the context of the fermion dynamical symmetry model (FDSM) [8-9] and the interacting boson model (IBM) [10-11] as well as in more general terms [12], have suggested that quantum chaos corresponds to broken dynamical symmetry. A concept of quantum chaos for a single eigenfunction has also been proposed [13]. Probably the best understanding of quantum chaos has come from periodic orbit theory and its applications to atomic systems (see, e. g., [14]). However, there remains the problem in nuclear physics of an unambiguous experimental signature for quantum chaos. In this regard, the fluctuation properties still seem to be the analysis of choice (see Sect. 3 for discussion of a possible alternative).

The only nuclear data currently suitable for a fluctuation analysis over a relatively wide energy range is that of ^{26}Al [15-17]. There the fluctuations are intermediate between a GOE and a Poisson description [3]. We have begun a series of measurements designed to obtain a complete level scheme for the nuclide ^{30}P from the ground state into the resonance region. Such measurements will permit the analysis of its fluctuation properties. The status of those measurements is described in the remainder of this section.

1A. Study of ^{29}Si(p,γ), ^{29}Si(p,p$_1\gamma$), and ^{29}Si(p,p$_2\gamma$)

(with S. C. Frankle, E. G. Bilpuch, G. E. Mitchell, and C. R. Westerfeldt)

As a first step toward establishing a complete level scheme for ^{30}P, we have studied resonances in the p + ^{29}Si reaction. Previously, Nelson et al. [18] had studied ^{29}Si(p,p) and ^{29}Si(p,p') over the energy range E_p = 1.29 - 3.31 MeV and had identified 66 resonances, while Reinecke et al. [19] had studied 32 resonances in ^{29}Si(p,γ) for E_p < 2.3 MeV. We started by measuring excitation functions for ^{29}Si(p,γ), ^{29}Si(p,p$_1\gamma$), and ^{29}Si(p,p$_2\gamma$) for the energy range E_p = 2.0 - 3.3 MeV; the lower part of this energy range provides data which overlap with that of Reinecke et al. and allow us to check for consistency between the two data sets. These data were collected with two 7.62 cm $\times$ 7.62 cm NaI(Tl) detectors. Excitation functions for a portion of the data are shown in Fig. 1.

A total of 64 resonances were observed in this energy region. In the region of overlap with Reinecke's work, we observed all previously identified resonances with greater sensitivity (our energy resolution was $\approx$ 400 eV FWHM;

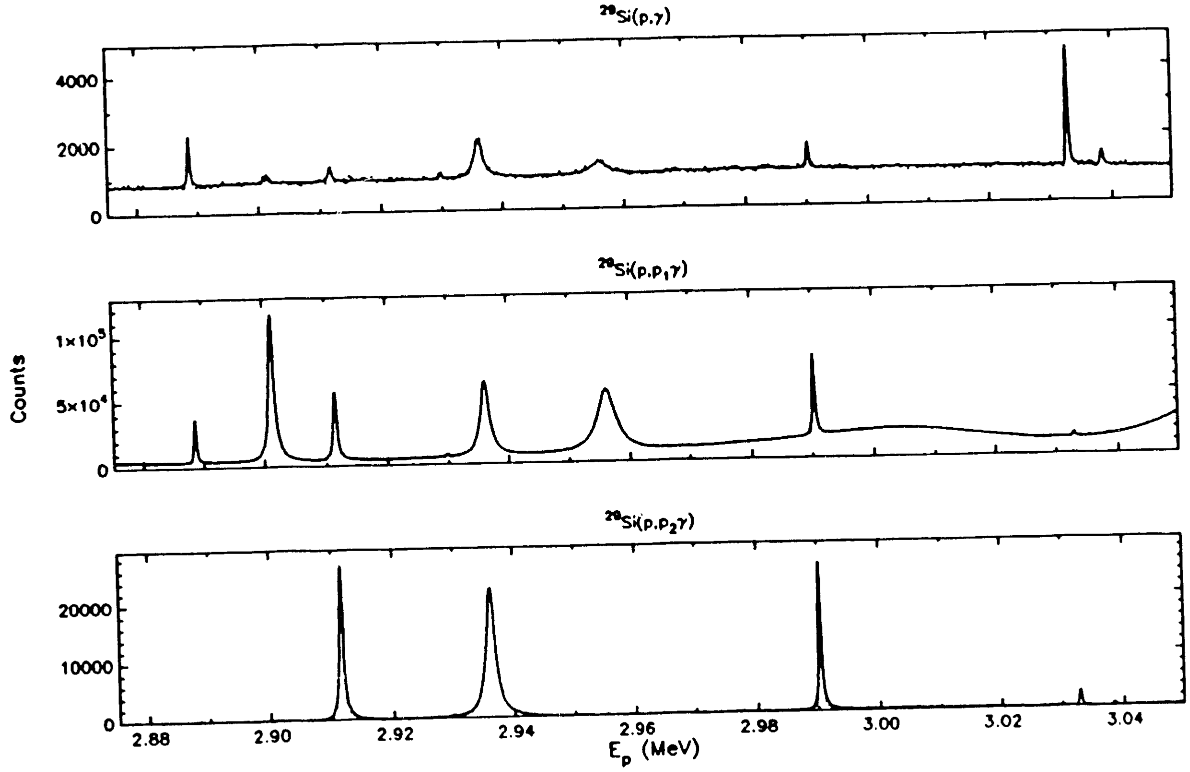

Figure 1. Data and fit for the $^{29}Si(p,\gamma)$, $^{29}Si(p,p_1\gamma)$, and $^{29}Si(p,p_2\gamma)$ reactions over the energy range E_p = 2.875 - 3.050 MeV.

that of Reinecke et al. was ≥ 1 keV). At energies above the previous capture studies, 13 previously unknown resonances were identified. Since our goal is to obtain as complete a level scheme as possible, knowledge of these newly found levels is important. Absolute strengths were determined for 49 $^{29}Si(p,\gamma)$ resonances, and relative strengths were obtained for the other two reactions.

1B. Study of $^{29}Si(p,p_0)$, $^{29}Si(p,p_1)$, and $^{29}Si(p,p_2)$

(with S. C. Frankle, E. G. Bilpuch, G. E. Mitchell, and C. R. Westerfeldt)

The next step in our study of ^{30}P was a careful search for the resonances which had not previously been observed in elastic scattering. The primary purpose of this set of measurements is to assist in the identification of the total angular momentum J and the parity π of the resonance levels. Elastic scattering cross sections are frequently a good indicator of the orbital angular momentum ℓ, which determines π; J itself often remains ambiguous from elastic scattering alone [20]. Data for inelastic cross sections frequently place further constraints on possible J values.

Five surface barrier detectors were placed at laboratory angles of 90°, 108°, 135°, 150°, and 165°. 23 resonances between $E_p = 0.95$ MeV and $E_p = 3.33$ MeV had previously not been observed in elastic scattering. We measured excitation functions for $^{29}Si(p,p_0)$, $^{29}Si(p,p_1)$, and $^{29}Si(p,p_2)$ in the region of each of these resonances. A single NaI(Tl) detector was placed outside the scattering chamber to simultaneously monitor the γ-ray reactions.

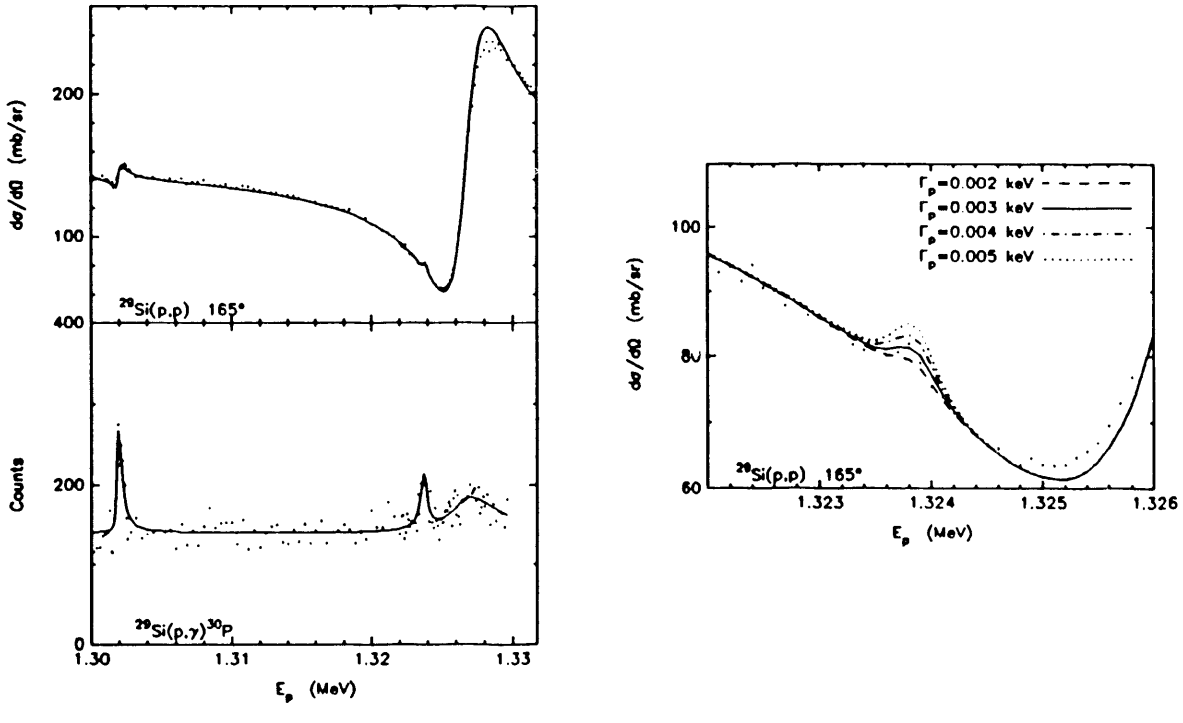

Figure 2. Data and fit for $^{29}Si(p,p_0)$ and $^{29}Si(p,\gamma)$ in the region of the E_p = 1.3238 MeV resonance. The right portion of the figure shows a magnified view of elastic scattering data and several possible fits.

Most of these levels were too weak to observe in elastic scattering even with prior knowledge of their existence. Those which were observed had very small widths; an example is shown in Fig. 2. For some resonances which were unobserved in this work but for which J^π was already known, an upper limit on Γ_p was deduced. One new resonance was observed in $^{29}Si(p,\gamma)$ at $E_p = 1.7464$ MeV. Identification of J and π for many of these levels will require the use of the detector system described in Section 1.C.

The studies described in Sections 1.A and 1.B comprised the Ph.D. thesis of S. C. Frankle [21]. She included in her dissertation an up-to-date compilation of what is known about energy levels in ^{30}P in light of our recent work. Fig. 3 shows the cumulative sum of levels in ^{30}P as currently known.

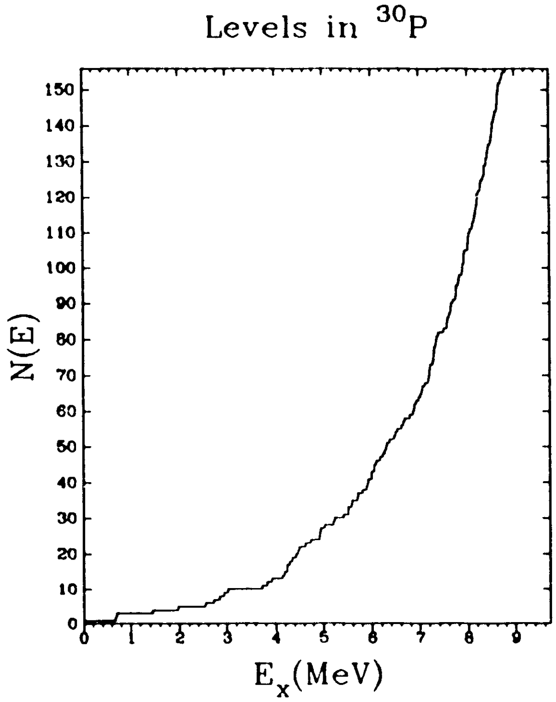

Figure 3. Cumulative sum of levels as a function of excitation energy for ^{30}P.

1C. Compton-suppressed Spectrometer Design

The capture reaction is an effective method of locating resonance levels. However, detailed γ-ray studies are often required to determine J^π for these levels, and such studies cannot be performed with NaI(Tl) detectors due to these detectors' limited energy resolution. Energy levels near the ground state of a nucleus can often be studied via stripping or pickup reactions; however, if one wants to study levels at higher excitation energies (yet still below the separation energy), both kinematics and limited resolution can severely limit the available information from particle reactions. Here again, γ-ray decay studies are an effective tool for identifying states and their quantum numbers. Since our goal is to obtain as complete a level scheme as possible for ^{30}P and since study of γ-rays is the most effective method over much of the energy range of interest, we are designing a detector system which will allow us to study in detail the γ-ray decay of states populated via $^{29}Si(p,\gamma)$ resonances. In those cases where J^π of the resonance is known, we hope to determine J^π of bound states to which that resonance decays. Where J^π of the resonance is unknown, we hope to find decays to bound states of known J^π and thereby determine the resonance J^π. What is needed for such measurements is a high-efficiency, high-resolution γ-ray detector. The following sections describe our designs for such a detector and the current status of the project.

1C.1. Detector Design

(with S. S. Patterson, E. G. Bilpuch, C. R. Bybee, J. M. Drake, G. E. Mitchell, and C. R. Westerfeldt)

Similar measurements to those we wish to make have been performed for the p + ^{25}Mg system by Endt et al. [15-17]. They employed a 20% Ge detector with a NaI shield for Compton suppression [22] and an additional unshielded Ge detector. We plan to employ a similar method with several improvements. First we will have larger HPGe detectors (each of 60% efficiency relative to a 7.62 cm × 7.62 cm NaI(Tl) crystal). Two detectors will allow us to perform coincidence measurements when appropriate to help establish the decay scheme. One of the detectors will have a Compton-suppression shield made of bismuth germanate (BGO); BGO is much denser than NaI, and thus the shield can be smaller. To design the shield, we started with the NaI shield described by Aarts et al. [22], scaled it down by a factor to approximately account for the change to BGO, and then ran extensive modelling calculations using the code BOCKVI [23] to optimize the dimensions. The BGO shield will be a right circular cylinder with a taper on the front to allow it to be positioned closer to the beam line and a well to allow insertion of the Ge detector. The Ge detector will be mounted in the shield in a transverse configuration, thereby allowing substantial shielding in the γ-rays' forward direction. Drawings of the proposed BGO shield are shown in Fig. 4. The Ge detectors have been ordered, and a final design for the BGO shield will be determined soon.

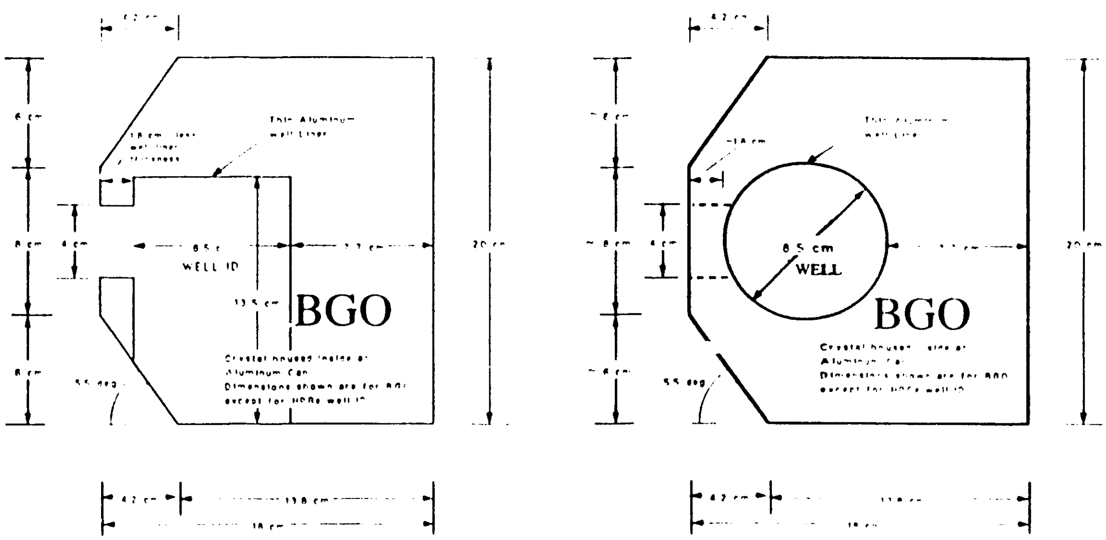

Figure 4. Top (left) and side (right) view of the proposed BGO shield.

1C.2. Electronics Design

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

In order to incorporate the new detectors into our data acquisition system, a variety of new electronics is required. The desire to measure γ-γ coincidences, something which has not previously been done in TUNL's High Resolution Laboratory, is the primary reason that new equipment is needed. Improvements and new developments in NIM electronics have also played a role in our considerations. We have decided to employ what might be called a traditional γ-γ setup, where each event will consist of two energy signals (provided by spectroscopy amplifiers) and a timing signal (provided by a TAC). Timing amplifiers and constant-fraction discriminators will be bought to process the timing signals. A logic unit has been purchased to enable the Compton suppression. An analog spectrum stabilizer will be employed on the linear signal from each amplifier; we feel these are necessary because the count rates for capture are typically quite small, and therefore spectra will need to be collected for extended periods of time. A new NIM bin will also be purchased to house most of these new modules. Orders for these items have been placed.

1C.3. Software Design

(with A. A. Adams, C. R. Bybee, and C. R. Westerfeldt)

We have begun developing new data acquisition software for these experiments. Our current plans are to record event tapes for γ-γ coincidences as well as to store singles spectra from each γ-ray detector and from a single surface barrier detector. We anticipate running three different XSYS subprocesses while collecting data: one will handle the coincidence signals, one will handle the γ-ray singles, and the third will process the charged particle singles spectrum. An Ortec AD413 Quad CAMAC ADC will be used for the coincidence events. We have been testing this module in its various modes and have determined which mode seems most suitable for our needs. Our next step in this phase will be to actually write the DAP and EVL files necessary for each of the three subprocesses and test them.

1C.4. Beamline Design

(with C. R. Westerfeldt and E. A. Moore)

Use of these new detectors will require the fabrication of a new scattering chamber, along with collimators, beam line, etc. At present two scattering chambers located on the same beam line are used in the High Resolution Laboratory; one is designed for charged particle detection and the other for γ-ray detection. One possibility is to replace the present γ-ray chamber with a new one which will accommodate the new detectors. Another possibility would be to introduce an analyzing magnet on the current beam line and split off new lines for each chamber. Using the program OPTIC, we explored this latter possibility; in particular, we examined whether focusing elements (quadrupoles) would be necessary on each separate beam line (if so, the cost of additional quadrupoles must be considered). Our conclusion is that such elements would indeed be essential. Once the details of the BGO design are finalized, design of the new chamber will become the next major step.

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)

It has recently been suggested that large enhancements of time-reversal-invariance (TRI) violations might be observed by tests of detailed balance near two interfering resonances [24]. We have searched our large collection of (p,α) resonance data for pairs of resonances which might be particularly suitable for such a test; targets include ^{23}Na, ^{27}Al, ^{31}P, ^{35}Cl, and ^{39}K.

We found 33 cases in which adjacent resonances had the same J^{π}; these include 7 different combinations of target spin and compound state spin/parity. While Bunakov and Weidenmüller examined the total cross section, the differential cross section is much more relevant for (p,α) measurements; thus, in the spirit of [24], we have examined the quantity

$$\Delta(E,\theta) = 2\,\frac{\frac{k_p^2}{g_{(p,\alpha)}}\frac{d\sigma}{d\Omega}_{(p,\alpha)}(E,\theta) - \frac{k_\alpha^2}{g_{(\alpha,p)}}\frac{d\sigma}{d\Omega}_{(\alpha,p)}(E,\theta)}{\frac{k_p^2}{g_{(p,\alpha)}}\frac{d\sigma}{d\Omega}_{(p,\alpha)}(E,\theta) + \frac{k_\alpha^2}{g_{(\alpha,p)}}\frac{d\sigma}{d\Omega}_{(\alpha,p)}(E,\theta)} \quad (1)$$

where $k = 2\pi/\lambda$ and g is the usual statistical factor. We have derived the appropriate differential cross section expressions for all 7 spin/parity combinations for which data are available. A Hamiltonian of the form

$$H = H_0 + H' \quad (2)$$

has been assumed, where H_0 is time-reversal-invariant and H' is not. The matrix elements of H' are then purely imaginary and are denoted by iW. Following the discussion of Moldauer [25], we have then derived the appropriate collision matrix elements for H, assuming only internal mixing and only two states. With these assumptions, Δ is (to first order) proportional to W. Due to the complexity of the differential cross sections (which depend in general on several Legendre polynomials), the collision matrix elements, and of Δ itself, a closed-form expression for Δ is not very useful. Thus, we have written a computer program to calculate Δ for any of the pairs of resonances under consideration. The energy dependence shows strong variation from pair to pair, and very sharp resonances as a function of angle have been observed for some pairs; a sample plot for one pair of resonances is shown in Fig. 5. We are currently studying how best to characterize and display the energy and angle dependences.

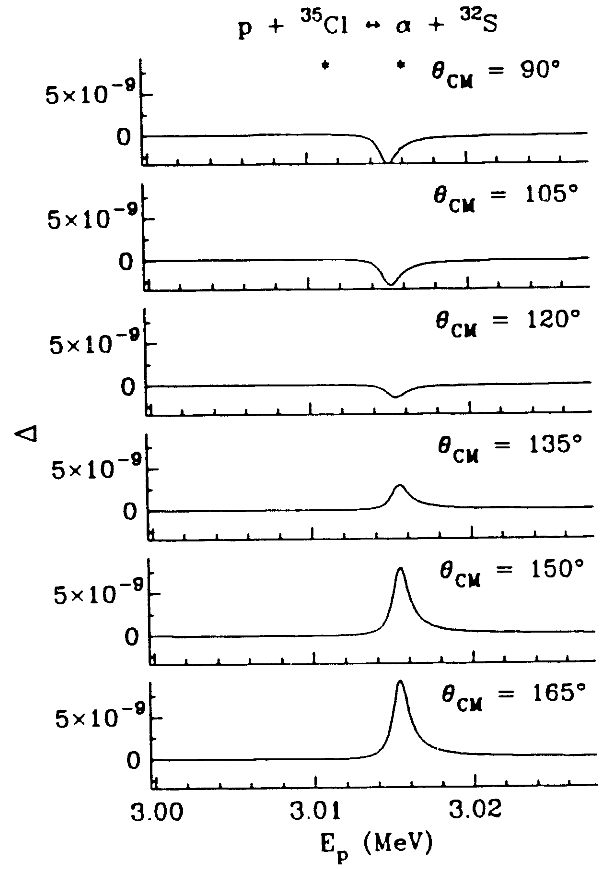

Figure 5. Behavior of Δ as a function of energy for several angles for a resonance pair in the compound nucleus ^{36}Ar. The asterisks at the top of the drawing mark the energies of the two resonances.

3. The Fourier Transform as a Tool for Detecting Chaos

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

While analyzing the fluctuation properties of a quantum system seems to offer insights into quantum chaos (see Section 1), the requirements of pure and complete sequences impose severe constraints -- the technique can only be used with very high quality data. A less restrictive method would be of great use in examining data of various types and understanding whether the underlying behavior is chaotic or regular. One tool proposed [26] to serve such a purpose is the Fourier transform of the spectrum. We have begun a numerical study to determine the strengths and weaknesses of the Fourier transform employed in this manner.

Our intent is to analyze both GOE and Poisson spectra of various sizes with the goal of understanding how sample size affects the results when the Fourier transform is used. Then we plan to explore the effects of incomplete and impure spectra, which are of course the usual result of experimental measurement. The first analysis is shown in Fig. 6, where we display the square of the absolute magnitude of the Fourier transform (F. T.) for both GOE and Poisson spectra containing 100 levels. The spectra have been analyzed as having amplitude one at each energy level and zero at all other energies. The results shown are actually the average of the F. T. of 500 spectra of the given symmetry (GOE or Poisson); this effectively smooths the statistical fluctuations and yields an estimate of the ensemble average. A "hole" is observed at small values of the dimensionless parameter E^{-1}/ρ (ρ is the level density of the system) in the F. T. of the GOE spectra. This hole is the proposed signature for quantum chaos. It was suggested to us [27] that the appearance of the hole is sensitive to exactly how one calculates the F. T.; in particular, one should <u>not</u> pad the spectra with zeros so that the total number of data points is exactly a power of 2, as is commonly done. We have confirmed that this aspect of the analysis is indeed crucial. Our analysis is continuing.

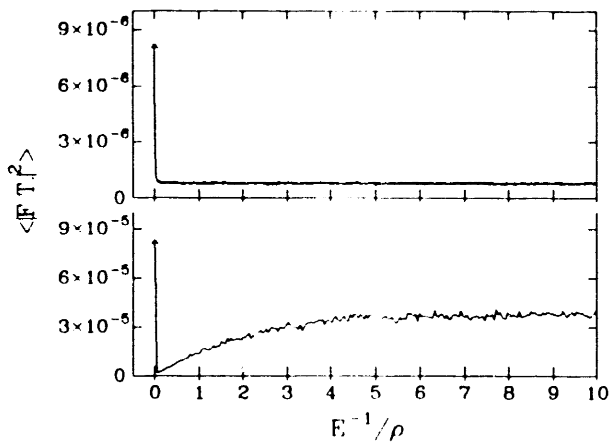

Figure 6. Average behavior of $|F.T.|^2$ for GOE (bottom) and Poisson (top) spectra with 100 levels.

4. Entrance Channel Correlations in p + ^{27}Al

(with C. T. Coburn and J. T. Slayton)

Entrance channel reduced widths for 3 channels and the relative signs of the reduced width amplitudes for 2 of those channels have been determined for ten 2^+ resonances in the p + ^{27}Al reaction. The motivation of this experiment was to gain further experimental data appropriate for the question of whether reduced width amplitudes in the entrance channel show behavior consistent with a Gaussian distribution. The measurements included (p,α_0) angular distributions and (p,p_0) and (p,α_0) excitation functions. In a previous measurement of entrance channel amplitudes in p + ^{39}K [28], the data did not appear to agree with the expected Gaussian distribution.

For the 2^+ states studied here, conservation of angular momentum and conservation of parity allow an exit channel orbital angular momentum of $\ell' = 2$ and entrance channel orbital angular momenta of $\ell = 0$, 2, or 4; the $\ell = 4$ channel has been neglected in the analysis due to its low penetrability relative to the other allowed channels. The proton channels included in the analysis are thus $s = 2$, $\ell = 0$; $s = 2$, $\ell = 2$; and $s = 3$, $\ell = 2$ (s denotes channel spin). The only channel allowed for α_0 decay is $s' = 0$, $\ell' = 2$. The reduced width amplitudes in the proton channels are denoted by γ_{20}, γ_{22}, and γ_{32}, respectively. Because only relative signs of amplitudes can be determined, it is convenient to define a pair of mixing ratios

$$\delta_1 = \frac{\gamma_{22}}{\gamma_{20}} \qquad \delta_2 = \frac{\gamma_{32}}{\gamma_{20}} \quad . \tag{3}$$

The angular distribution for an isolated 2^+ resonance in this particular reaction has the form $W(\theta) = a_0 [1 + a_2P_2(\theta) + a_4P_4(\theta)]$, where P_2 and P_4 are Legendre polynomials and

$$a_2 = \frac{-\frac{2}{7}\sqrt{70}\,P^{1/2}\cos(\xi_0-\xi_2)\delta_1 - \frac{15}{49}P\delta_1^2 - \frac{40}{49}P\delta_2^2}{1+P\delta_1^2+P\delta_2^2},$$

$$a_4 = \frac{\frac{36}{49}P\delta_1^2 - \frac{9}{49}P\delta_2^2}{1+P\delta_1^2+P\delta_2^2}. \qquad (4)$$

In these equations P is the ratio of the $\ell = 2$ penetrability to the $\ell = 0$ penetrability, and $\cos(\xi_0-\xi_2)$ is a term that includes the effect of Coulomb and hard sphere phase shifts; the cosine term ranges from -0.27 to -0.08 for these data.

Because δ_2 appears quadratically in eq. (4), determination of a_2 and a_4 cannot determine the sign of δ_2. At best these measurements determine δ_1 and $|\delta_2|$. More careful examination of eq. (4) reveals that in some cases two values of δ_1, each with a corresponding $|\delta_2|$, correctly describe the angular distribution. In such cases the elastic scattering cross section may identify the correct solution.

If time-reversal-invariance holds, the appropriate version of random matrix theory is the Gaussian orthogonal ensemble (GOE) [2]. The GOE predicts that reduced widths in a single channel should have a $\chi^2(1)$ distribution; in nuclear physics this is often called a Porter-Thomas distribution [29]. The distribution of reduced widths for the three proton channels is shown and compared to a Porter-Thomas distribution in Fig. 7. The distribution has been determined separately for each of the three channels, and the overall distribution shown was obtained by averaging the three individual distributions. The agreement between data and GOE is generally quite good.

The large step observed in $\int P(y)$ for small values of y arises because three of the 10 angular distributions are consistent with values of zero for γ_{32}^2.

If the reduced widths obey a Porter-Thomas distribution, then the reduced width amplitudes in a single channel should be normally distributed [30]. Thus, the agreement of the reduced width distribution with a Porter-Thomas suggests that the amplitudes observed in this experiment are indeed Gaussian. However, knowledge of the relative signs of amplitudes may offer additional insights. The product $\gamma_{20}\gamma_{22}$ is plotted in Fig. 8 as a function of energy. Nine of the 10 resonances have a positive relative sign between these two amplitudes. This behavior clearly contradicts the random signs expected from the Bohr compound nuclear model. One method of quantifying these results utilizes the linear correlation coefficient

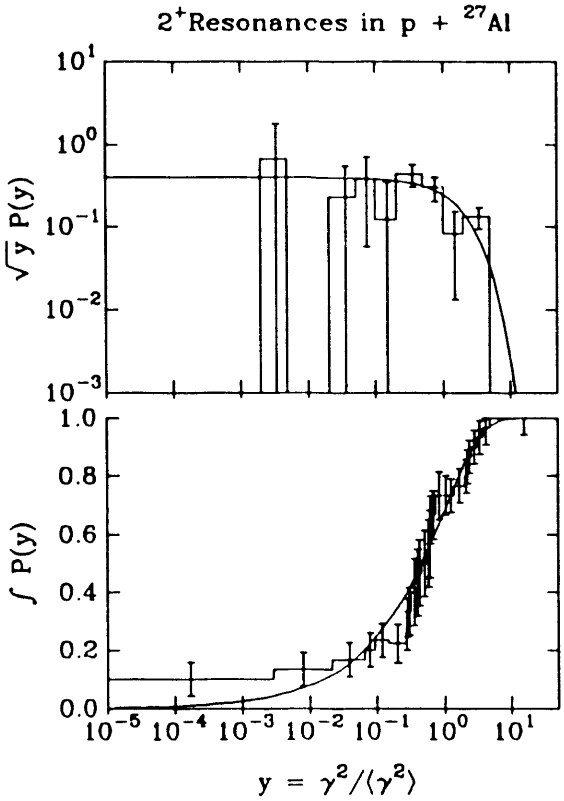

Figure 7. The overall reduced width distribution for the three proton channels. The smooth curve denotes the Porter-Thomas distribution.

$$\rho(x,y) = \frac{\sum_i (x_i-\bar{x})(y_i-\bar{y})}{\left[\sum_i (x_i-\bar{x})^2 \sum_i (y_i-\bar{y})^2\right]^{1/2}} \quad . \tag{5}$$

Krieger and Porter showed [30] that the GOE predicts a multivariate Gaussian distribution for the amplitudes; if this holds and each channel has a mean value of zero for the amplitudes, then

$$\rho^2(\gamma_1, \gamma_2) = \rho(\gamma_1^2, \gamma_2^2) \qquad (6)$$

for any pair of channels. Therefore, eq. (6) can be applied to test whether amplitudes are consistent with a multivariate Gaussian distribution.

The linear correlation coefficients between each pair of reduced widths and between the one available pair of reduced width amplitudes are listed in Table 1, along with estimates of the uncertainties and significance levels. The amplitude correlation is significant at the 99% level. Although two of the six values of ρ_w are larger in magnitude than the amplitude correlation, none of them differs from zero at a significance level greater than 91%.

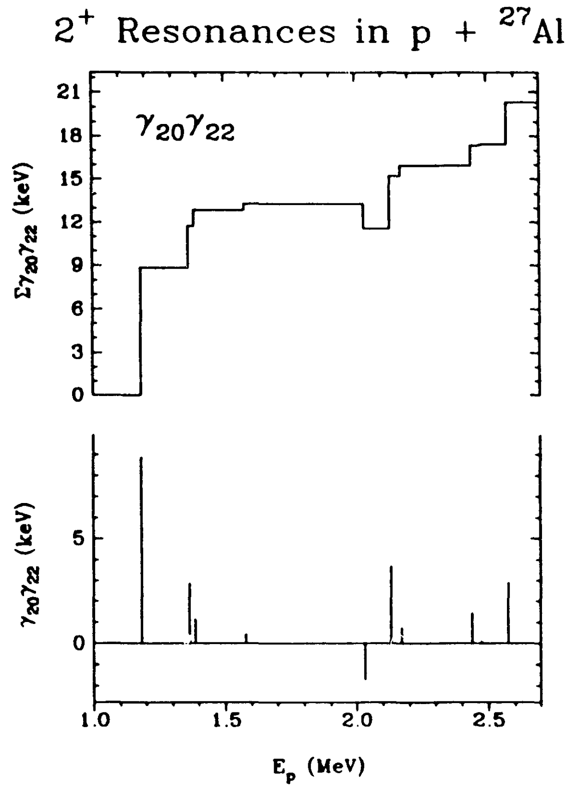

Figure 8. The products of reduced width amplitudes and the cumulative sum of products for one pair of proton channels.

Table 1. Linear Correlation Coefficients for 2^+ Resonances in p + ^{27}Al.

γ_1	γ_2	ρ_w	σ_ρ	Signif.	ρ_a	σ_ρ	Signif.
γ_{20}	γ_α	0.03	0.37	51%	--		
γ_{22}	γ_α	0.77	0.40	91%	--		
γ_{32}	γ_α	0.28	0.42	68%	--		
γ_{20}	γ_{22}	-0.02	0.34	58%	0.59	0.21	99%
γ_{20}	γ_{32}	0.31	0.34	81%	--		
γ_{22}	γ_{32}	0.64	0.19	90%	--		

It is now generally agreed that a comparison of width and amplitude correlations is best made in a representation where the amplitude correlation is zero [31]. We have transformed these data to such a representation; in this "zero representation," $\rho(\gamma_1^2, \gamma_2^2) = 0.58$ with an estimated uncertainty of 0.45 and significance level of 83%. Therefore, these data are consistent with a Gaussian distribution for amplitudes at the 2σ level. This result can be compared to that for the p + ^{39}K system [28], where $\rho_w = 0.53 \pm 0.24$ in the zero representation with a significance of 97%. A manuscript describing these results has been prepared and submitted to Z. Phys. A.

5. **The Parity Dependence of Level Densities in ^{49}V**

(with B. W. York)

The study of level densities is one of the oldest problems in nuclear physics and dates back to early work by Bethe [32-33]. For many purposes a phenomenological approach, such as that of Gilbert and Cameron [34], proves suitable. Two more recent models of this type which incorporate different features are those of Ignatyuk et al. [35] and Kataria et al. [36]. One facet of nuclear physics which is often not included in such models is a parity dependence. We are in the process of experiments to study the parity dependence of level densities in ^{49}V.

A recent study by Li et al. [37] has located over 700 resonances in p + ^{48}Ti with excitation energies in the range 9.8 - 10.5 MeV. This large sample should be ideal for a study of level densities. Approximately 100 of the states are $\ell = 0$, $J^\pi = 1/2^+$ states, and Li's analysis suggests that this sequence is relatively pure and complete. Another 270 states have been assigned $\ell = 1$; for these states J^π can be either $1/2^-$ or $3/2^-$, and the assignment of J from elastic scattering cross sections is often ambiguous.

We are measuring $^{48}Ti(p,p_1)$ and $^{48}Ti(p,p_1\gamma)$ angular distributions for each of these $\ell = 1$ states in order to clarify the J assignments. If an isolated state has $J^\pi = 1/2^-$, both of these angular distributions will be isotropic. If an isolated state has $J^\pi = 3/2^-$, at least one of the angular distributions cannot be isotropic. Thus, we will be able to identify J for resonances which do not interfere too much with their neighbors. The level densities of $J^\pi = 1/2^+$ states and $J^\pi = 1/2^-$ states can then be compared.

Thus far, we have studied 68 $\ell = 1$ resonances in the energy range E_p = 3.080 - 3.308 MeV. Due to the high level density, interference between resonances is a common occurrence. Definite spin assignments have been made for only 18 of these states, but we plan to remeasure several of the others where better energy resolution could significantly affect the separation of nearby states. A talk on the current status of this work was presented by B. W. York at the Fifth National Conference on Undergraduate Research in Pasadena.

6. A Computer Program for the Calculation of Angular Momentum Coupling Coefficients.

(with D. F. Fang)

Due to the importance of angular momentum in resonance reactions, it is crucial to have a computer program which can calculate coupling coefficients. While numerous codes to do this exist, we wanted one which would express the results in rational rather than decimal form. Thus a program COEFF was written, which calculates angular momentum coupling coefficients and expresses them as a quotient of two integers multiplied by the square root of the quotient of two integers. This is accomplished by using a representation in which an integer number is converted into an array of prime factors and by redefining the basic arithmetic functions to manipulate these arrays. The program provides the capability of calculating coupling coefficients for large angular momenta with minimal overflow problems.

The program is written in FORTRAN, and versions for VAX and IBM PC (and compatible) computers are available. Sample output is shown in Table 2. A

Table 2. Sample session with COEFF. Input from the user is shown in italics

$ *run coeff*

> Type CG (or cg) to calculate CG coefficients.
> Type 3J (or 3j) to calculate 3-j symbols.
> Type W (or w) to calculate Racah coefficients.
> Type 6J (or 6j) to calculate Wigner 6-j symbols.
> Type ZB (or zb) to calculate Z bar coefficients.
> Type Z1B (or z1b) to calculate Z1 bar coefficients.
> Type 9J (or 9j) to calculate 9-j symbols.
> Type EX (or ex) to exit.

> *cg*

> enter cg(a,b,alpha,beta,c,gamma) *2,.5,1,.5,1.5,1.5*

```
                   1/2
 -(     1/     5)
```

> *w*

> enter w(a,b,c,d,e,f) *4,4,4,4,4,4*

```
    -467/ 18018
```

> *9j*

> enter: 9-j(a,b,c,d,e,f,g,h,i) *1,1,2,1,1,2,1,1,2*

```
                                 1/2
       1/    30 (      7/     3)
```

> *ex*

FORTRAN STOP

paper describing the algorithm and use of the program has been accepted by Computer Physics Communications.

SUMMARY

Measurements with the goal of establishing a complete level scheme for ^{30}P have continued. Resonances in the range $E_p = 2.0 - 3.3$ MeV have been studied with both charged particle and γ-ray detectors, and the analysis has been performed. Design of a Compton-suppressed spectrometer to allow more detailed study of the electromagnetic decay of these states is in progress. We have continued our analysis of pairs of resonances which might prove especially suitable for a recently proposed test of detailed-balance violation; the preliminary calculations are complete, and we are trying to determine the most meaningful way to characterize and present the results. A possible alternative method of characterizing chaotic behavior of the nucleus, use of the Fourier transform, is being explored. The analysis of entrance channel correlations in p + ^{27}Al is finally complete, and the results have been submitted for publication. A measurement of the parity dependence of $J=1/2$ level densities in ^{49}V has begun, although the amount of data acquired thus far is small.

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APPENDIX I

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APPENDIX II

PUBLISHED ARTICLES

"Nearly Complete Level Scheme of ^{116}Sn below 4.3 MeV," S. Raman, T. A. Walkiewicz, S. Kahane, E. T. Jurney, J. Sa, Z. Gácsi, J. L. Weil, K. Allaart, G. Bonsignori, and J. F. Shriner, Jr., Phys. Rev. C **43**, 521 (1991).

"Fluctuation Properties of Spacings of Low-lying Nuclear Levels," J. F. Shriner, Jr., G. E. Mitchell, and T. von Egidy, Z. Phys. **A338**, 309 (1991).

"Chaotic Behavior of Nuclear Spectra," G. E. Mitchell, E. G. Bilpuch, P. M. Endt, J. F. Shriner, Jr., and T. von Egidy, Nucl. Instrum. and Methods **B56/57**, 446 (1991).

"Chaos in Nuclear Level Schemes," J. F. Shriner, Jr., G. E. Mitchell, and T. von Egidy, in **Capture Gamma-Ray Spectroscopy**, Richard W. Hoff, ed., American Institute of Physics, New York, 1991, p. 655.

ARTICLES IN PRESS

"Small Sample Size Effects in Statistical Analyses of Eigenvalue Distributions," J. F. Shriner, Jr. and G. E. Mitchell, Z. Phys. A.

"A Computer Program for the Calculation of Angular Momentum Coupling Coefficients," D. F. Fang and J. F. Shriner, Jr., Computer Physics Communications.

"Parity Dependence of Level Densities in ^{49}V," B. W. York, in *Proceedings of the Fifth National Conference on Undergraduate Research*, edited by K. M. Whatley.

ARTICLES SUBMITTED FOR PUBLICATION

"Entrance Channel Correlations for 2^+ Resonances in p + ^{27}Al," C. T. Coburn, J. F. Shriner, Jr., and C. R. Westerfeldt, submitted to Z. Phys. A.

CONTRIBUTED ABSTRACTS

"A Search for Proton Resonances Suitable for Tests of Detailed Balance Violation," J. M. Drake, G. E. Mitchell, C. R. Bybee, J. F. Shriner, Jr., and E. G. Bilpuch, B.A.P.S. **36**, 2729 (1991).

"A Compton-suppression Spectrometer for the Study of ^{29}Si(p,γ)," C. R. Bybee, J. M. Drake, G. E. Mitchell, S. S. Patterson, J. F. Shriner, Jr., E. G. Bilpuch, and C. R. Westerfeldt, B.A.P.S. **36**, 2730 (1991).

Ph.D. DISSERTATIONS

S. C. Frankle, "Nuclear Resonance Spectroscopy in ^{30}P," North Carolina State University (co-directed with G. E. Mitchell).

SEMINARS AND COLLOQUIA PRESENTED

"Chaos in the Atomic Nucleus?", Oak Ridge National Laboratory.

"Chaos in the Atomic Nucleus?", University of Kentucky.

END

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