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PREFACE

This report summarizes the progress on Grant No. DE-FG05-87ER40353 during the period February 1, 1990 to November 30, 1990. The primary focus of the research during this period has been on fluctuations of nuclear levels and possible connections with fundamental symmetries. In Sect. 1 the analysis of low lying nuclear levels for a large collection of nuclides is discussed, and the analysis of just the levels in ^{116}Sn is presented in Sect. 2. The current status of experiments to study fluctuation properties in ^{30}P is summarized in Sect. 3, while the development of hardware and software for the next phase of these measurements is outlined in Sect. 4. We discuss in Sect. 5 the early stages of a project to search for a particular type of detailed-balance violation.

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. Chris Coburn (currently a senior) performed the data analysis on the $p + ^{27}\text{Al}$ experiments described in Sect. 6. Brent York (a senior) and Barry Winn (a junior) have taken the major responsibility for the work on level densities in ^{49}V (discussed in Sect. 7); these responsibilities included target preparation, chamber setups, development of analysis programs, and data acquisition, as well as the analysis of the small amount of data obtained thus far from this experiment. Both of these 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. Fluctuation Properties of Low-lying Nuclear Levels

(with G. E. Mitchell, T. von Egidy, and B. L. Winn)

Random matrix theory (RMT) [1] has long been used as a tool to characterize the fluctuations of energy levels. The Gaussian orthogonal ensemble (GOE) version of RMT predicts that nearest-neighbor spacings for a sequence of levels should have (very nearly) a Wigner distribution [2] and that the long-range behavior of eigenvalues should agree with the Δ_3 statistic of Dyson and Mehta [3]. Recently there has been renewed interest in RMT due to the conjecture [4] that quantum systems which are time-reversal-invariant and whose classical analogs are chaotic show GOE fluctuations. This original conjecture was based on the quantization and analysis of Sinai's billiard; since then calculations for several other systems [5-7] have supported this conjecture and have also suggested that quantum systems whose classical analogs are regular display Poisson fluctuations. However, there are known counterexamples [8-10]. Because of these ambiguities and because the connection between "quantum chaos" and GOE fluctuations is not completely understood, a less ambiguous signature of quantum chaos is clearly desired. However, despite great interest in the subject (see, e.g. [11-13]), there does not at present appear to be a clear experimental signature of quantum chaos. Analysis of the fluctuation properties currently seems to be the most direct way to look for evidence of chaotic behavior in the nucleus.

Nuclear resonance data are known to show good agreement with GOE [14-15]. If GOE-type fluctuations are indicative of chaotic behavior, then tests of RMT applied to energy levels not in the resonance region may suggest limits on the energies where a chaotic description is applicable. The best available data in a single nuclide for such a study are from ^{26}Al where a nearly complete

level scheme is known from the ground state up to an excitation energy of ≈ 8 MeV [16-18]. Our analysis of these data [19-20] focused on two statistics, the nearest-neighbor spacing (NNS) distribution and Δ_3 . We found a spacing distribution intermediate between GOE and Poisson, although slightly favoring GOE, and Δ_3 behavior near the GOE limit. The fluctuations are consistent with being independent of isospin, although the statistical uncertainties are too large to make a definitive statement on this aspect of the behavior.

For nuclides other than ^{26}Al , the data are much more limited (although data for ^{116}Sn are discussed in Sect. 2). Here we discuss the fluctuation properties of low-lying nuclear levels for a collection of nuclear data from many different nuclides. This work is an extension of previous, less extensive studies along the same lines [21-23].

When comparing data to the predictions of RMT, it is necessary to consider only levels which have the same symmetries (i.e., the same quantum numbers). For nuclear physics applications this requirement generally means the same total angular momentum J and the same parity π , although additional quantum numbers are required in some cases. We shall use the term "sequence" to mean a group of levels from one nuclide with the same quantum numbers.

A meaningful analysis of the fluctuation properties of a set of energy levels requires data of extremely high quality. The sequence being studied must be both complete (few or no missing levels) and pure (few or no misassigned levels) over the energy range considered, since failure to meet either of these conditions severely affects the fluctuation behavior. We have chosen for examination data from 90 nuclides whose level schemes appear to be complete over an energy region starting at the ground state and over some range of angular momenta; the masses range from $A = 24$ to $A = 244$. In

choosing these nuclides, we required that at least the first ten levels of the level scheme have definite spin and parity assignments. The upper limit of the selected levels frequently is determined by the absence of a well-established spin and/or parity for one level. In a few cases where spin/parity assignments were ambiguous, model information has been used. A large fraction of the nuclides have been investigated by the neutron capture reaction, as the non-selectivity and sensitivity of this reaction guarantees a high degree of completeness.

Testing the completeness of a level scheme in a given energy and spin range is difficult. The level schemes included here have been checked by considering the experimental reactions and the quality of the measurements, by comparing adjacent nuclides, and by considering theoretical predictions of level schemes. For instance, in ^{233}Th there is a one-to-one correspondence between observed and predicted levels below 800 keV; this provides an argument for completeness. We estimate that, for the level schemes included in this analysis, less than 5% of the levels are missing or have erroneous spin or parity assignments.

We have performed Monte Carlo studies which indicate that the NNS distribution is the most reliable of the commonly used statistics for the small sample sizes considered here. We find that spacing distributions can be used to distinguish between GOE and Poisson behavior with sequences of as few as 5 levels, provided that several such sequences are combined. Requiring a minimum of five levels in a sequence yields 168 sequences in 60 different nuclides (the other 30 nuclides originally selected have no sequences meeting this criterion).

Nearest-neighbor spacings S_1 for a sequence of levels are generated by

calculating the energy differences between adjacent levels of that sequence. It is simplest to express the spacing distribution as a function of the dimensionless parameter $x=S/D$, where D is the average spacing. If the nearest-neighbor spacings obey GOE statistics, the spacing probability distribution function will be nearly a Wigner distribution

$$P(x) = \frac{\pi}{2} x e^{-\pi \frac{x^2}{4}}. \quad (1)$$

If the spacings are Poisson distributed, then

$$P(x) = e^{-x}. \quad (2)$$

An interpolation formula between these two extremes has been proposed by Brody [24]:

$$P(x; \omega) = \alpha (\omega+1) x^\omega e^{-x^{\omega+1}}; \quad (3)$$

$$\alpha = \left[\Gamma\left(\frac{\omega+2}{\omega+1}\right) \right]^{\omega+1}$$

In this expression $\omega = 0$ corresponds to a Poisson distribution, while $\omega = 1$ yields a GOE distribution. The value of ω provides a convenient method of characterizing NNS distributions; however, it must be emphasized that this is an empirical formula, and no physical significance is known for the parameter ω . However, it has recently been observed by Cheon [25] that this formula provides a surprisingly good description of the transition from Poisson to GOE.

To compare the different sequences to each other, each set of energy levels must be converted to a set of normalized spacings $\{x_i\}$, where $x_i=S_i/D$ and D is the average level spacing for that sequence. However, D itself is a function of energy and decreases as the excitation energy increases; knowing D

is equivalent to knowing the level density ρ , since $\rho(E)=1/D(E)$. We have normalized the spacings by fitting each sequence to a constant temperature level density [26]. The NNS distribution is then determined for each sequence; errors are estimated using the bootstrap method [27]. Because of the small sample sizes for most of these sequences, the data from several sequences are combined by averaging their NNS distributions.

The spacing distributions for six different mass regions are shown in Fig. 1. The distribution for the lightest masses appears very close to GOE

Figure 1. NNS distributions and cumulative distributions for all levels in six different mass regions.

behavior, while the heaviest masses show a distribution which is only slightly different from a Poisson. Visually there is an obvious trend from GOE to Poisson as the mass increases. The visual trend is emphasized in Fig. 2

Figure 2. Values of ω for six different mass regions. The straight line is a fit to the six data points.

where the values of ω are plotted for each of these mass regions, along with a straight-line fit. Within the errors the data show good agreement with the straight line.

Several other effects have been noted. The 2^+ and 4^+ states in deformed nuclides are close to Poisson ($\omega = 0.16 \pm 0.13$), while the 0^+ and 3^+ states in the deformed

nuclides are near the other extreme ($\omega = 0.74 \pm 0.52$), albeit with limited statistical accuracy. States with other spins or 2^+ and 4^+ states from spherical nuclides generally show values of ω which are intermediate between these two groups of states. The nuclear shape also has some effect on NNS distributions in even-even nuclides. The 2^+ and 4^+ states behave quite differently for deformed and spherical nuclides ($\omega = 0.16 \pm 0.13$ vs. $\omega = 0.52 \pm 0.15$), while the remainder of the states show NNS distributions which have little if any shape dependence ($\omega = 0.51 \pm 0.21$ for deformed vs. $\omega = 0.57 \pm 0.16$ for spherical).

In attempting to understand these results, it is interesting to consider what could cause a transition from GOE to Poisson fluctuations. In light of the earlier discussion, one might expect this to be indicative of the system moving from chaotic behavior to regular behavior. However, it is well known

(see, e.g., Mehta [28]) that the NNS distribution also would move from GOE toward Poisson if the spacings result from a superposition of unrelated sequences. Therefore, if there were a conserved quantum number which had not been considered when the sequences were identified, GOE behavior would not be expected, even if that were the true underlying behavior of the system.

Considering the role of other quantum numbers leads quickly to the question of what a broken symmetry does to the fluctuation properties. This general problem has been studied by Dyson [29] and by Pandey [30]. A summary was given by Pandey: "...even a small breaking of a fundamental or model symmetry is shown to yield fluctuation patterns which would be found in the complete absence of the symmetry." Therefore, even small amounts of symmetry-breaking may be equivalent to the absence of the symmetry, at least as measured by the fluctuation behavior.

In nuclei two additional quantum numbers which come to mind are isospin and the K quantum number (used in describing rotational nuclei). The only experimental data available for a broken symmetry test of this type are from the ^{26}Al data discussed earlier. There the data are qualitatively consistent with the predictions of Dyson and Pandey, although even for a pure isospin sequence the behavior is not GOE. A detailed examination of how isospin symmetry-breaking affects the fluctuation properties has been performed by Guhr and Weidenmüller [31], who constructed a random-matrix model for the process. Within the framework of this model, they were able to provide an explanation of the ^{26}Al data and extract a value for the Coulomb matrix element which was in agreement with previous results.

For the K quantum number there are not suitable data at present for an experimental test of how K symmetry-breaking affects the fluctuation

properties. However, K symmetry-breaking has been studied by Paar and Vorkapic [32] within the framework of the interacting-boson model. Study of a level scheme of ^{164}Er calculated with this model shows approximate K-independence for the fluctuation properties [33].

Do these theoretical studies offer any insights into the present results, in which the only symmetries considered are angular momentum and parity? When the data are examined as a function of mass, the two regions where nuclei are strongly deformed display the NNS distributions which are nearest to Poisson behavior. Of course, K is expected to be most relevant in these two regions. Thus, one might speculate that the fact that more regular behavior is observed in these two regions may simply reflect the importance of K, and that the failure to separate sequences by K (in addition to J and π) has biased these results. However, if K (or some other quantum number) explains the observed mass dependence, then the results for different spins in the deformed nuclides indicate different amounts of symmetry-breaking for different spin groups. Current experimental data, except for ^{26}Al , are insufficient to consider the effects of symmetry-breaking on the fluctuation properties in any single nuclide.

On the other hand, the lightest nuclides show behavior which is close to GOE. These nuclides are generally well described by the shell model, and it has long been known that shell-model states generally agree with the GOE (see, e.g., the discussion in Brody et al. [1]). Therefore, this behavior does not seem very surprising. As we pointed out earlier, even in the spherical nuclides the fluctuation properties appear to be moving toward regularity at heavier masses. It is not clear whether this represents the increasing importance of another quantum number or some other effect.

A paper on this topic has been accepted by Zeitschrift für Physik A. An invited talk was presented at the Seventh International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics.

2. Fluctuation Properties of Levels in ^{116}Sn

(with S. Raman)

Because of the possible connections with quantum chaos, it is of great interest to analyze the fluctuation properties of levels in individual nuclides. However, there are very few nuclides for which levels are known in sufficient quantity and quality for such analyses to yield statistically significant results. Recent data on the nuclide ^{116}Sn are an exception and provide a good testing ground.

The level scheme of ^{116}Sn has been constructed by combining recent $^{115}\text{Sn}(n,\gamma)$ and $^{116}\text{Sn}(n,n'\gamma)$ measurements with previous results. A total of 100 levels have been observed below an excitation energy of 4.3 MeV. The fluctuation properties of these states were analyzed following the procedure discussed in Sect. 1. The sequences with $J^\pi = 0^+, 1^+, 2^+, 3^+, 4^+$, and 5^- had sufficient states to be included in the analysis. The resulting NNS distribution is shown in Fig. 3. A fit to

Figure 3. The NNS distribution and cumulative distribution for levels in ^{116}Sn .

the parameter ω yields a value of 0.51 ± 0.19 , indicating behavior which is slightly closer to GOE than Poisson; this is in good agreement with the value $\omega = 0.55 \pm 0.11$ obtained for all nuclides in the mass region $100 < A \leq 150$. A paper describing the ^{116}Sn experiment and including the results of the fluctuation analysis has been submitted to Physical Review C.

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

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

As discussed in Sect. 1, the nuclide ^{26}Al is one of the few for which data of sufficient quantity and quality to permit an analysis of the fluctuation properties is available [20]. We have begun a study of ^{30}P with the goal of establishing as complete a level scheme as possible from the ground state into the resonance region. Ultimately we wish to analyze the fluctuation properties of the levels and compare the behavior of ^{30}P with that of ^{26}Al .

As a first step, we are studying the resonance region. Thus far, we have performed measurements of $^{29}\text{Si}(p,\gamma)$, $^{29}\text{Si}(p,p_1\gamma)$, and $^{29}\text{Si}(p,p_2\gamma)$ in the energy range $E_p = 2.0 - 3.3$ MeV using NaI detectors. A total of 13 resonances have been identified which were not previously observed by Reinecke et al. [34] in the capture reaction (below $E_p = 2.4$ MeV) or by Nelson et al. [35] in elastic scattering. In addition, the existence of 4 resonances which had previously been observed in (p,γ) but not (p,p) experiments was confirmed. We are currently searching more carefully for evidence of these resonances in elastic scattering in preparation for studies of the γ -ray deexcitation of these states with HPGe detectors.

4. Hardware and Software Development for Compton-Suppression Spectrometer (with C. R. Bybee and G. R. Westerfeldt)

As part of the preparation for studying individual resonances in $p + {}^{29}\text{Si}$ (see Sect. 3) with germanium detectors, we have acquired new hardware and are starting to modify software for the data acquisition process. An Ortec Model AD413 Quad 8k ADC has been purchased by TTU for this project, as the current data-acquisition electronics for the TUNL High Resolution Laboratory (HRL) will not be sufficient to run gamma-gamma coincidence measurements; this new module has been inserted into the CAMAC crate of the HRL computer, and testing has begun. We anticipate utilizing three of the four inputs, two for energy signals from the two Ge detectors and one for the relative timing signal. We have also realized that the Indiana University version of the XSYS software package is more suited to this type of experiment than is the TUNL version; therefore, we have begun studying this software package and are planning to use it in the data acquisition code for the new spectrometer.

5. A Search for Time-reversal-invariance Violation in Proton Resonances (with J. M. Drake, C. R. Bybee, G. E. Mitchell, and E. G. Bilpuch)

It has been proposed by Bunakov and Weidenmüller [36] that large enhancement factors for violation of detailed balance may exist when a pair of close-lying compound nuclear resonances interfere. Data which are appropriate for such tests exist for (p, α_0) resonances in the compound nuclei ${}^{24}\text{Mg}$ [37], ${}^{28}\text{Si}$ [38,39], ${}^{32}\text{S}$ [40], ${}^{36}\text{Ar}$ [41], and ${}^{40}\text{Ca}$ [42]. We have identified 25 cases in which a pair of adjacent resonances have the same J^π ; there are another 16 cases for which definite J^π values are not known but the possible assignments

include appropriate J^π values. We are searching to see if any of these pairs of resonances are especially suitable for a test of detailed balance of this type.

Bunakov and Weidenmüller discuss the two-channel case in some detail. However, all these resonances require a more general treatment, since there are at least three open proton channels plus an alpha channel. Thus far, we have developed the appropriate formalism for calculating the cross sections, following the work of Moldauer [43]. We are now programming the appropriate equations and will then examine each pair to see which, if any, show the suggested enhancement.

6. Entrance Channel Correlations in ^{28}Si

(with C. T. Coburn)

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 eight 2^+ resonances in the $p + ^{27}\text{Al}$ 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 $p + ^{39}\text{K}$ [44], the data did not appear to agree with the expected Gaussian distribution.

The sample size is much smaller in this case than in the previous measurements due to the reduced level density; furthermore, the widths are generally larger, leading to more interference between levels. Thus, unambiguous results could be obtained for only 8 resonances. The two channels

between which the relative sign could be determined are $s = 2, \ell = 0$ and $s = 2, \ell = 2$ (s denotes channel spin, and ℓ denotes orbital angular momentum). The product of the reduced width amplitudes $\gamma_{20}\gamma_{22}$ is shown in Fig. 4; six of

Figure 4. Products of amplitudes and cumulative sum of products.

the eight resonances show a positive sign for this product.

Since one cannot measure the absolute sign of a reduced width amplitude, a direct test of the distribution is precluded. However, an indirect test is possible utilizing the linear correlation coefficient

$$\rho(x, y) = \frac{\sum_i (x_i - \langle x \rangle)(y_i - \langle y \rangle)}{\left[\sum_i (x_i - \langle x \rangle)^2 \sum_i (y_i - \langle y \rangle)^2 \right]^{1/2}} \quad (4)$$

For our purposes the correlation

coefficient is convenient because it can be shown that if amplitudes are indeed Gaussian, then

$$\rho^2(\gamma_1, \gamma_2) = \rho(\gamma_1^2, \gamma_2^2) \quad (5)$$

for any pair of channels. We shall denote the correlation coefficient between two sets of reduced widths by ρ_w and that between two sets of reduced width amplitudes by ρ_a .

The linear correlation coefficients for the various widths and the one measured pair of amplitudes are listed in Table 1. Also included are estimates of the uncertainties and the significance (or confidence) levels of the coefficients; these quantities were calculated using the bootstrap method

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

γ_1	γ_2	ρ_w	σ_ρ	Signif.	ρ_a	σ_ρ	Signif.
γ_{20}	γ_α	-0.09	0.32	64%	--		
γ_{22}	γ_α	0.87	0.30	94%	--		
γ_{32}	γ_α	0.03	0.60	46%	--		
γ_{20}	γ_{22}	-0.01	0.38	49%	0.53	0.32	96%
γ_{20}	γ_{32}	0.74	0.55	77%	--		
γ_{22}	γ_{32}	0.01	0.57	56%	--		

of Efron [27]. The limited sample size leads to large errors, but the amplitude correlation and one of the width correlations both differ from zero at a confidence level of over 90%.

Comparisons between width and amplitude correlations are best made in a representation in which the amplitude correlation is zero [45]. When we transform the two sets of amplitudes for these data to this representation, we find $\rho_w=0.58$ with a standard deviation of 0.45 and a significance level of 83%. This does not agree with eq. (5) at the 1σ level. The only other entrance channel data of similar nature, a study of resonances in $p + {}^{39}\text{K}$ [44], also violates eq. (5). These results are in contrast to results from exit channel studies; the reason is presently unknown. A brief paper describing these measurements has appeared in the Proceedings of the Fourth National Conference on Undergraduate Research, and a more detailed manuscript will be prepared for publication in the near future.

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

(with B. L. Winn and B. W. York)

The study of level densities is a problem of long standing in nuclear physics and dates back to early work by Bethe [46,47]. An understanding of level densities is important for a variety of problems in pure and applied nuclear physics; as an example, it has recently become understood that level densities play a critical role in parity and time-reversal violation in compound nuclear systems.

For many purposes a phenomenological approach to level densities is appropriate. One such analysis was performed by Gilbert and Cameron [26]. More recently, phenomenological models that attempt to incorporate more complexities than did the early models have been introduced by Ignatyuk et al. [48] and Kataria et al. [49], among others. It is well understood that such models should show dependences on mass, excitation energy, and spin; however, a parity dependence is generally not included. Data to search for a parity dependence have always been difficult to obtain.

We have begun experiments in an attempt to compare the average level densities of $J^\pi \sim 1/2^+$ and $J^\pi = 1/2^-$ states in ^{49}V for excitation energies of 9.8 - 10.5 MeV. Recent proton resonance data by Li [50] have located over 700 states in this region and established the orbital angular momentum ℓ for most of them. Approximately 100 of the states have $\ell = 0$, and approximately 270 have $\ell = 1$. The $\ell = 0$ states have $J^\pi = 1/2^+$, and statistical tests suggest that the assignments are generally correct and that most of the $1/2^+$ states have indeed been observed. However, since elastic scattering cross sections often do not distinguish between $J = \ell + 1/2$ and $J = \ell - 1/2$, it was frequently difficult to determine whether the p-wave resonances are $J^\pi = 1/2^-$

or $J^\pi = 3/2^-$.

We have begun measurements of the angular distributions for ${}^{48}\text{Ti}(p, p_1)$ and ${}^{48}\text{Ti}(p, p_1 \gamma)$ for the $\ell = 1$ resonances. For an isolated resonance with $J^\pi = 1/2^-$, both these angular distributions will be isotropic; if $J^\pi = 3/2^-$, then at least one of the distributions will not be isotropic. Therefore, these measurements will eliminate the ambiguity in J for those resonances which do not interfere too much with their neighbors [51]. With definite spin assignments, we can proceed to compare the level densities of the different parities for $J = 1/2$. Thus far, we have measured (p, p_1) distributions for the resonances with $E_p = 3.08 - 3.30$ MeV.

SUMMARY

The fluctuation properties of a collection of low-lying nuclear energy levels have been analyzed. Effects due to mass, spin, and deformation are observed, suggesting that each of these parameters may play a role in understanding quantum chaos in the nucleus. A separate analysis of just the energy levels in ^{116}Sn revealed behavior intermediate between the extremes of GOE and Poisson statistics. Measurements with the goal of establishing a complete level scheme for ^{30}P are continuing, and development of new data acquisition hardware and software for use in the next phase of this project has begun. A search is in progress for pairs of resonances which might interfere in such a way as to enhance detailed-balance violation.

Studies of nuclear resonances continue to provide new insights. The analysis of entrance channel correlations in ^{28}Si is complete and suggests, although hardly conclusively, that these amplitudes may not have a Gaussian distribution. We have just begun experiments to determine whether J=1/2 level densities in ^{49}V show a parity dependence.

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APPENDIX I

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APPENDIX II

PUBLISHED ARTICLES

"Entrance Channel Correlations for 2^+ Resonances in $p + {}^{39}\text{K}$," J. S. Bull, E. G. Bilpuch, G. E. Mitchell, J. F. Shriner, Jr., and C. R. Westerfeldt, Z. Phys. A 335, 31 (1990).

"Fluctuation Properties of States in ${}^{26}\text{Al}$," J. F. Shriner, Jr., E. G. Bilpuch, P. M. Endt, and G. E. Mitchell, Z. Phys A 335, 393 (1990).

"Examination of 2^+ Resonances in $p + {}^{27}\text{Al}$ in the Proton Energy Range 0.9 - 3.0 MeV," C. T. Coburn, in *Proceedings of the Fourth National Conference on Undergraduate Research*, Vol. I, edited by K. M. Whatley (University of North Carolina Asheville, Asheville, 1990), p. 264.

PAPERS IN PRESS

"Fluctuation Properties of Spacings of Low-lying Nuclear Levels," J. F. Shriner, Jr., G. E. Mitchell, and T. von Egidy, Z. Phys. A.

PAPERS SUBMITTED FOR PUBLICATION

"Nearly Complete Level Scheme of ${}^{116}\text{Sn}$ below 4.3 MeV," S. Raman, T. A. Walkiewicz, S. Kahane, E. T. Journey, J. Sa, Z. Gácsi, J. L. Weil, K. Allaart, G. Bonsignori, and J. F. Shriner, Jr., submitted to Phys. Rev. C.

"Chaos in Nuclear Level Schemes," J. F. Shriner, Jr., G. E. Mitchell, and T. von Egidy, to be published in *Proceedings of the Seventh International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics*.

"Chaotic Behavior of Nuclear Spectra," G. E. Mitchell, E. G. Bilpuch, P. M. Endt, J. F. Shriner, Jr., and T. von Egidy, to be published in *Proceedings of the VI International School on Neutron Physics*.

"Chaotic Behavior of Nuclear Spectra," G. E. Mitchell, E. G. Bilpuch, P. M. Endt, J. F. Shriner, Jr., and T. von Egidy, to be published in *Proceedings of the Eleventh International Conference on the Applications of Accelerators in Research and Industry*, Nucl. Instrum. and Meth. A.

INVITED TALKS

"Chaos in Nuclear Level Schemes," Seventh International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Pacific Grove, CA.

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