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, 1991 to November 30, 1992. The primary focus of the research during this period has been preparation to study the $^{29}\text{Si}(p,\gamma)$ reaction in order to establish a complete level scheme for ^{30}P . These measurements will allow us to study the fluctuation properties of the energy levels with the goal of gaining greater understanding of the role of both chaotic behavior and isospin mixing in this nucleus. The current status is described in Section 1. A search for pairs of resonances which might be particularly suitable for tests of detailed-balance violation is outlined in Section 2; it appears that this method may prove more sensitive than previous detailed balance tests, but further study is necessary to confirm this. In Section 3, we describe one possible alternative method for identifying chaotic behavior in nuclei, the Fourier transform, and our current understanding of its effectiveness. Plans to study the statistical behavior of electromagnetic transition strengths obtained from the shell model are discussed in Section 4, and the current status of a new control system for the lab's electrostatic analyzer is presented in Section 5.

One of the important aspects of the research supported by this grant is the involvement of undergraduate students. This year two Tennessee Technological University undergraduates have worked on the project. Travis Slayton (a junior) and Brian Faircloth (a sophomore) spent the summer at TUNL, where they were involved in the maintenance of the laboratory and the general day-to-day activities of the High Resolution Group there. Brian worked primarily on a 3D graphics program (output is shown in Sect. 2 in the discussion of our detailed balance calculations), while Travis worked on a

variety of jobs, including preparation of Al and Ti targets.

Support by TTU and by Oak Ridge Associated Universities are allowing me to spend the 1992-93 academic year at TUNL. The secretarial and accounting duties for this grant have been performed by Gloria Julian of the TTU Department of Physics, and as always I wish to express my appreciation (especially for her work in my absence). 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

(with E. G. Bilpuch, C. R. Bybee, J. M. Drake, S. C. Frankle, G. E. Mitchell, E. F. Moore, J. T. Slayton, P. M. Wallace, and C. R. Westerfeldt)

We have continued preparations to study $^{29}\text{Si}(p,\gamma)$ with the goal of establishing as complete a level scheme as possible for ^{30}P . Knowledge of the energy levels will allow us to study their statistical behavior for information on chaotic behavior and isospin mixing in the nuclide (the analysis techniques were described in our earlier work on ^{26}Al [1]).

We began by studying $^{29}\text{Si}(p,\gamma)$ with NaI detectors in the energy range $E_p = 2.0 - 3.3$ MeV. Next, we studied $^{29}\text{Si}(p,p_0)$, $^{29}\text{Si}(p,p_1)$, and $^{29}\text{Si}(p,p_2)$ at resonances not previously observed in elastic scattering in the energy range $E_p = 0.95 - 3.33$ MeV. An up-to-date level scheme incorporating this new information was developed. This work comprised the Ph.D. studies of S. C. Frankle and was recently published in Phys. Rev. C [2]. A total of 94 resonances are now known in $p + ^{29}\text{Si}$, and 156 levels have been identified in ^{30}P . Of these 156, definite J^π assignments exist for about 100, but T (isospin) values are known for only about 40.

Since the statistical analysis requires extremely high quality data [3], we need J^π and T assignments for as many levels as possible. Therefore, we will study $^{29}\text{Si}(p,\gamma)$ with high resolution HPGe detectors using the high resolution proton beam of the TUNL KN Van de Graaff accelerator. The germanium detectors will allow us to resolve individual γ -ray transitions from the resonance levels, and the good beam resolution will allow us to study most of the resonances individually. By using the appropriate selection rules for electromagnetic transitions and Endt's recommended upper limits (RUL's) for reduced transition probabilities [4], we expect to be able to make definite

assignments for most of the states.

Preparations for these measurements are still underway. Two 60% efficient HPGe detectors have been purchased, along with necessary NIM electronics (two detectors will allow us to perform coincidence measurements if desired). A new scattering chamber has been designed and is ready for installation, along with a new turbomolecular pump. One of the two germanium detectors will have a BGO shield for Compton suppression; this is on order. The design of mounts for the detectors is nearly done, and many of the drawings have been submitted to Duke University Instrument Shop for fabrication. Software for both data acquisition and data analysis is being developed. Beam scanners have been installed in the beamlines to improve beam transport. We have also studied information on the $^{27}\text{Al}(p,\gamma)$ reaction and identified several resonances which are suitable for calibrating the germanium detectors at γ -ray energies higher than available from radioactive sources.

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

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

Bunakov and Weidenmüller [5] suggested that tests of detailed balance might be especially sensitive in the neighborhood of two interfering resonances. We have continued an analysis of (p,α) resonance data to see which resonances are best suited for such a test.

We have identified 33 pairs of adjacent resonances in the systems $p + ^{23}\text{Na}$ [6], $p + ^{27}\text{Al}$ [7], $p + ^{31}\text{P}$ [8], $p + ^{35}\text{Cl}$ [9], and $p + ^{39}\text{K}$ [10] which had been assigned the same J^π and which each have measured proton and

alpha widths. For each of these pairs, we calculated 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. A value of Δ differing from zero is evidence for violation of detailed balance (and thus time-reversal-invariance). To evaluate the matrix elements that appear in the

Figure 1. Δ/W as a function of energy and angle for four pairs of (p, α) resonances.

differential cross-section, we followed the formalism of Moldauer [11]: A Hamiltonian of the form

$$H = H_0 + iH_{\text{TRIV}} \quad (2)$$

has been assumed, where H_{TRIV} is the time-reversal-invariance violating portion of the Hamiltonian. The matrix element of H_{TRIV} is denoted by W . We have further assumed that only two states mix and that only internal mixing is important. With these assumptions, Δ is proportional to W to first order. Due to the complexity of Δ , it is best examined graphically; plots of Δ/W as a function of energy and angle are shown in Fig. 1 for four different pairs of resonances. It is clear that the results are strongly dependent on energy, on angle, and on the specific pair of resonances.

Since realistically one expects only to measure an upper bound on Δ , one must translate this into a limit on W . Consider the pair of resonances in $p + {}^{31}\text{P}$ for which Δ/W is shown in Fig. 2. The maximum absolute value of Δ/W is $\approx 6 \times 10^{-3}$. Suppose that an upper limit for Δ can be determined at the 10^{-2} level (this was approximately the level attained by Driller et al. [12] in their detailed balance measurement); then for this pair of resonances an upper limit of ≈ 2 eV is obtained for W . Other pairs have different maximum values of Δ/W and would

Figure 2 Δ/W as a function of E and θ for the pair of resonances in $p + {}^{31}\text{P}$ at $E_{\text{cm}} = 3.1356 \text{ MeV}$ and 3.1490 MeV .

therefore lead to different upper limits on W .

One useful method of discussing symmetry breaking is in terms of spreading widths: $\Gamma^{\text{TRIV}} \approx 2\pi\langle W^2 \rangle/D$, where D is the average level spacing. However, because W is a statistical variable and is expected to vary from one resonance pair to the next, determining $\langle W^2 \rangle$ from measurements of upper limits on W can be quite complicated (e.g., see the discussion by Davis and Hartmann [13]). However, a simple

first-order estimate can be obtained by replacing W_{rms} by our limit on W , leading to $\Gamma^{\text{TRIV}} \leq 5 \times 10^{-4}$ eV. This can be compared to the previous result from

detailed balance of $\Gamma^{\text{TRIV}} \leq 5.5 \times 10^{-2}$ eV with 80% confidence [14]. While this analysis is only

preliminary, it is clear that the method deserves serious consideration. In addition to the conversion from limits on W to W_{rms} , other factors which must be considered include the

cross-section of the

reaction (usually a maximum Δ corresponds to a minimum cross-section, and an

Figure 3. Values of Δ_{num}/W , $d\sigma/d\Omega$, and Δ/W at $\theta_{\text{cm}} = 180^\circ$ for the same two resonances in ${}^{32}\text{S}$ as shown in Fig. 2. The arrows at the top mark the locations of the resonances.

extremely small cross-section creates additional experimental difficulties), experimental energy and angular resolution, and the sensitivity of Δ to the experimental widths (which often have significant uncertainties). Fig. 3 shows the (p, α_0) cross-section at 180° for this same pair of resonances, along with Δ/W and the numerator of Δ/W at this same angle; the small cross-section at the energy where Δ/W is largest is clearly evident. We plan further study of this topic.

3. The Fourier Transform as a Tool for Studying Chaos

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

While analyzing fluctuation properties has provided numerous insights into chaos in quantum systems, a technique which does not require such high quality data would be most useful. Leviander et al. [15] have suggested that the Fourier transform of a spectrum can serve this purpose. Their interests were in the field of molecular physics; we have been studying numerical simulations of the behavior of the Fourier transform to evaluate its usefulness for nuclear spectra.

We start by generating a set of eigenvalues (E_i) obeying either a GOE or Poisson distribution; from the eigenvalues we form the spectrum $S(E)$, which has spikes of unit height at each eigenvalue and is zero elsewhere. The Fourier transform of $S(E)$ is defined as

$$\hat{S}(q) = \int_{-\infty}^{\infty} S(E) e^{-2\pi i q E} dE. \quad (3)$$

Fig. 4 shows the average behavior of $|\hat{S}(q)|^2$ for several different situations.

In each case the dependent variable is q/ρ where ρ is the level density. The upper left figure, for pure GOE spectra with 100 levels,

shows the "correlation hole" near $q/\rho = 0$; Leviander et al. state that this hole is the signature of chaos. No such hole occurs, on average, for Poisson spectra,

Figure 4. The average squared amplitude of the Fourier transform for four different sets of spectra.

as shown in the upper right. The lower two figures show the effects of missing or spurious levels on a GOE spectrum; in each case, the hole remains, although its shape is different. All the results shown have been obtained by numerically generating 500 spectra with the appropriate characteristics, determining $|\hat{S}(q)|^2$ for each one, and averaging the results. Thus these

results represent the ensemble-averaged behavior. However, the individual spectra show much noisier behavior, and the presence or absence of the hole is not as obvious. We are currently examining the individual spectra to determine how best to characterize them and whether an appropriate measure of a single spectrum can be identified.

4. Analysis of Shell-model States in ^{22}Na

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

Shell-model calculations for ^{22}Na are being performed using the OXBASH code. In general, such calculations will serve two distinct purposes in our investigations of chaos. The first is that we expect to have some states for which experimental measurements will not uniquely assign quantum numbers; comparison with calculations may offer suggestions. The second is that we wish to explore the statistical behavior of transition strengths and see if that leads to new insights for chaos; since there are many more transitions than there are energy levels, this approach may not have the same statistical limitations that analysis of the eigenvalues does. These latter studies should complement work by Alhassid and Novoselsky [16] on the fluctuations of $B(E2)$ values in the interacting-boson model.

Although we are primarily interested in ^{30}P , experiments to study ^{22}Na have also been discussed. Since ^{22}Na is easier to calculate within the shell model (fewer particles), those calculations are being done first. Energy levels have been calculated, as well as $B(M1)$ and $B(E2)$ values for transitions involving states with $J = 0$ or $J = 1$. When the remaining transition probabilities are available, we will proceed with studies of their fluctuation properties.

5. Electrostatic Analyzer Control

(with C. R. Bybee and C. R. Westerfeldt)

Since about 1985, the electrostatic analyzer in the TUNL High Resolution Laboratory has been set and controlled via a PDP-11 microcomputer communicating with the VAX 11/750 used for data acquisition. Last year, the PDP failed, and repairs proved futile. Thus a new system for analyzer control is necessary. After considering several options, including a new PDP, a μ VAX, and the VAXStation 3200 currently used for data acquisition, we have decided to use a 486-based PC with the software package LabVIEW for Windows. We feel this method will allow maximum flexibility and can ultimately be used for a number of other tasks in the laboratory. Orders for both the hardware and software have been placed.

Summary

Preparations for studying ^{30}P via $^{29}\text{Si}(p,\gamma)$ have continued. We are exploring both the use of the Fourier transform and the statistical behavior of electromagnetic transition strengths within the shell model as alternate approaches to identifying quantum chaos in nuclei. Our analysis of interfering resonances in (p,α) resonances suggests that improvements in the limits on detailed balance in nuclear reactions are possible, but several issues still must be considered before a definitive conclusion can be reached. Plans for a new control system for the High Resolution Laboratory's electrostatic analyzer are being implemented.

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Appendix I

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Appendix II

PUBLISHED ARTICLES

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"Fluctuation Properties and Broken Symmetries," G. E. Mitchell and J. F. Shriner, Jr., in Group Theory and Special Symmetries in Nuclear Physics, ed. by J. P. Draayer and J. Jänecke, World Scientific (Singapore), 1992, p. 286.

ARTICLES SUBMITTED FOR PUBLICATION

"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., submitted to appear in *Proceedings of the 12th International Conference on the Applications of Accelerators in Research and Industry*.

"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., submitted to *Nucl. Phys. A*.

CONTRIBUTED ABSTRACTS

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