

FINE STRUCTURE OF ISOBARIC ANALOGUE RESONANCES

G.E. Mitchell

North Carolina State University, Raleigh, North Carolina 27650

and

Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706*

ABSTRACT

The several thousand proton resonances studied by our group provide a body of resonance data unmatched in charged particle spectroscopy. Since these data include both analogue and background regions, a large amount of statistical information is available in addition to analogue state properties. Statistical information is obtained for both average properties (proton strength functions, average level densities, average capture widths) and for local properties (long- and short-range correlations for level spacings, correlations between partial widths in different channels). Recent results on the relative sign of width amplitudes verify predicted properties of doorway states and establish new non-statistical effects.

INTRODUCTION AND OVERVIEW

For many years our group has been involved in the systematic study of proton resonances with very good beam energy resolution. The vast majority of this work is at proton energies below 3.3 MeV, with overall resolution of a few hundred eV, and on targets in the 2s-1d or the 1f-2p shells. The initial motivation for these experiments was to examine the fine structure of analogue states. In addition to the detailed properties of the fine structure distributions, a large amount of more conventional spectroscopic information was obtained. These results on analogue states, as well as a description of the experimental method, are presented in a comprehensive review.¹

Although the initial major interest concerned analogue states, analogue and background effects are so intertwined that it is necessary to study both. A dual interest in statistical and non-statistical effects has been maintained. The first statistical results involved global statistical information such as average level densities, proton strength functions, average capture widths, etc. The next stage was a more detailed study of level spacings. With our excellent resolution and identification techniques, we were able to confirm the short- and long-range correlations first observed experimentally with neutrons in a different region of the periodic table.² Another area of interest was the measurement of the correlation of partial widths in different channels. This area was widely explored for individual resonances in neutron studies,³ and in averaged data by proton polarization studies (see references in the recent review by Mahaux and Weidenmüller⁴). However, the examination of the fine structure of analogue states provides the clearest test case for expected properties of doorway states.

Our recent efforts have emphasized detailed properties of width amplitudes. In these measurements one determines the relative sign of width amplitudes in multichannel processes. These new experiments not only have

*Supported by the U.S. Department of Energy

verified predictions concerning doorway states, but also provide tests which are much more sensitive to the existence of non-statistical effects than previously available. More non-statistical behavior has been observed than expected.

Below our results are summarized briefly. Analogue state properties are merely summarized, as are the average statistical properties. In the talk more emphasis will be placed on detailed statistical properties. Since the newest results are for width amplitudes, and are mostly unpublished, the most time will be devoted to this topic.

SUMMARY OF RESULTS

Our results on analogue states are covered in a comprehensive review.¹ The Coulomb energies agree well with simple models,⁵ but the analogue spectroscopic factors are systematically lower than expected (~35% in the 1f-2p shell). This result is unexplained. The spreading widths and asymmetry parameters agree qualitatively with the predictions of the Robson⁶ single channel (external mixing) model. The fine structure data suggest that the effects of inelastic channels neither dominate the elastic channel nor are negligible, but that instead the elastic and inelastic effects are comparable.

Average level densities are in good agreement with densities determined by other techniques^{7,8}. Average capture widths⁹ are consistent with the general trends from neutron capture data¹⁰; the effective number of degrees of freedom for the proton capture widths are also consistent with the neutron values. The proton strength function data establish the location of the 2p size resonances ($A \approx 40$), but through $A=64$ there is no evidence for the 3s size resonance.

Some selected sets of data¹¹ are of sufficient quality to provide an essentially complete single-level population. Results in ^{45}Sc and ^{99}V provide strong evidence for the existence of both short- and long-range correlations. The widths of the k th nearest neighbor spacing distributions agree well with GOE theory, as do the values of the Dyson-Mehta Δ_3 statistic and the linear correlation between adjacent spacings.¹²

It was established with fragmented analogue states that the partial widths in different channels are correlated for common doorway states.¹³ Correlations were observed in several cases^{14,15} where predicted (e.g., for analogue elastic and inelastic widths, for elastic and capture widths (for a beta-analogue)), while no significant correlation was observed in cases where the correlation is expected to be small or zero (e.g., for analogue elastic and neutron widths). Thus one may invert this process and use a statistically significant linear correlation as evidence for the existence of some "intermediate structure". This approach is more sensitive than methods involving only one channel.

Our most recent experiments involve width amplitudes. Interference effects in multichannel processes appear to be the most sensitive tests available. In these measurements singles measurements of inelastically scattered protons and the subsequent deexcitation γ -rays are sufficient to determine both the magnitudes and the relative signs of the inelastic

amplitudes and thus determine amplitude correlations. With this simple method¹⁶ and our good energy resolution, we are able to study many resonances. The method has been applied to p-, d-, f-, and g-wave resonances (mostly p and d) and both to fragmented analogue states and to analogue-free regions. For a fragmented $3/2^-$ analogue resonance in ^{45}Sc we verified^{17,18} a prediction by Lane¹⁹ that the relative sign between the amplitudes of the fine structure states is constant for a common doorway. The off-diagonal strength function agreed well with the prediction of the theory of analogue state broadening²⁰. An additional measurement on a fragmented $3/2^-$ analogue in ^{47}V confirms these results²¹. We then turned our attention to analogue-free regions. An extensive study of $3/2^-$ resonances in ^{49}V revealed the existence of intermediate structure²². In one case this structure is not apparent in the behavior of γ^2 , nor even in the correlation between the reduced widths in the two inelastic channels, but only appears in the amplitude correlation. Preliminary results on $d_{5/2}$ resonances in an analogue-free region of ^{49}V also yield anomalous results. Thus far our attempts to provide a more sensitive test of the random phase approximation have only yielded more examples of non-statistical effects.

This work was performed in collaboration with Prof. E.G. Bilpuch of Duke University. We thank our past graduate students for their invaluable assistance. The unpublished work is due to J.R. Chandler, B.H. Chou, K. Sales, W.A. Watson, W.K. Wells, and C.R. Westerfeldt.

REFERENCES

1. E.G. Bilpuch, A.M. Lane, G.E. Mitchell, and J.D. Moses, *Phys. Reports* **28**, 145 (1976).
2. H.L. Liou, H.S. Camarda, S. Wynchank, M. Slagowitz, G. Hacken, F. Rahn, and J. Rainwater, *Phys. Rev.* **C5**, 974 (1972).
3. R.E. Chrien, *Statistical Properties of Nuclei*, ed. J.B. Garg (Plenum, New York, 1972) p. 233.
4. C. Mahaux and H. Weidenmüller, *Ann. Rev. Nucl. Sci.* (to be published).
5. J. Jänecke, *Isospin in Nuclear Physics*, ed. D.H. Wilkinson (North-Holland, Amsterdam, 1969) p. 297.
6. D. Robson, *Phys. Rev.* **137**, B535 (1965).
7. J.R. Huizenga, *Statistical Properties of Nuclei*, ed. J.B. Garg (Plenum, New York, 1972) p. 425.
8. M. Beckerman, *Phys. Lett.* **69B**, 389 (1977).
9. C.R. Westerfeldt, G.E. Mitchell, E.G. Bilpuch, and D.A. Outlaw, *Nucl. Phys.* **A303**, 111 (1978).
10. J.E. Lynn, *The Theory of Neutron Resonance Reactions* (Clarendon, Oxford, 1968).
11. W.M. Wilson, E.G. Bilpuch, and G.E. Mitchell, *Nucl. Phys.* **A245**, 262 (1975); *Nucl. Phys.* **A245**, 285 (1975).
12. T.A. Brody, J. Flores, P.A. Mello, J.B. French, and S.M.M. Wong, *Notas de Física* **1**, 1978 (Instituto de Física, UNAM).
13. G.E. Mitchell, E.G. Bilpuch, J.D. Moses, W.C. Peters, and N.H. Prochnow, *Statistical Properties of Nuclei*, ed. J.B. Garg (Plenum, New York, 1972) p. 299.
14. W.C. Peters, E.G. Bilpuch, and G.E. Mitchell, *Phys. Lett.* **42B**, 244 (1972).
15. J.F. Wimpey, G.E. Mitchell, and E.G. Bilpuch, *Nucl. Phys.* **A269**, 46 (1976).

16. T.R. Dittrich, C.R. Gould, G.E. Mitchell, E.G. Bilpuch, and K. Stelzer, Phys. Lett. 59B, 230 (1975); Nucl. Phys. A279, 430 (1977).
17. A.M. Lane, T.R. Dittrich, G.E. Mitchell, and E.G. Bilpuch, Phys. Rev. Lett. 41, 454 (1978).
18. G.E. Mitchell, T.R. Dittrich, and E.G. Bilpuch, Z. Phys. A289, 211 (1979).
19. A.M. Lane, Ann. of Phys. 63, 173 (1971).
20. A.M. Lane, Isospin in Nuclear Physics, ed. D.H. Wilkinson (North-Holland, Amsterdam, 1969) p. 509.
21. J.R. Chandler, G.E. Mitchell, and E.G. Bilpuch, Phys. Rev. (to be published).
22. W.K. Wells, E.G. Bilpuch, and G.E. Mitchell, Phys. Lett. (to be published).