COMPETING STRUCTURES IN NUCLEI NEAR CLOSED SHELLS

Progress Report

September 1, 1995- July 10, 1996

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Preface

This report summarizes the progress made during the period September 1, 1995 through July 10, 1996 on Grant No. DOE-FG05-93ER40809.

The study of quadrupole-octupole coupled (QOC) states in ^{144}Nd has been continued. Firstly, the analysis of the experiment on weak transition intensities in ^{144}Nd , following the electron-capture decay of ^{144}Pm , has been completed and a manuscript submitted for publication. Secondly, an experiment to measure the lifetime of the 5^- and 4^- levels (using the GRID technique) at the Institut Laue Langevin (ILL) was performed in May 1996. Preliminary analysis of the data suggests that the experiment was successful in greatly reducing the error limits of the 5^- state lifetime and in obtaining a definite lifetime for the 4^- level.

Development of the fast electronic timing system has been continued. A new 'centroid difference' technique for analyzing data from the system has been developed. By eliminating the need to calibrate a 'prompt' position, this technique is capable of measuring lifetimes of only a few picoseconds. This new technique has been applied to data taken both in the lab. at TTU and on-line in a thermal neutron capture experiment.

The secretarial and accounting duties for this grant have been performed by Ms. Gloria Julian of the TTU Physics Department, and her efforts are greatly appreciated.

1. GRID lifetime measurements in ^{144}Nd

collaboration with C. Doll, H. Börner (Institut Laue Langevin), M. Harder (University of Brighton) and A. Shadkam (TTU undergraduate).

One of the crucial pieces of evidence for quadrupole-octupole coupling in ^{144}Nd is the large $B(E3; 5_1^- \rightarrow 2_1^+)$ value of ~ 30 W.u. The large errors on this published value [1] were due to large uncertainties in both the lifetime of the 5^- level and the branching ratio for the relevant 1396 keV transition. With our remeasurement of this branching ratio [2] a new $B(E3; 5_1^- \rightarrow 2_1^+)$ value of 26_{-12}^{+15} W.u. was calculated. Unfortunately, this value allows no new insight into the structure of the 5^- state, but the uncertainty is now dominated by the error in the lifetime of the 2093 keV 5^- level.

An attempt to measure the lifetimes of the 4^- and 5^- levels in ^{144}Nd using the GRID technique at the Institut Laue Langevin (ILL) was made in June, 1995. Unfortunately, this experiment failed due to mechanical problems with the target support mechanism used for the GAMS crystal spectrometers at the ILL. Another proposal was submitted to the ILL for consideration, and 21 days of beam time were granted in May, 1996. This experiment was completed successfully and *preliminary* results are given below.

We have measured the Doppler broadened profile of the 778-keV branch from the 2093-keV level 21 times. The previously published value [1] for the lifetime of this level was $1.2_{-0.4}^{+1.1}$ ps. Initial analysis of our new data, based on the procedure outlined in Ref. 1, indicates a lifetime of $1.1_{-0.2}^{+0.3}$ ps. This translates to $B(E3; 5_1^- \rightarrow 2_1^+) = 29 \pm 7$ W.u. and $B(E2; 5_1^- \rightarrow 3_1^-) = 25 \pm 6$ W.u.

The preliminary result for the lifetime of the 2204 keV 4^- state is $\tau = 1.0_{-0.2}^{+0.4}$ ps. This, coupled with the measured mixing ratio of the relevant 694-keV transition [3] leads to $B(E2; 4_1^- \rightarrow 3_1^-) < 1$ W.u., which is not consistent with the 4^- state being of a quadrupole-octupole coupled nature. Since there is only one measurement of this mixing-ratio we intend to try and measure this again, by performing angular correlations in the lab. at TTU, using a ^{144}Pm source.

In addition to these two results we have also measured Doppler profiles for the 1909 keV transition from the 3_2^- state at 2605 keV and the 864 keV transition from the 3_1^+ state at 2179 keV. Both of these lines show broadening and so should produce finite lifetimes, but a detailed analysis has yet to be performed.

[1] S. J. Robinson *et al.*, Phys. Rev. Lett., 73 (1994) 412.

[2] S. J. Robinson *et al.*, to be published in Phys. Rev. C.

[3] M. Behar *et al.*, Nucl. Phys. A219 (1974) 516.

2. Fast timing system development

collaboration with P. Miocinovic and B. Faircloth (TTU undergraduates)

As senior lab. projects Predrag Miocinovic and Brian Faircloth performed the final detailed tests on the BaF₂ - BaF₂ timing system. Using a ⁶⁰Co source they optimized the energy dependent 'walk' behavior of each branch of the system by carefully adjusting the slewing compensation on the ORTEC 9307 pico-TIMING Discriminators.

Next, the system was tested using a ¹³³Ba source and level lifetimes were measured in ¹³³Cs. Using standard slope analysis and convolution techniques the lifetimes of the 161 keV and 81 keV levels were extracted from the BaF₂ - BaF₂ coincidence data. The results, shown in Table 1, are in good agreement with the accepted values [1].

Table 1. Comparison of measured and accepted lifetimes for levels in ¹³³Cs.

Coincidence	Level	τ (measured)	τ (accepted) ^a
356 keV - 81 keV and 303 keV - 81 keV	81 keV	9015 ± 90 ps	9050 ± 30 ps
276 keV - 80 keV	161 keV	281 ± 38 ps	274 ± 22 ps

^aTaken from reference [1]

Next, the system was tested in the picosecond range, using a ¹⁴⁴Pm source to measure lifetimes in ¹⁴⁴Nd. A preliminary experiment on the same source last year had already shown the feasibility of such measurements, but for this data we applied our newly developed centroid difference analysis technique (see below). The remarkable results achieved in this experiment, shown in Table 2, indicate that electronic timing is capable of measuring lifetimes of only a few picoseconds.

Table 2. Comparison of measured and accepted lifetimes for levels in ¹⁴⁴Nd.

Coincidence	Level	τ (measured)	τ (accepted) ^a
618 keV - 696 keV	696 keV (2 ⁺)	4.8 ± 1.2 ps	4.6 ± 0.1 ps
476 keV - 618 keV	1314 keV (4 ⁺)	8.4 ± 1.5 ps	9.7 ± 0.7 ps
476 keV - 696 keV	696 keV + 1314 keV	11.7 ± 1.5 ps	14.3 ± 0.8 ps

^aAccepted values taken from an average of results derived from refs. [2-5]

It should be noted that the present results have been derived from the simple BaF₂ - BaF₂ double coincidence timing system. Because of the poor energy resolution of the BaF₂ detectors the energy gates on the 476 keV peak also include significant contributions from the Compton background of the 696 keV or 618 keV peaks (depending on the gating). This effect

will tend to produce results for the relevant level lifetimes slightly shorter than the true values. We have now added a Ge detector to the system and are currently recording BaF₂ - BaF₂ - Ge triple coincidences. By gating on transitions in the Ge detector we should be able to eliminate such Compton contributions. Using this technique we will attempt to measure the lifetime of the 1796 keV (6⁺) level in ¹⁴⁴Nd, which is, at present, unknown. We will also apply this technique to the ¹³³Ba source to see if we can measure the lifetime of the 384 keV level, which has an accepted value of ~20 ps.

Last summer (1995) we also shipped the components of the TTU lifetime system to the ILL to test the system for use in neutron capture experiments. The system was set up at the end of a thermal neutron guide and double and triple coincidences were recorded for both the ¹⁴³Nd(n,γ)¹⁴⁴Nd and ³⁵Cl(n,γ)³⁶Cl reactions. The results of this test were disappointing in terms of new lifetime data, but we have learned what will be needed to perform such experiments in the future. It is evident that at least (BaF₂ - BaF₂ - Ge) triple coincidences will be needed to compensate for the poor energy resolution of the BaF₂ detectors. In addition we will need to design a special target chamber to maximize the detector solid angles and, since the limiting factor seems to be the singles count rate in the Ge detector, we will probably need to incorporate more than one Ge detector into the system. On the positive side, we have established that the resolution of the timing system did not degrade significantly under the higher count rate conditions and that, with the appropriate modifications, the technique is feasible. We are currently investigating setting up a regular collaboration with the University of Brighton to study picosecond lifetimes in nuclei accessible by neutron capture.

- [1] R. B. Firestone and V. S. Shirley, Table of Isotopes 8th Ed., (Wiley - Interscience, 1996)
- [2] J. K. Tuli, Nucl. Data Sheets **56** (1989) 607.
- [3] C. Fahlender *et al.*, Inst. Phys. Conf Ser. **49** (1980) 291.
- [4] P. D. Cottle *et al.*, Phys. Rev. C **43** (1991) 59.
- [5] M. Pignanelli *et al.*, Nucl. Phys. **A559** (1993) 1.

3. The Centroid Difference Technique

3.1 Introduction

Electronic timing is a standard technique which can be used to measure nuclear level lifetimes. In its basic form it simply uses two detectors to start and stop a timing circuit when coincident gamma-rays (or other radiations) feeding and depopulating a level of interest are detected. In the case of a long-lived state (compared to the time resolution of the system) the exponential decay pattern can be observed directly in the time spectrum. For shorter lifetimes the centroid shift method is used. In this method the position of the centroid of the relevant time spectrum is compared to a 'prompt' position which represents the centroid of a timing distribution for a state with an infinitesimally short lifetime.

One of the major problems in the standard centroid shift technique is the determination of the 'prompt' position and its dependence on the energy detected. This latter effect is often called 'walk' and depends on two factors; i) the varying penetration depth of different energies into the detector and ii) the varying response of the electronic circuitry to different pulse heights. Such effects can be calibrated using suspected 'prompt' transitions in the source being studied but this can lead to complications if there are contributions from 'delayed' transitions in the Compton background. In such cases a primary calibration of the walk function can be performed with a source which has a simple decay pattern that is known to be 'prompt', such as ^{24}Na . However, the speed of light (0.3 mm/ps) means that on the picosecond scale the exact position of the 'prompt' curve is extremely sensitive to details of source and detector geometry. Because of this the primary calibration is used only to determine the shape of the walk curve, and the fixing of its absolute position must be done on a case-by-case basis.

The combination of these effects means that, even in the very best case, the position of the 'prompt' distribution can only be fixed to a precision of about 10 ps. This limits the effective usefulness of the standard centroid shift method to lifetimes above ~15 ps [1,2].

3.2 Centroid Difference Technique

However, with the recently established TTU timing system, a new variation of the centroid shift method has been developed which eliminates the need to determine a 'prompt' position. This centroid difference method employs both 'forward' and 'reverse' gating of gamma cascades to generate two timing spectra which can be analyzed as follows.

Consider a simple two-gamma cascade whose intermediate level lifetime (τ) is to be determined, as shown in Fig 1. Now suppose these two gammas are detected by the two detectors comprising a fast-timing system. In particular, suppose γ_1 enters the 'Start' detector and γ_2 enters the 'Stop' detector. (See Fig. 2.)

Fig 1. A simple two-gamma cascade.

Fig. 2. A simple two-gamma coincidence circuit.

Now, if we consider a large number of cases then the average time elapsed between the emission of γ_1 and the arrival of the corresponding signal at the start side of the time-to-amplitude converter (TAC) can be broken down into three parts:

$$T_1^{START} = t_{TOF,1}^{START} + t_{TRANS,1}^{START} + t_{ELEC,1}^{START} \quad (1)$$

where

$t_{TOF,1}^{START}$ is the average time of flight for γ_1 to reach the front face of the start detector.

$t_{TRANS,1}^{START}$ is the average transit time elapsed between when γ_1 penetrates into the detector and when the fluorescence photons strike the photocathode of the photomultiplier. This term includes the average fluorescence time of the scintillator material.

$t_{ELEC,1}^{START}$ is the average time it takes for the detector and subsequent electronics to process the resulting signal.

Similarly, we can write the average time elapsed between the emission of γ_1 and the arrival of the γ_2 signal at the stop side of the time-to-amplitude converter (TAC) as

$$T_2^{STOP} = t_{TOF,2}^{STOP} + t_{TRANS,2}^{STOP} + t_{ELEC,2}^{STOP} + t_{DELAY} + \tau \quad (2)$$

where the first three terms correspond to those given above and

t_{DELAY} is the extra time taken for the signal to pass through the cable delay

τ is the mean life of the intermediate state.

The TAC records the difference between these two times which is

$$T_{12} = T_2^{STOP} - T_1^{START} = t_{TOF,2}^{STOP} + t_{TRANS,2}^{STOP} + t_{ELEC,2}^{STOP} + t_{DELAY} + \tau - t_{TOF,1}^{START} - t_{TRANS,1}^{START} - t_{ELEC,1}^{START} \quad (3)$$

Notice that the position of the 'prompt' distribution would be given by a similar expression, with $\tau = 0$.

Now consider the reversed situation where γ_2 enters the start detector and γ_1 the stop detector. The TAC will now record the time difference

$$T_{21} = T_1^{STOP} - T_2^{START} = t_{TOF,1}^{STOP} + t_{TRANS,1}^{STOP} + t_{ELEC,1}^{STOP} + t_{DELAY} - \tau - t_{TOF,2}^{START} - t_{TRANS,2}^{START} - t_{ELEC,2}^{START} \quad (4)$$

Now the difference between the centroids of these two TAC positions is given by

$$\begin{aligned} T_{12-21} &= T_{12} - T_{21} = (t_{TRANS,2}^{STOP} - t_{TRANS,1}^{STOP}) + (t_{TRANS,2}^{START} - t_{TRANS,1}^{START}) + (t_{ELEC,2}^{STOP} - t_{ELEC,1}^{STOP}) + (t_{ELEC,2}^{START} - t_{ELEC,1}^{START}) + 2\tau \\ &= \Delta t_{TRANS,21}^{STOP} + \Delta t_{TRANS,21}^{START} + \Delta t_{ELEC,21}^{STOP} + \Delta t_{ELEC,21}^{START} + 2\tau \end{aligned} \quad (5)$$

Notice that because the time-of-flight terms have canceled out, this centroid difference is independent of the source/detector geometry. The remaining terms have been grouped such that they represent *differences* in average transit time or circuit response. If the two detectors used are of the same material and dimensions then the average transit time difference is the same in both and we can further simplify this expression to

$$T_{12-21} = 2\Delta t_{TRANS,21} + \Delta t_{ELEC,21}^{STOP} + \Delta t_{ELEC,21}^{START} + 2\tau \quad (6)$$

Determination of Transit Terms

The transit terms in Eqs. 3 and 4 contain three contributions

- i) the average penetration time of the gamma-ray into the detector before interaction. This can be calculated using known absorption coefficients.
- ii) the fluorescence time of the scintillator material. This contribution cancels out in the transit difference terms in Eqs. 5 and 6, assuming that the fluorescence time is independent of the gamma-ray energy.
- iii) the average time of flight of the fluorescence photons through the scintillator to the photocathode. Since these are the photons used to determine the timing signal we will assume the relevant ones are those which travel directly to the photocathode without reflecting inside the crystal. The time can then be calculated using the known length of the crystal, the average interaction depth, and the speed of UV photons in the scintillator material.

Determination of Walk Differences

Since the 'walk' difference terms appear separately for each detector in Eqn. (6) they can be determined independently and then applied as separate corrections. To do this coincidences have been recorded, using the fast-timing system, from a ^{60}Co source which has a simple two-gamma cascade (1173 keV - 1332 keV). By gating on the 1332-keV transition in one detector we produce an energy spectrum in the other detector consisting of the 1173-keV full-energy peak and its associated Compton distribution at lower energies. It should be realized at this stage that all of these Compton events were produced by the penetration of an 1173-keV gamma-ray into the same detector, so that all events have the *same* average penetration depth and average time-of-flight, and the only difference between different regions of the energy spectrum is in the *detected* energy. Thus, if gates are set on regions representing the energies of interest the difference in the centroids of the corresponding timing distributions will give a direct measure of the 'walk' difference, $\Delta t_{\text{ELEC},21}$, of the corresponding detector. In practice this is done by creating a matrix of 'time' versus 'energy' for the desired detector, while gating on the 1332 keV transition in the other detector. Notice that the lifetime of the intermediate state in ^{60}Co (~1 ps) does not play a role here since it will contribute the *same offset* to both timing distributions but the difference between them will remain the same.

3.3 Example in ^{144}Nd

To illustrate how this analysis technique is applied a detailed example of how the lifetime of the 697 keV level in ^{144}Nd was extracted from 618-697 keV coincidences is now given.

Fig. 3 shows the raw gamma-gamma energy coincidence matrix from a ^{144}Pm source, recorded with the BaF_2 - BaF_2 timing system. Also shown are the 2D-gates used to select 618-697 keV and 697-618 keV coincidences. Timing (TAC) spectra were extracted from events lying in these gates.

Fig. 3. Gamma-gamma energy coincidence matrix for a ^{144}Pm source.

The centroid difference of these two raw TAC spectra was determined to be

$$T_{12-21} = 21.0 \pm 0.6 \text{ ps}$$

The average penetration depths of 618 keV and 697 keV gamma rays into a 1.3 cm BaF₂ crystal are 0.572 cm and 0.578 cm respectively. These lead to a transit time difference of

$$\Delta t_{TRANS,21} = 0.1 ps$$

The error in this value is too small to contribute to the total error budget and so it is ignored.

The walk difference terms were determined with a ⁶⁰Co source to be

$$\Delta t_{ELEC,21}^{STOP} = 13.8 \pm 1.8 ps$$

$$\Delta t_{ELEC,21}^{START} = -2.8 \pm 1.4 ps$$

where the quoted errors are mainly statistical.

Combining all of these values leads to

$$2\tau = 9.8 \pm 2.3 ps$$

and hence

$$\tau = 4.9 \pm 1.2 ps,$$

which agrees well with the accepted value of 4.6 ± 0.1 ps, derived from Coulomb excitation experiments.

- [1] H. Mach, R. L. Gill and M. Moszynski, Nucl. Inst. Meth. A **280** (1989) 49.
- [2] M. Moszynski and H. Mach, Nucl Inst. Meth A **277** (1989) 407.

Appendix I : Personnel

FACULTY

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TTU UNDERGRADUATES

Predrag Miocinovic

Senior lab. project, Spring 1996

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Appendix II: Publications and Preprints

PUBLISHED ARTICLES

"Absolute Intensity of Internal Bremsstrahlung from the EC decay of ^{125}P "

M. M. Hindi, R. L. Kozub and S. J. Robinson, Phys. Rev. C. 52 (1995) 2780.

IN PRESS

"Weak gamma-transition intensities in the electron capture decay of ^{144}Pm "

S. J. Robinson, A. S. Altgilbers, M. M. Hindi, E. B. Norman and R. -M. Larimer, accepted for publication in Phys. Rev. C.

SUBMITTED

"Study of the phonon creation process in solids using neutrino induced Doppler broadening"

J. Jolie, N. Stritt, H. G. Börner, C. Doll, M. Jentschel, S. J. Robinson and E. G. Kessler

PUBLISHED ABSTRACTS

"Determination of Weak Transition Intensities in ^{144}Nd "

S. J. Robinson, A. Altgilbers, M. M. Hindi, E. B. Norman and R. -M. Larimer. APS Nuclear Division Meeting, Bloomington, Indiana, October, 1995.