COMPETING STRUCTURES IN NUCLEI NEAR CLOSED SHELLS

Final Report

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CONTENTS

Preface

This report summarizes the progress made during the period September
November, 1996 on Grant No. DOE-FG05-93ER40809. It should be noted tha
project was renewed and funded under Grant No. DOE-FG02-97ER41024, which c
in January, 1997, and continues.

A series of experiments on levels in ^{144}Nd have led to the identification of q
octupole coupled (QOC) states in this nucleus. These experiments included C
lifetime measurements at the Institut Laue Langevin in Grenoble, France.
measurement of weak transition intensities in the lab. at Tennessee Tech. University

A fast electronic timing system for the measurement of level lifetim
picosecond range has been set up at Tennessee Tech University, and a new centroid
technique has been developed. By eliminating the need to calibrate a 'prompt' pos
technique is capable of measuring lifetimes of only a few picoseconds.

The secretarial and accounting duties for this grant were performed by M
Julian of the TTU Physics Department, and her efforts are greatly appreciated.

1. Quadrupole-octupole coupled states in ^{144}Nd

collaboration with:

Institut Laue Langevin, France

Univ. of Göttingen, Germany

University of Fribourg, Switzerland

University of Brighton, England

Lawrence Berkeley National Lab., US

Enhanced (several 10's of W.u.) E2 and E3 transitions from the lowest lying 2^+ and 3^- states to the 0^+ ground state in such even-even nuclei near closed shells attest to the existence of single phonon (quadrupole and octupole) vibrational excitations. It has long been realized that the coupling of these quadrupole and octupole excitations will give rise to a quintuplet of negative parity states (1^- - 5^-) with characteristic E2 and E3 decay patterns [1,2] but identification of such states had been based only on enhanced E1 transitions ($\approx 10^{-3}$ W.u.) [3]. Such evidence is less direct since it relies on two body terms in the E1 transition operator [4] but, none-the-less, had indicated that the N=82, 83 and 84 nuclei is a good region to study such excitations.

An extensive experimental study of the N=84 nucleus ^{144}Nd has been carried out, using the (n,γ) reaction and via the electron capture decay of ^{144}Pm. This study included the measurement of excited level lifetimes using the GRID technique [5], the measurement of transition conversion coefficients (both at the Institut Laue Langevin in Grenoble, France) and the measurement of weak transition intensities (at Tennessee Tech. University. The most significant results concern the lifetimes of negative parity states in this nucleus and the identification of enhanced E2 and E3 transitions to identify four members of the quadrupole-octupole coupled (QOC) quintet of states.

1.1 GRID lifetime measurements

The GRID technique [5] relies on the ultra-high resolution of the GAMS4 spectrometer at the Institut Laue Langevin (ILL) to observe the gamma-ray induced Doppler

broadening produced in secondary transitions following thermal neutron capture. Three separate GRID experiments were performed to determine level lifetimes in ^{144}Nd.

In the first experiment, the lifetimes of many states of both positive and negative parity were determined, and it was primarily this data which led to the initial identification of the 5$^-$ and 1$^-$ members of the QOC multiplet [6]. One of the crucial pieces of evidence in this identification was the large $B(E3;5_1^- \rightarrow 2_1^+)$ value of ~30 W.u. However, the large errors on this measured value [6] 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 re-measurement of this branching ratio [7] a new $B(E3;5_1^- \rightarrow 2_1^+)$ value of 26_{-12}^{+15} W.u. was calculated. Unfortunately, this value allowed no new insight into the structure of the 5$^-$ state, but the uncertainty was then dominated by the error in the lifetime of the 2093 keV 5$^-$ level.

An attempt to re-measure the lifetime of the 5$^-$ level, and make the first measurement of the newly proposed 4$^-$ level, using the GRID technique at the 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 during which time the experiment was completed successfully.

To reduce the error on the lifetime of the 2093-keV 5$^-$ level, the Doppler broadened profile of the 778-keV branch from the 2093-keV level 21 times. The result translates to $B(E3;5_1^- \rightarrow 2_1^+) = 29\pm7$ W.u. and $B(E2;5_1^- \rightarrow 3_1^-) = 25 \pm 6$ W.u., which indicate that the dominant component in the wave-function of this state is of a QOC nature.

TABLE 1.1. Lifetimes of negative parity levels in ^{144}Nd extracted from GRID data. The figures in parentheses give the uncertainties in the least significant digits for each result.

E_x (keV)	$J\pi$	E_γ (keV)	$\tau_{extreme}$ (ps)	τ_{stat} (ps)	τ_{lit}[a] (ps)
2093	5-	778	$0.7 < \tau < 2.2$	1.1 (+3, -2)	1.2 (+11, -4)
2204	4-	694	$0.7 < \tau < 1.5$	1.0 (+4, -2)	
2605	3-	1909	$0.01 < \tau < 0.45$	0.20 (+8, -5)	

[a] Ref. [1].

The result for the lifetime of the 2204 keV 4⁻ state, coupled with the measured mixing ratio of the relevant 694-keV transition [8] gave $B(E2; 4_1^- \rightarrow 3_1^-)$ < 1 W.u., which is not consistent with the 4⁻ state being of a quadrupole-octupole coupled nature. Since there was only one measurement of this mixing-ratio we have since measured this again, by performing angular correlations in ^{144}Nd, using a ^{144}Pm source. This experiment was performed under Grant No. DOE-FG02-97ER41024 (which commenced in January, 1997) and is not discussed here. The results of the lifetime experiments discussed above have been incorporated into a later paper, together with the angular correlation results.

1.2 Uncertainties in the analysis of GRID data

In heavy nuclei, the extraction of lifetime results from the GRID data is non trivial, since many factors must be taken into account, such as:

- i) Unresolved cascade feeding of the states in question.
- ii) Slowing down process in complex target (Nd_2O_3).

These factors have been studied in detail in the analysis of the ^{144}Nd GRID data.

The first problem can be overcome by calculating the cascade feeding using a statistical model of the nuclear level density and transition strengths. To check the possible influence of random variations (Porter Thomas fluctuations) in the cascade feeding calculations, ten different feeding calculations were made for each of nine levels for which GRID data has been obtained. It was found that in all cases the systematic variation from the

different feeding calculations is less than the statistical error in the measurement. However, it is apparent that any improvement in the statistical error in future measurements will demand a more thorough investigation of the effects of Porter Thomas fluctuations in the statistical feeding calculations.

In the Mean Free Path Approximation (MFPA) for the analysis of GRID data [5] the slowing down process is approximated by a succession of binary collisions of the recoiling atom (Nd) with other atoms in the target material (Nd or O). It is evident that the energy lost by the recoiling atom will depend on the partner in each collision and hence the overall velocity profile will depend of the collision sequence. Since this will then affect the lifetime extracted from the measured data, a study has also been made of the effect of different collision sequences on two of the extracted lifetimes. It was found that collision sequences which preserve the stochiometric composition of the target material (Nd_2O_3) produce essentially the same results for the longer living levels since, over the (relatively) long slowing down process the variations average out. In the case of short lived levels, where all decays take place within the first few collisions, the extracted lifetime is sensitive to the ordering of the sequence. Again, these results do not significantly affect the current work on Nd (due to the larger statistical errors involved), but show that such aspects must be included in any analysis of more precise data.

1.3 Weak Transition Intensities in [144]Nd

One of the crucial pieces of evidence for quadrupole-octupole coupling in [144]Nd was the large $B(E3; 5_1^- \rightarrow 2_1^+)$ value of ~32 W.u [6]. One of the large contributions to this error came from the branching ratio for the relevant 1396 keV transition. We therefore re-measured the intensity of this very weak branch in the laboratory at TTU following the electron-capture decay of a [144]Pm source. The source was manufactured at Lawrence Berkeley Lab. using the [141]Pr(α,n) reaction.

Gamma rays from the source were counted for a period of several weeks using a 20% Ge detector with a resolution of ~4 keV at 1332 keV. To reduce the effects of coincidence summing and random pile-up in the region around 1400 keV an absorber of 3.8 cm of lead was placed between the source and the detector. Corrections were also made for known background lines in the spectrum. From our measurements we were able to deduce an absolute

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intensity of $(4.9 \pm 0.7) \times 10^{-4}\%$ for the 1396 keV transition, which is consistent with the only previous measurement [9] of $(6 \pm 2) \times 10^{-4}\%$, but the error has been reduced from 33% to 13%. In addition, we were able to extract an absolute intensity of $(2.0 \pm 1.5) \times 10^{-4}\%$ (previously quoted as $< 7 \times 10^{-4}\%$) for the 1508 keV (4^- to 2^+) transition and we have also identified a weak electron-capture decay branch ($4.3 \times 10^{-3}\%$) to the previously established 2^+ level at 2109 keV. The final results of this measurement were published in Ref. [7].

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2. Fast Electronic Timing System

A fast electronic timing system has been set-up in the research laboratory at Tennessee Tech. This system, which uses completely 'off-the-shelf' components, has a timing resolution of under 200 ps and can be used to measure nuclear excited state lifetimes in the range from 5 ps upward. To measure lifetimes in the ps range a new data analysis technique has been developed, which eliminated many of the systematic errors inherent in standard electronic timing measurements.

2.1 The timing system and its performance

The initial system consisted of two complete photomultiplier assemblies, purchased from Hamamatsu Corp. These assemblies are based on the R4998 1" diameter phototube, which has superior timing characteristics. One assembly (H5023) was coupled to a small (1 cm diameter, 2mm thickness) plastic scintillator with a fast decay time (BC422Q), and used to detect β-particles and conversion electrons. The other assembly (H5321) has a quartz window and was coupled to a small, truncated, BaF_2 cone. Both assemblies were connected directly to ORTEC 9307 pico-TIMING Discriminators.

The rise time of the output pulses from the BaF_2 detector assembly has been measured using two leading edge timing modules set at 10% and 90% of the observed pulse height for various gamma-ray energies. Results of these measurements indicate that, within errors, the *average* rise time is independent of gamma energy between 80 keV and 1.3 MeV. In fact, the average rise time over this energy range (0.82 ns) is a factor of three faster than that observed using a Phillips XP2020Q photomultiplier coupled to a similar BaF_2 crystal [1] in a timing system set up at Oak Ridge National Lab. An output pulse rise time of less than 1 ns has also been observed (using a fast oscilloscope) for the plastic scintillator/H5023 photomultiplier assembly, but since the BC422Q has no energy resolution, no energy dependence of the rise time could be measured. The ratio of fast to slow light components in the prompt signal from the BaF_2 detector has been measured as approximately 25:1. The walk characteristics and timing resolution of this system have been studied using a ^{60}Co source. Both the walk and

resolution are about the same as that observed in the ORNL timing system [1], but considerably worse than that obtained at TRISTAN [2].

One aspect which this timing system was set up to study directly is the use of low energy gammas and X-rays for fast timing. The initial step in this study was to measure the time resolution between conversion electrons (detected in the plastic scintillator) and X-rays (31 keV) from the highly converted 662 keV transition in the decay of ^{137}Cs. A resolution of 480 ps was obtained for this system, which compares very favorably with the 630 ps obtained using the ORNL system [1], when operated in a β-X(81 keV) mode.

A third photomultiplier assembly (H5321) was purchased in 1995 and also coupled to a small truncated BaF$_2$ cone. This assembly (together with the one purchased in 1994) was used to conduct tests of a BaF$_2$ - BaF$_2$ timing system, also using ORTEC 9307 pico-TIMING Discriminators. The walk characteristics and timing resolution of this system were studied using a ^{60}Co source, and by limiting the peak amplitude of the pulses fed to the timing discriminators to ≤1.5 V we were able to reduce the walk to ±25 ps in the energy range from 300 to 1200 keV. This is a factor of two smaller than that obtained previously and is almost the same as the best reported for the Brookhaven fast-timing system [1]. The timing resolution between the 1173 keV and 1332 keV full energy peaks was consistently measured at around 180 ps., which is only slightly better than that obtained previously and still considerably worse than the Brookhaven system [1]. However, it should be noted that the TTU system is essentially "off-the-shelf" with no alterations having been made to any components and that this resolution was reproducible.

The event data gathered during these tests were recorded using a new acquisition system based on a Pentium PC computer, coupled to a CAMC mini-crate. This acquisition system is based on one already set up at TTU by Dr. Munther Hindi and has performed perfectly to date. By installing a Linux operating system on the machine we have also been able to use it for data analysis using the Oak Ridge program package.

In 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

^{143}Nd(n,γ)^{144}Nd and ^{35}Cl(n,γ)^{36}Cl 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 (BaF$_2$ - BaF$_2$ - Ge) triple coincidences will be needed to compensate for the poor energy resolution of the BaF$_2$ detectors. In addition a special target chamber will be needed 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

2.2. Level lifetime measurements

After optimizing the energy dependent 'walk' behavior of each branch of the timing system, it was first tested using a ^{133}Ba source to measure level lifetimes in ^{133}Cs. Using standard slope analysis and convolution techniques the lifetimes of the 161 keV and 81 keV levels were extracted from the BaF$_2$ - BaF$_2$ coincidence data. The results, shown in Table 2.1, are in good agreement with the accepted values [3].

Table 2.1. Comparison of measured and accepted lifetimes for levels in ^{133}Cs.

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

[a]Taken from reference [3]

Next, the system was tested in the picosecond range, using a ^{144}Pm source to measure lifetimes in ^{144}Nd. A preliminary experiment on the same source had already shown the feasibility of such measurements, but for this data we applied our newly developed centroid difference analysis technique (see Section 3). The remarkable results achieved in this

experiment, shown in Table 2.2, indicate that electronic timing is capable of measuring lifetimes of only a few picoseconds.

Table 2.2. Comparison of measured and accepted lifetimes for levels in ^{144}Nd.

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

[a]Accepted values taken from an average of results derived from refs. [4-7]

It should be noted that these results were derived from the simple BaF_2 - BaF_2 double coincidence timing system. Because of the poor energy resolution of the BaF_2 detectors the energy gates on the 476 keV peak also included 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 since added a Ge detector to the system and recorded BaF_2 - BaF_2 - Ge triple coincidences. By gating on transitions in the Ge detector we were able to eliminate such Compton contributions.

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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 Basis of the Technique

We have developed a new variation of the centroid shift method has been developed which eliminates the need to determine a 'prompt' position. This centroid difference method

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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 3.1. A simple two-gamma cascade.
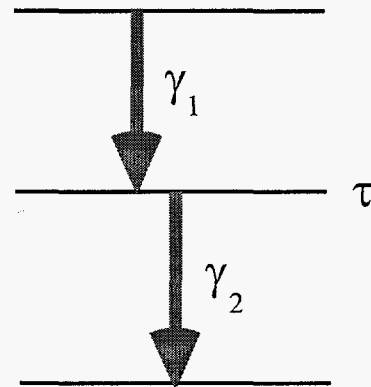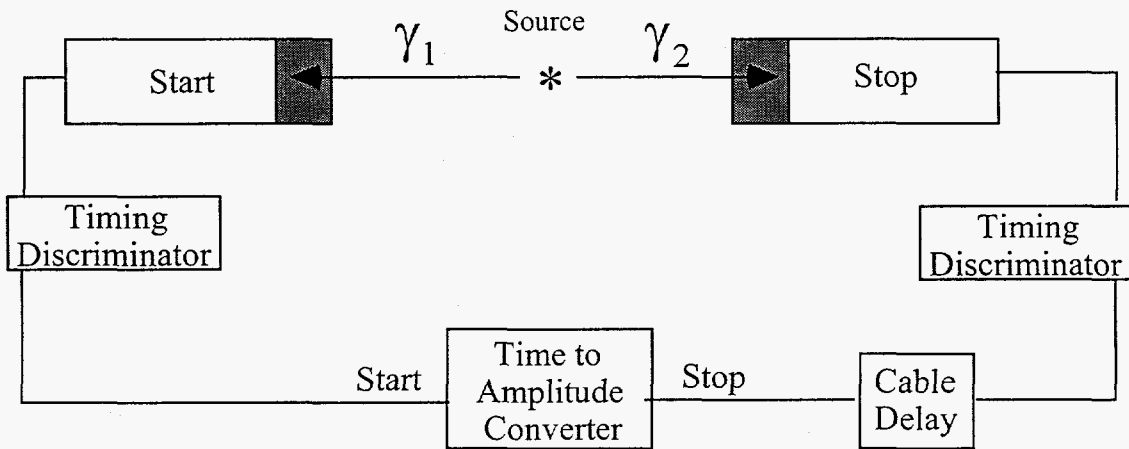

Fig. 3.2. A simple two-gamma coincidence circuit.

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:

$$T_1^{START} = t_{TOF,1}^{START} + t_{TRANS,1}^{START} + t_{ELEC,1}^{START} \tag{3.1}$$

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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

$$T_2^{STOP} = t_{TOF,2}^{STOP} + t_{TRANS,2}^{STOP} + t_{ELEC,2}^{STOP} + t_{DELAY} + \tau \tag{3.2}$$

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

$$T_{12} = T_2^{STOP} - T_1^{START} = t_{TOF,2}^{STOP} + t_{TRANS,2}^{STOP} + t_{ELEC,2}^{STOP} + t_{DELAY} + \tau - t_{TOF,1}^{START} - t_{TRANS,1}^{START} - t_{ELEC,1}^{START} \tag{3.3}$$

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

$$T_{21} = T_1^{STOP} - T_2^{START} = t_{TOF,1}^{STOP} + t_{TRANS,1}^{STOP} + t_{ELEC,1}^{STOP} + t_{DELAY} - \tau - t_{TOF,2}^{START} - t_{TRANS,2}^{START} - t_{ELEC,2}^{START} \tag{3.4}$$

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

$$T_{12-21} = T_{12} - T_{21} = (t_{TRANS,2}^{STOP} - t_{TRANS,1}^{STOP}) + (t_{TRANS,2}^{START} - t_{TRANS,1}^{START}) + (t_{ELEC,2}^{STOP} - t_{ELEC,1}^{STOP}) + (t_{ELEC,2}^{START} - t_{ELEC,1}^{START}) + 2\tau$$

$$= \Delta t_{TRANS,21}^{STOP} + \Delta t_{TRANS,21}^{START} + \Delta t_{ELEC,21}^{STOP} + \Delta t_{ELEC,21}^{START} + 2\tau \tag{3.5}$$

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 simply this expression to

$$T_{12-21} = 2\Delta t_{TRANS,21} + \Delta t_{ELEC,21}^{STOP} + \Delta t_{ELEC,21}^{START} + 2\tau \tag{3.6}$$

3.3 Determination of Transit Terms

The transit terms in Eqs. 3.3 and 3.4 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. 3.5 and 3.6, 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.

3.4 Determination of Walk Differences

Since the 'walk' difference terms appear separately for each detector in Eqn. (3.6) 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, $\Delta t_{ELEC,21}$, 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

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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.

3.5 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.
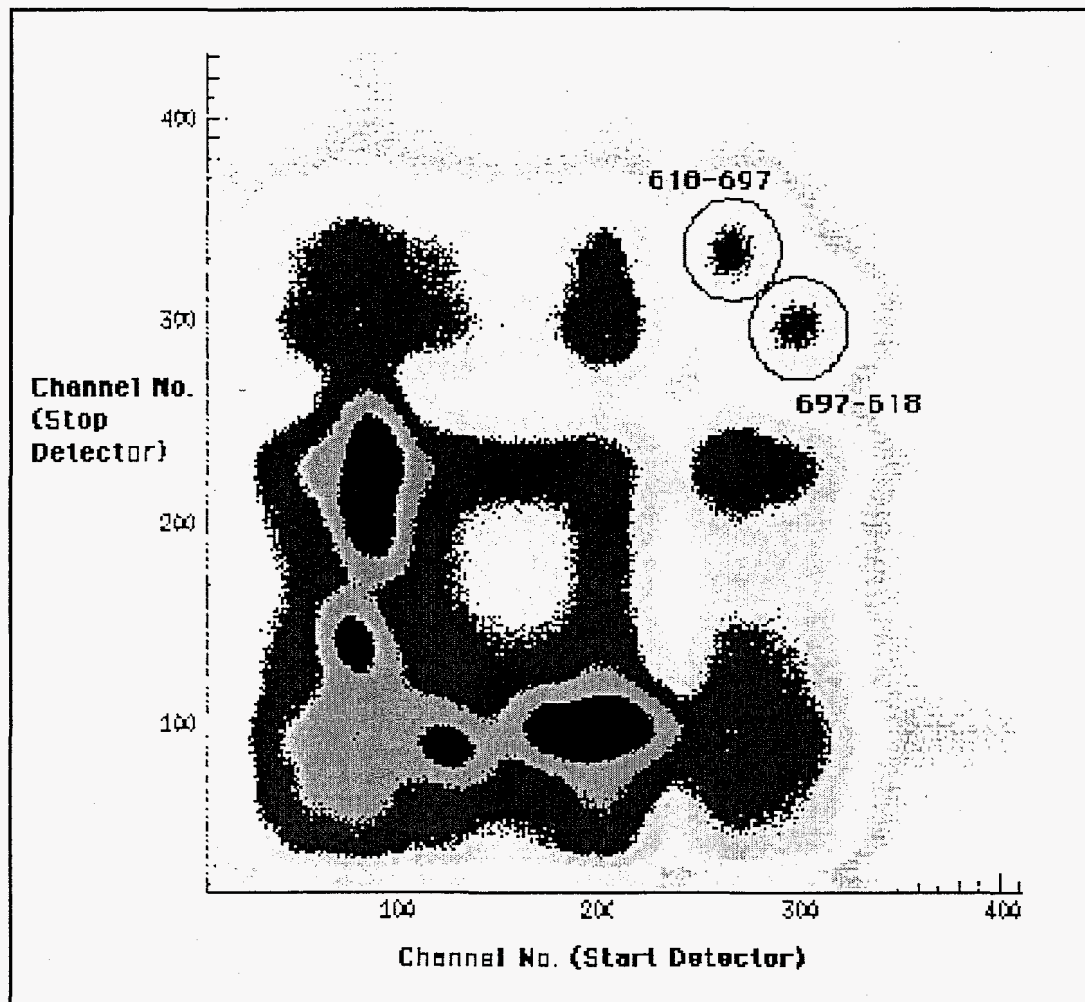

Fig. 3.3. Gamma-gamma energy coincidence matrix for a ^{144}Pm source.

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

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

The average penetration depths of 618 keV and 697 keV gamma rays into a 1.3 cm BaF_2 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 to small to contribute to the total error budget and so it is ignored.

The walk difference terms were determined with a ^{60}Co 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.

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4. Other work

4.1 Massive neutrino searches

Work on massive neutrino searches, begun before this grant was awarded (in collaboration with M. M. Hindi and R. L. Kozub of TTU) has continued. A search for a 17 keV neutrino branch in the IB spectrum of ^{125}I was concluded and published [1]. In addition the energy and velocity of recoiling ^{37}Cl ions were measured, following the EC decay of ^{37}Ar, at Montana State University [2].

4.2 Neutrino induced Doppler broadening

In a variation on the standard GRID technique, the Doppler broadening of gamma-rays emitted following electron capture decay can also be observed. These recoil velocities are due to neutrino emission and since the resulting velocities are extremely small, the recoiling atom loses its energy by phonon creation processes in the solid matrix, rather than two-body collisions. Thus these experiments can be used to study the phonon creation mechanism.

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5. Student involvement

Since the Tennessee Tech. Physics Dept. does not have a graduate program, undergraduate students are employed on research projects. During the three-year course of this award six undergraduate students have worked on various aspects of the project.

- In the summer of 1994, Erin Moore and Sarah Mitchell worked on some of the mechanical aspects of the fast timing system.
- In the summer of 1995, Alex Altgilbers participated in experiments at the ILL, was involved in the preliminary data analysis, and played a major part in an experiment to measure weak transition intensities in ^{144}Nd, including co-authorship of a conference contribution and the resulting publication [1,2].
- For their senior lab. projects, Brian Faircloth and Predrag Miocinovic worked on the final testing of the timing system, and the development of the centroid difference technique. They were co-authors of a conference presentation on the technique [3], and will be included as authors on a paper to be published.
- In the summer of 1996, Arbee Shadkam worked on the preliminary analysis of GRID data for lifetimes in ^{144}Nd.

Of these six students, four have gone on to graduate school at the University of Tennessee, Vanderbilt University, Washington University, and Berkeley.

References

[1] S. J. Robinson, A. Altgilbers, M. M. Hindi, E. B. Norman and R. -M. Larimer. Bull. Am. Phys. Soc. **40**, 1616 (1995).

[2] S. J. Robinson, A. S. Altgilbers, M. M. Hindi, E. B. Norman and R. -M. Larimer, Phys. Rev. C54 (1996) 1478.

[3] S. J. Robinson, P. Miocinovic, B. Faircloth, Bull. Am. Phys. Soc. **42**, 1662 (1997).

Appendix I : Personnel

FACULTY

Stephen J. Robinson

TTU UNDERGRADUATES

Erin A. Moore	Part time, Summer 1994
Sarah Mitchell	Part time, Summer 1994
Alex S. Altgilbers	Full time, Summer 1995
Predrag Miocinovic	Senior lab. project, Spring 1996
Brian Faircloth	Senior lab. project, Spring 1996
Arbee Shadkam	Employed full time, Summer 1996

COLLABORATORS

H. G. Börner	Institut Laue Langevin, Grenoble, France
J. Jolie	Institut Laue Langevin, Grenoble, France, and University of Fribourg, Fribourg, Switzerland
K. P. Lieb	University of Göttingen, Germany
E. F. Zganjar	Louisiana State University
P. K. Joshi	Louisiana State University
M. M. Hindi	Tennessee Technological University
R. L. Kozub	Tennessee Technological University
M. Harder	University of Brighton, Brighton, England
E. B. Norman	Lawrence Berkeley Lab., Berkeley, CA
R. -M. Larimer	Lawrence Berkeley Lab., Berkeley, CA
C. Doll	Institut Laue Langevin, Grenoble, France

Appendix II: Published articles

"E2 and E3 Transitions from Quadrupole-Octupole Coupled States in ^{144}Nd"
S. J. Robinson, J. Jolie, H. G. Börner, P. Schillebeeckx, S. Ulbig and K. P. Lieb, Phys. Rev. Lett. **73** (1994) 412.

"Search for a 17 keV neutrino in the internal bremsstrahlung spectrum of ^{125}I"
M. M. Hindi, R. L. Kozub and S. J. Robinson, Phys. Rev. C **49** (1994) 3289.

"Lifetimes of the $0^+{}_2$ Configuration in ^{186}Hg and ^{188}Hg"
P. K. Joshi, E. F. Zganjar, D. Rupnik, S. J. Robinson, P. F. Mantica, H. K. Carter, J. Kormicki, R. L. Gill, W. B. Walters, C. R. Bingham, A. V. Ramayya, W. C. Ma and J. H. Hamilton, Int. J. of Mod. Phys. E. **3** (1994) 757.

"Neutrino Recoil Induced Desorption"
L. Zhu, R Avci, G. J. Lapeyre, M. M. Hindi, R. L. Kozub and S. J. Robinson, J. Vac. Sci. Technol. A **12**(4) (1994) 2037.

"Absolute Intensity of Internal Bremsstrahlung from the EC decay of ^{125}I"
M. M. Hindi, R. L. Kozub and S. J. Robinson, Phys. Rev. C. 52 (1995) 2780.

"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, Phys. Rev. C54 (1996) 1478.

"The neutrino induced Doppler broadening technique and its application to the study of phonon creation in solids"
J. Jolie, N. Stritt, H. G. Börner, C. Doll, M. Jentschel, S. J. Robinson, E. G. Kessler, Z. Phys. B 102 (1997) 1.

Appendix III: Abstracts and conference contributions

"Neutrino Recoil Desorption and Internal Relaxation of ^{37}Cl following Electron Capture decay of ^{37}Ar"
R Avci, L. Zhu, G. J. Lapeyre, M. M. Hindi, R. L. Kozub and S. J. Robinson, Bull. Am. Phys. Soc. **39**, 780 (1994).

"The Auger Relaxation of ^{37}Cl following Electron Capture decay of ^{37}Ar"
L. Zhu, R Avci, G. J. Lapeyre, M. M. Hindi, R. L. Kozub and S. J. Robinson, 41st Nat. Symp. Am. Vac. Soc., Denver, Colorado, 318 (1994).

"Determination of Weak Transition Intensities in ^{144}Nd"
S. J. Robinson, A. Altgilbers, M. M. Hindi, E. B. Norman and R. -M. Larimer. Bull. Am. Phys. Soc. **40**, 1616 (1995).

"Cosmic-Ray Half-Life of ^{144}Pm"
E. B. Norman, Y. D. Chan, M. C. P. Isaac, R. -M. Larimer, A. O. Macchiavelli, R. W. Macleod, M. R. Dragowsky, K. S. Krane, K. Zaerpoor, D. E. Digregorio, M. M. Hindi, S. J. Robinson, P. Miocinovic, Bull. Am. Phys. Soc. **42**, 1655 (1997).

"Angular Correlations in ^{144}Nd using Gammasphere"
S. J. Robinson, M. M. Hindi, E. B. Norman, Y. D. Chan, M. C. P. Isaac, R. -M. Larimer, A. O. Macchiavelli, R. W. Macleod, M. R. Dragowsky, K. S. Krane, K. Zaerpoor, D. E. Digregorio, P. Miocinovic, Bull. Am. Phys. Soc. **42**, 1659 (1997).

"Centroid-difference technique for picosecond lifetime measurements"
S. J. Robinson, P. Miocinovic, B. Faircloth, Bull. Am. Phys. Soc. **42**, 1662 (1997).

"Quadrupole-octupole coupled states and the influence of the $(1i_{13/2})$ orbital"
S. J. Robinson, H. G. Börner, J. Jolie, P. Schillebeeckx, K. P. Lieb, and S. Ulbig, Int. Conf. On Nuclear Shapes and Nuclear Structure at Low Excitation Energies, Antibes, France, June 20-25, 1994.

"On the Cosmic-Ray Half-Life of ^{144}Pm"
Y. D. Chan, D. E. Digregorio, M. R. Dragowsky, M. M. Hindi, M. C. P. Isaac, K. S. Krane, R. -M. Larimer, A. O. Macchiavelli, R. W. Macleod, P. Miocinovic, E. B. Norman, S. J. Robinson, K. Zaerpoor, Proc. 25th Int. Cosmic Ray Conf, Durban, South Africa, July 28 – August 8, 1997.