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A NEW METHOD FOR PICOSECOND LIFETIME MEASUREMENTS USING ELECTRONIC TIMING: NUCLEAR STRUCTURE APPLICATIONS.

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ABSTRACT

A technique to measure the lifetimes of nuclear states with half lives <10 ps has been developed in conjunction with the TRISTAN mass separator at the High Flux Beam Reactor at BNL. The method uses fast plastic and BaF_2 scintillators and Ge detectors in a triple coincidence (β-γ-γ) fast-slow counting system. The timing information is derived from the fast plastic-BaF_2 coincidence, while the higher resolution of the Ge detector (in slow coincidence) serves to insure that the β-γ event lies in the cascade of interest. The calibrations and corrections necessary to achieve precise results and the methods of data reduction and results from recent measurements on the A=97 mass chain are presented.

INTRODUCTION

The measurement of absolute transition rates provides very sensitive tests of nuclear models. This is particularly so for collective transitions where the E2 transition strengths provide the key signatures to their character. Near stability, absolute B(E2) values are readily obtained via Coulomb excitation and inelastic scattering techniques. On the neutron deficient side of stability, many Doppler-based techniques are employed to measure nuclear lifetimes (τ), from which absolute B(E2) values are deduced. However, for neutron rich nuclei that are far from stability, whose production and separation methods preclude the easy adaptation of Doppler techniques, electronic timing techniques must be employed. Until recently, this has limited the regime of reliable measurements to those nuclear states with τ>100 ps. This paper presents a new technique that makes it possible to measure lifetimes, with high precision, in the regime of <10 ps and with improved reliability for lifetimes >40 ps.

TIMING TECHNIQUE

The timing technique was developed for use at the TRISTAN mass separator, which supplies ion beams of neutron-rich, far from stability nuclei. The reader is referred to technical publications[1,2] where the details of the technique are presented and to numerous application-oriented publications in the few-picosecond range[3,4] and in

the sub-nanosecond range[5,6]. These references are not intended be all inclusive, there are many other references, but those mentioned contain information that is germane to a discussion of the technique. The system employs a fast-slow coincidence counting system, with the β-γ timing information being derived from an NE111A plastic scintillator, coupled to an XP2020 photomultiplier, and a BaF_2 scintillator, coupled to an XP2020Q photomultiplier. The slower Ge detector provides a high resolution selection of a γ-ray in cascade with the desired β-γ event. Although this approach is rather standard, it employs a few novel features. First, is the use of a BaF_2 crystal (1.3 cm thick) which provides a fast signal[7] (especially when used with dynode timing[8]) as well as a moderate (~10%) energy resolution. Thus, in certain cases, the triple coincidence (with the Ge detector) is unnecessary and better statistics can be accumulated in shorter experiments. Secondly, a <u>thin</u> (3 mm) plastic scintillator is used. Since the β decay of far from stability nuclei usually involves high Q values, only a fraction of the total energy will be detected. The thickness of the scintillator was chosen so that an energy loss of about 600 keV (for $E_\beta \geq 1.5$ MeV) would be recorded, <u>independent</u> of the incident β energy. The importance of this feature is that it is no longer necessary to map the system response for ranges of both β and γ energies: only the γ response needs to be known. Thus, at least in principle, it is possible to calibrate the system over a wide dynamic energy range with a single calibration. Although other corrections which complicate this simple picture must be applied, it remains possible to measure lifetimes from many transitions in a single experiment. Not only does this reduce the measurement time, it also makes it possible to measure the same level lifetime via different, essentially independent, paths and provides for important internal consistency checks, as will be discussed later.

Figure 1 illustrates the timing apparatus. The ion beam is deposited onto an Al window which also serves to absorb β rays with energy below 1.5 MeV. The BaF_2 detector is covered with a Pb absorber to prevent betas from giving a signal in that detector. Two Ge detectors are positioned at 90° to the other detectors. A slit is provided for external positioning of a calibration source. When gates are set to select the desired β-γ-γ events, a semi-gaussian TAC peak with a

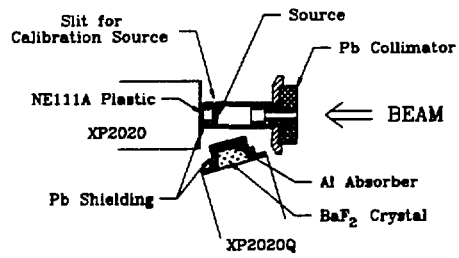

Fig. 1. Picosecond timing apparatus. The Ge detectors are not shown.

timing resolution (FWHM) of 96 ps for 1.3 MeV γ rays and 130 ps for 0.5 MeV γ rays can be achieved for prompt transitions. For $\tau \geq 200$ ps, an exponential fit to the delayed side of the TAC spectrum yields the half life. For $\tau \geq 40$ ps, the half life is deconvoluted from the TAC spectrum using an approximation to a prompt shape and an exponential tail. Neither of the above two cases require any detailed calibration, and provide greatly improved results in the regime of $\tau \geq 40$ ps, especially where previous techniques required the use of the centroid shift analysis method. Shorter lifetimes require a measurement of the apparent shift of the centroid of the TAC peak from the position that would correspond to that of a prompt transition of the same γ energy, as shown in Fig. 2, where the corresponding prompt peak is shown as the dashed curve. Although shifts of 1-3 ps can be readily measured, detailed calibrations and corrections are required to translate these shifts into a lifetime.

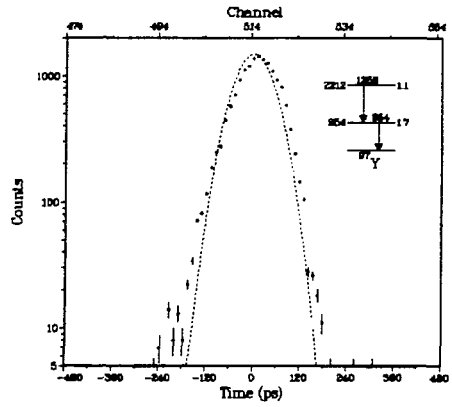

Fig. 2. TAC spectrum obtained from the 1258→954→0 cascade in ^{97}Y.

To illustrate the application of the centroid shift technique, consider the partial level scheme of ^{97}Y shown in Fig. 3. The level at 2212 keV is strongly fed by a β transition. If Ge and BaF_2 gates are set on the 1258-and 954-keV γ rays, respectively, the shift between the prompt TAC position and the β-γ centroid gives the sum of the mean lives $\tau_{2212}+\tau_{954}$. This is the situation shown in Fig. 2. If the gates are reversed, such that the Ge gate is at 954 keV and the BaF_2 gate is at 1258 keV, then the shift corresponds to just τ_{2212}. Each of these lifetimes involves an absolute measurement based on

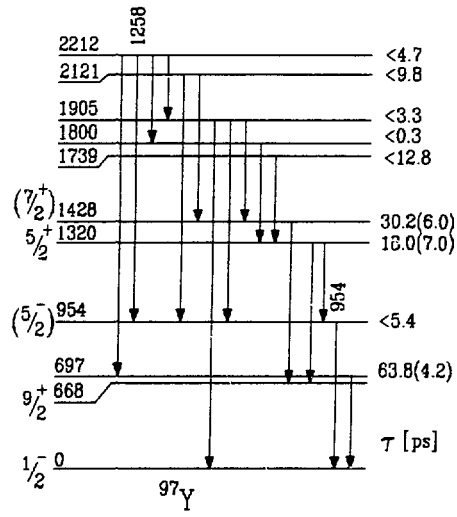

Fig. 3. Partial level scheme of ^{97}Y. The measured lifetimes are on the right.

the centroid shift from a known prompt position. If the difference of these positions is taken, the result is τ_{954}, and many uncertainties (and occasionally the corrections themselves) will cancel. By examining the level scheme, it can be seen that many paths to measure the lifetime of a particular level can be constructed. By determining the lifetime using a number of paths, each of which represents an independent measurement, an internal check of the corrections and calibrations is possible.

DATA ANALYSIS

The first step in extracting a lifetime via the centroid shift technique is to determine the energy dependence of the position of the TAC peak. A source of ^{24}Na is used to calibrate the system since it has a reasonable half life, is easily produced in the reactor, has a relatively high Q_β and high energy γ-ray cascades with no significant lifetimes. A gate is set on the β spectrum, another on the γ spectrum in the Ge detector, and a series of energy gates are selected over the range of the γ-ray spectrum from the BaF_2 detector. A plot of the position of the TAC peak for each BaF_2 energy slice for a prompt transition then results. The lower dotted curve in Fig. 4 shows the result of this calibration. This actually serves to calibrate the shape of the prompt curve, since the ^{24}Na source is located in a different position than the source of interest. The importance of careful geometrical positioning is evident when one considers that light requires 3 ps to traverse 1 mm. In addition, there are other factors that cause the actual prompt curve to shift. These include: electronic drifts, geometrical factors, a dependence on the energy collected in the BaF_2 detector, the initial γ-ray energy and a small, residual, dependence on β energy in the plastic scintillator. Nevertheless, the shape of the prompt curve remains the same and only the magnitude of the shift needs to be determined.

In order to determine the magnitude of the shift, transitions in the decay chain of interest that are known to be prompt (usually high energy γ rays) are used. This assumption may not always be correct, but it is usually possible to test its validity. If a number of high energy γ rays

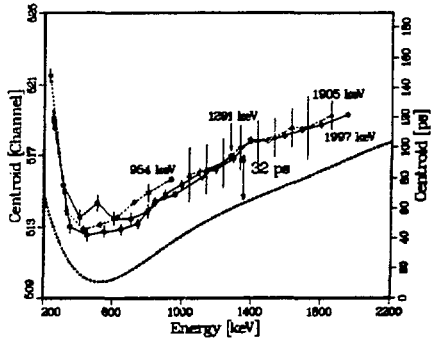

Fig. 4. Prompt curve (lower dotted line) and some ^{97}Y and ^{97}Zr centroids.

are present, select those with the smallest shift from the prompt curve. Typically, these will all have not only the smallest shifts, but will have the same shift. It is, therefore, unlikely that all these high energy γ rays will have a lifetime, and even more unlikely that they will all have the same lifetime. Thus, it is safe to assume that these transitions have no delayed component. In even-even nuclei it is often possible to find transitions with energies of 2 MeV, or higher. However, this is not always the case for odd-mass nuclei, and additional uncertainties may need to be included.

In the development of this technique, it was determined that the shift between the prompt curve and the centroids of prompt transitions depends on the transition energy itself.[1,2,3] To determine the magnitude of this transition energy (TE) correction, calibration measurements using sources of ^{88}Rb, ^{116}Ag and ^{142}Cs were made. A number of transitions in the daughters of these nuclides have well known lifetimes over a wide energy range. In addition, these sources are produced on-line at TRISTAN and, therefore, have a geometry identical to the source of interest. High energy transitions in the nuclide of interest are selected (in ^{97}Y, 1291 and 1997 keV), using the above arguments, as being prompt. The TE correction for these transitions is defined as zero. The relative shifts due to the lifetimes of the known transitions, after correction for the lifetimes, then gives the TE correction for the corresponding energy. The result of such a procedure is shown in Fig. 5 for ^{97}Y. However, for this case, due to the relatively low transition energy and the small number of transitions available, there remains the additional uncertainty that one (or both) of the so-called prompt ^{97}Y transitions may, indeed, have a lifetime of a few ps. Thus, the uncertainty associated with this correction must be increased to accommodate an undetected lifetime. The dotted line illustrates the difference in the TE correction if the 1997-keV transition is assumed to have an undetected lifetime of 3 ps (a lifetime larger then 3 ps would be readily observable). Thus, the uncertainty must be adjusted to allow for this possibility.

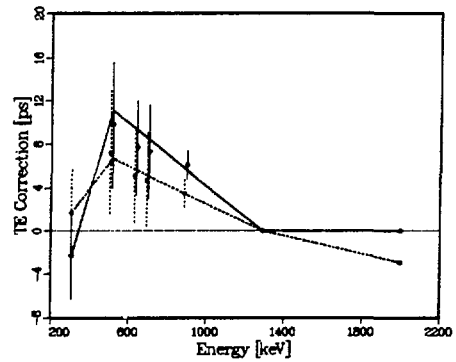

Fig. 5. Data points used for calculation of the transition energy (TE) correction.

There is another correction that must be applied to the centroid shift data before a final lifetime can be

extracted. As in other coincidence data, these events will have a background due to accidental coincidences, scattering and other phenomena. Thus, these contributions must be removed. However, unlike the case of γ-γ coincidences, this does not involve a simple reduction of the number of events. The background events here will arise from phenomenon which originate from differing energies or have been delayed through scattering. In any case, the background will have a different centroid from the desired events. Thus, the background must be properly shifted before it can be subtracted from the desired events. Fortunately, since the shape of the prompt curve is known, this can be easily accomplished.

Before leaving the discussion of techniques, it is worth noting that, although the method was developed to obtain lifetime information from β-γ coincidences, the technique should be readily adaptable to γ-γ coincidences in neutron capture γ-ray experiments. This can be accomplished by replacing the β detector by another BaF_2 detector. The timing resolution should remain similar to that of the β-γ system, due to the fast response of BaF_2. The primary analysis method would be the deconvolution technique, since the use of two BaF_2 detectors would necessitate the mapping of γ-ray response curves for each detector, thereby, at least in the worst case, requiring a family of curves to be determined. Thus, due to the energy dependence of the γ detector, the centroid shift technique will be more difficult to apply, and the primary region of interest would be lifetimes $\geq$40 ps.

VIBRATIONAL STRUCTURE IN ^{97}Y AND ^{97}Sr

The lifetimes measured in ^{97}Y are indicated in Fig. 3. From the 18.0(7) ps lifetime determined for the 1320-keV level a B(E2) value of 11(4) SPU (0.03(1) e^2b^2) was deduced. From the limit of τ<5.4 ps for the 954-keV level a B(E2) value of >7 SPU (>0.1 e^2b^2) was deduced. Both of these B(E2) values suggest the interpretation of the levels as 2^+_{phonon} excitations of a spherical band head or ground state. The B(E2) values can be compared to the vibrational transitions in ^{97}Sr and even-even ^{96}Sr, as shown in Fig. 6. The B(E2) value for ^{97}Sr was determined in the experiment described by Büscher, et al.[4] (which is high-

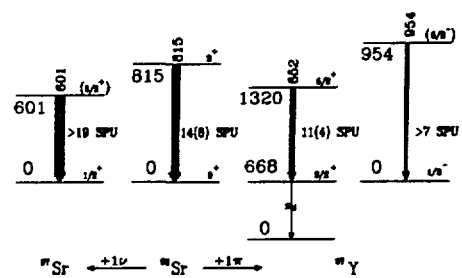

Fig. 6. Systematics of the quadrupole vibrational excitations in ^{96}Sr, ^{97}Sr and ^{97}Y.

lighted in this paper). The experimental B(E2) value for ^{96}Sr was determined by Mach et al.[9] from the lifetime of the $2^+ \rightarrow 0^+$ transition (7(4) ps) using the technique described here. Thus, the data suggest the existence of vibrational bands built on the ground states in both ^{97}Y and ^{97}Sr. The B(E2) values for the vibrational transitions favor aligned states in ^{97}Y and ^{97}Sr and are of the same order of magnitude as in their even-even neighbors.

Although the focus of this paper is on ^{97}Y, it is worth noting that many lifetimes in other A=97 nuclides were also measured. In ^{97}Sr the lifetime measurements were able to confirm that these levels were part of a rotational band that was postulated earlier.[10] The deformation [β=0.34(4)] and quadrupole moment ($|Q_0|$=3.5(4) eb) of the deformed levels was deduced. Thus, the data from this experiment provided information on spherical, vibrational and deformed levels in ^{97}Sr. It was also possible to extract the coefficients for the mixing between the vibrational and deformed states. The data limited these values to upper limits of $V_{mixing} \leq 31$ keV for the spherical-deformed states and ≤ 5.2 keV for the vibrational-deformed states. These data can be combined with that from neighboring Sr isotopes to follow the development of the deformed intruder state, as shown in Fig. 7.

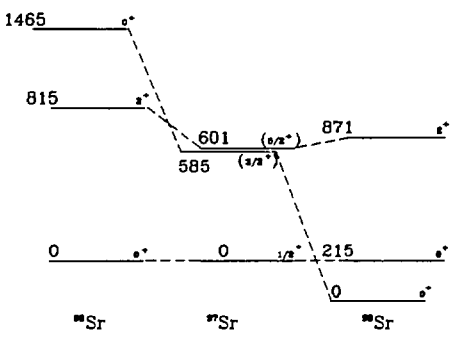

Fig. 7. Spherical and deformed states in ^{96,97,98}Sr. The relative lowering of the deformed intruder state relative to the spherical states is indicated.

CONCLUSION

Thus, a wealth of information, only part of which was discussed here, is available from a single experiment. The ability to simultaneously measure lifetimes of essentially <u>all</u> levels in a nucleus contributes, not only to the interpretation of level schemes, but also leads to increased confidence in the results due to numerous built-in cross checks. The wide dynamic energy range of the technique is possible due to the novel use of a thin β detector that has an energy independent response and no γ-ray sensitivity. In addition, the use of BaF_2 crystals yields a timing resolution that is far superior to any previously available for such measurements. This provides, even without the centroid shift method, greatly improved accuracy and precision for states with $\tau \geq 40$ ps. This

technique has been applied to many nuclei, in addition to those mentioned in this paper, at TRISTAN and other facilities, and is proving itself to be a valuable tool in the investigation of nuclear structure.

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