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NUCLEAR STRUCTURE RESEARCH AT TRIUMF*

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The radioactive beam laboratory at TRIUMF is currently the highest power ISOL facility in the world. Taking advantage of the high-intensity beams, major programs in nuclear astrophysics, nuclear structure, and weak interaction studies have begun. The low-energy area, ISAC-I, is capable of delivering beams up to mass 30 at ≈ 1.7 MeV/u or 60 keV up to the mass of the primary target, whereas ISAC-II will ultimately provide beams up to mass 150 and ≈ 6.5 MeV/u. Major γ-ray spectrometers for nuclear structure research consist of the 8π spectrometer at ISAC-I, and the TIGRESS spectrometer now being constructed for ISAC-II. Results from recent experiments investigating the β-decay of nuclei near $N = 90$ and Coulomb excitation of ^{20,21}Na are presented that highlight the capabilities of the spectrometers.

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1. Introduction

Nuclear physics has undergone a renaissance due to the development of new radioactive-ion beam facilities at several laboratories around the world. Of these, the Isotope Separator and Accelerator facility (ISAC), of the ISOL type, located at TRIUMF in Vancouver, Canada, currently has the highest beam power available worldwide at 50 kW. ISAC employs a 500 MeV proton beam, delivered by a cyclotron, with currents up to 100 μA that may be delivered onto production targets. To date, only the Ta targets have been developed that are capable of sustaining this high-power. Other targets developed (with their maximum current used for experiments to date) are SiC (65 μA), $CaZrO_3$ (10 μA), Nb (40 μA), TiC (70 μA), and ZrC (50 μA). Additional targets to be developed are a LaC and UC, the latter especially important to provide access to heavy neutron-rich beams. Ion sources available include a surface-ionization source, a laser ion source (TRILIS), and a FEBIAD source. Other sources planned are an ECR and a negative-ion source. Some of the most notable achievements have been beams of ^{11}Li up to 5×10^4 s^{-1}, currently the greatest intensity in the world, ^{21}Na at 1.1×10^{10} s^{-1}, ^{26}Al at 3×10^{10} s^{-1}, the separation of isomeric from ground state Ag beams with the laser ion source, and the observation of a $t_{1/2} = 3.1$ ms ^{179m}Lu beam released from the Ta target. The ISAC facility (hereafter referred to as ISAC-I) is able to provide mass-separated beams at low energy (typically 30 keV) as well as accelerated up to approximately 1.7 MeV/nucleon and mass 30. An extension of the laboratory, known as ISAC-II, will be able to accelerate beams up to mass 150, and approximately 6.5 MeV/nucleon for $A/q \leq 7$ or 14 MeV/nucleon for $A/q \leq 3$, when completed. The wide variety of intense radioactive beams provides for a full programme of nuclear astrophysics, nuclear structure, weak interaction tests, and materials science. In the present work, the focus is on the nuclear structure programme using the 8π and TIGRESS γ-ray spectrometers.

2. Nuclear structure with the 8π spectrometer

Long one of the main probes of nuclei, β-decay has enjoyed renewed interest as radioactive beam facilities have provided access to the neutron-rich region of the nuclear chart. At ISAC, the main instrument for β-decay experiments is the 8π spectrometer and its associated auxiliary detectors consisting of four different detector systems: the 8π array, with twenty HPGe detectors each with a relative efficiency of 20–25% surrounded by BGO shields for Compton suppression; the SCintillating Electron Positron Tagging ARray (SCEPTAR), consisting of twenty 1.6 mm thick plastic scintillators; the Pentagonal Array for Conversion Electron Spectroscopy (PACES), consisting of five 5 mm thick Si(Li) detectors; and the Di-Pentagonal Array for Nuclear Timing Experiments (DANTE), consisting of 10 BaF_2 detectors. The radioactive beam, typically at 30-keV energy, is deposited in the centre of the array, on either a metallic target or on a Moving Tape Collector (MTC). The tape of the MTC forms a continuous loop and has its movement governed by the programming of a controller unit. All aspects of the counting cycle can be controlled, including the beam-on and dwell times, measurement time, time of the tape movement, *etc.*, offering extraordinary flexibility in the collection of data. As beams from ISOL facilities are often isobaric cocktails, this degree of flexibility is extremely useful in separating out decay data of the isobars by their half lives. The Ge photopeak efficiency is $\approx 1.5\%$ at 1.33 MeV. The plastic scintillators of SCEPTAR cover $\approx 80\%$ of the 4π solid angle, and are positioned so that there is a one-to-one match with the solid angle of the Ge detectors. This enables a veto of the Ge event by the matching plastic scintillator, useful in reducing the bremsstrahlung and background from high-energy β particles often encountered in the β-decay of nuclei far from stability. The Si(Li) detectors of PACES cover $\approx 8\%$ of the solid angle, and are located upstream of the target position.

In order to highlight the capabilities of the spectrometer, data on the $A = 160$ nuclei from an experiment in July 2006 are presented. The $A = 160$ decay data are part of a program of study of nuclei in the $N = 90$ region that are transitional between spherical and well deformed. This program, initiated using the 8π spectrometer while at Lawrence Berkeley Laboratory, has required the development of methods of ultra-high sensitivity γ-ray spectroscopy at low spin [1–5]. The initial successes of this work led to the central role the 8π has in the on-line decay scheme spectroscopy facility at TRIUMF. The $N \approx 90$ region was selected because there is considerable interest in the possibility of a shape phase transition [6, 7]. This was initiated with two studies [8, 9] of the decay of ^{152}Eu to ^{152}Sm. However, the study of ^{152}Eu decay to ^{152}Sm using the 8π spectrometer [5] is in serious disagreement with this [8, 9]. This result depended on the extraordinarily high sensitivity that can be achieved using the 8π spectrometer. In consequence, further studies have been undertaken which take advantage of this sensitivity. With this aim, the β decay of ^{156}Dy and ^{158}Er have been studied at TRIUMF–ISAC. The mass 160 experiment recently conducted yields data on the $N = 92$ nucleus ^{160}Er through ^{160}Ho decay, required for detailed systematics from the $N = 88$ to the $N = 92$ isotones. Since the isobars cannot be separated, a large amount of data on ^{160}Tm from ^{160}Yb decay was collected concurrently. A total of 34 hours of running time was used, with data collected from the Si detectors of PACES only during the final 24 hours.

Fig. 1 displays selected $\gamma\gamma$ coincidence spectra obtained in the experiment. The top panel shows the γ-ray spectrum in coincidence with the 264-keV $4_1^+ \rightarrow 2_1^+$ transition in ^{160}Er, whereas the bottom panel displays the spectrum in coincidence with the 41-keV γ ray in ^{160}Tm, a major iso-

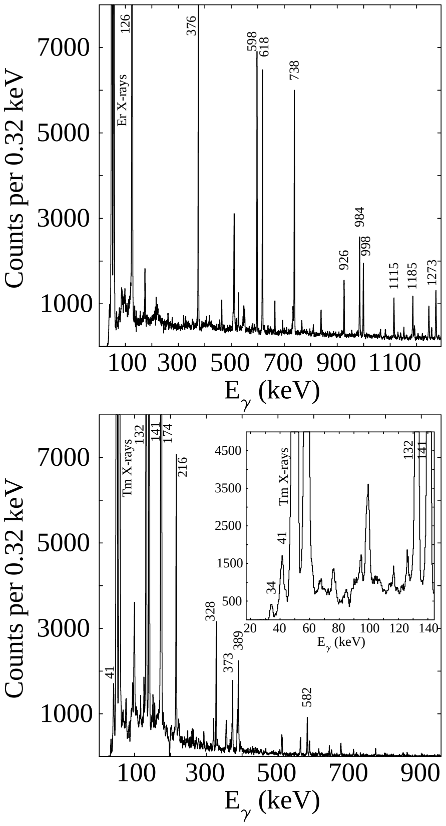

Fig. 1. Results of selected $\gamma\gamma$ coincidences. The top panel displays the γ-ray spectrum in coincidence with the 264-keV $4_1^+ \rightarrow 2_1^+$ transition in ^{160}Er, and the bottom panel the resulting spectrum in coincidence with the 41-keV transitions in ^{160}Tm.

baric contaminant. Of note is the presence of the 34-keV $M1$ transition, clearly displayed in the spectrum shown in the inset, expected from the level scheme presented in Ref. [10].

Fig. 2 displays portions of the Si(Li) spectra in coincidence with the ^{160}Er $2^+_\gamma \rightarrow 0^+_{\rm gs}$ γ ray (top panel), and reveals that, as expected, the only strong peak is that associated with the K_α X-ray. The gate on the $2^+_\gamma \rightarrow 2^+_1$ γ ray (middle panel), however, indicates the presence of the K_α X-ray along with the conversion electrons from the 126-keV $2^+_1 \rightarrow 0^+_{\rm gs}$ transition, as expected.

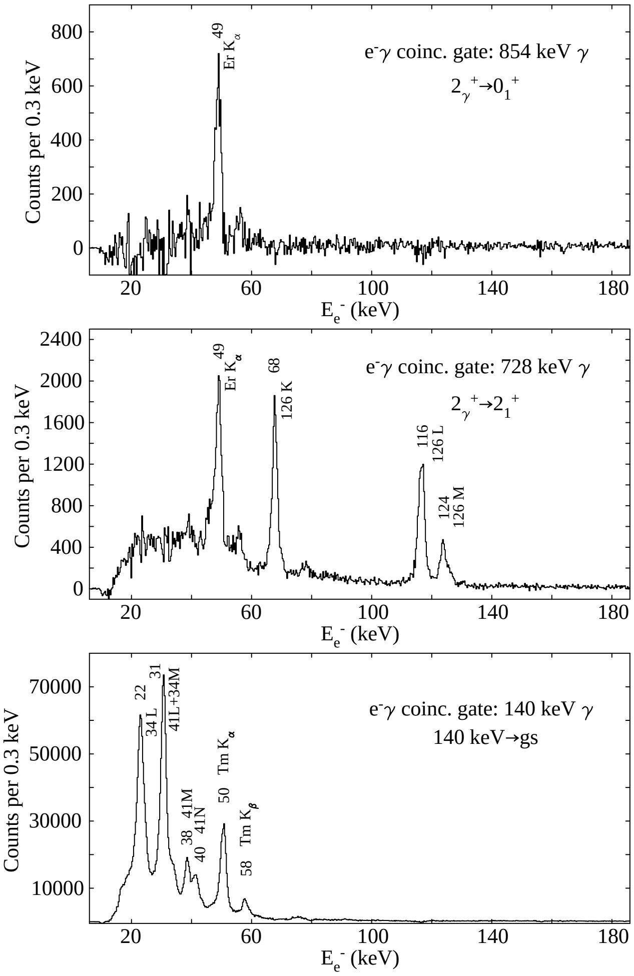

Fig. 2. Results of selected $e^-\gamma$ coincidences. The top, middle, and bottom panels display the e^- spectra in coincidence with the 854-keV $2^+_\gamma \rightarrow 0^+_{\rm gs}$ and 728-keV $2^+_\gamma \rightarrow 2^+_1$ γ-ray transitions in ^{160}Er, and the 140-keV ground state transition in ^{160}Tm, respectively.

Coincidences with the 140-keV transition in ^{160}Tm are shown in the bottom panel of Fig. 2, and demonstrates the excellent low-energy sensitivity of PACES — the L conversion (at 22 keV) from the 34-keV $M1$ transition being readily apparent. These spectra demonstrate the remarkable ability of the system to separate isobaric decay sequences using coincidence gating. The utility of γ-gated conversion electron spectra in extracting the multipolarity of the transitions is obvious. The five Si(Li) detectors of PACES enable not only $e^-\gamma$ coincidences, but also e^-e^- coincidences. This latter possibility has been rarely achieved in past β-decay stations, and Fig. 3 demonstrates its power aptly. The top panel displays the PACES spectrum in coincidence with the 22-keV electrons from the 34-keV L transition in ^{160}Tm. Even

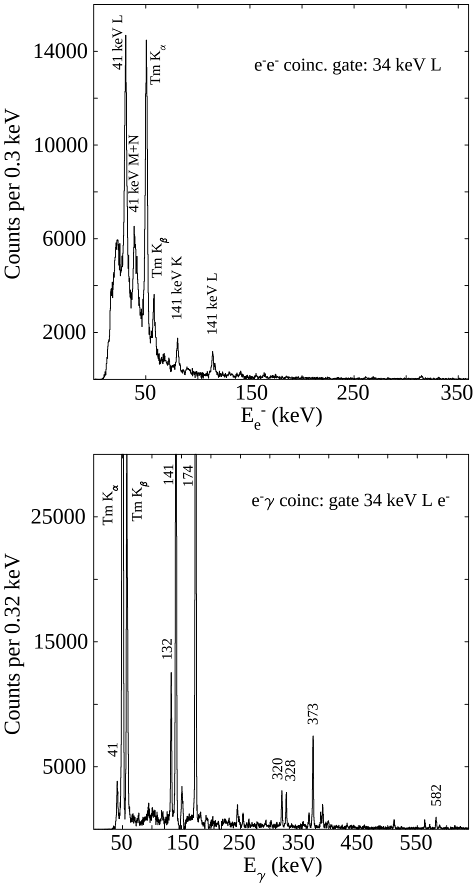

Fig. 3. Results of selected e^-e^- and $e^-\gamma$ coincidences. The top panel displays the e^- spectrum in coincidence with the 22-keV electrons from the 34-keV L transition in ^{160}Tm, and the bottom spectrum the γ-ray spectrum with the same coincidence condition.

though the background may be high, the spectrum readily demonstrates the usefulness of such coincidences, especially important for studies of odd–odd nuclei where there may be abundant low-energy transitions. The bottom panel shows again an example of a $e^-\gamma$ coincidence but displays a portion of the γ-ray spectrum in coincidence with the 34-keV L conversion peak in the PACES spectrum.

Using results like those presented in Figs. 1 and 2, a very preliminary partial level scheme for ^{160}Er has been established. The level scheme in Fig. 4 displays only the γ band and the first excited $K^\pi = 0^+$ band. In previous ^{160}Tm decay studies, the even-spin members of the γ band were not well-established, and the first excited $K^\pi = 0^+$ band was known only to spin 2. The extensions to these bands, consistent with a recent in-beam study [11], will be important to investigate the nature of these excitations as one moves away from the $N = 90$ transition point. Further work will search for weaker decay branches and examine angular correlations. In addition, the low-lying level scheme of ^{160}Tm can be considerably extended, and may require significant modification as well.

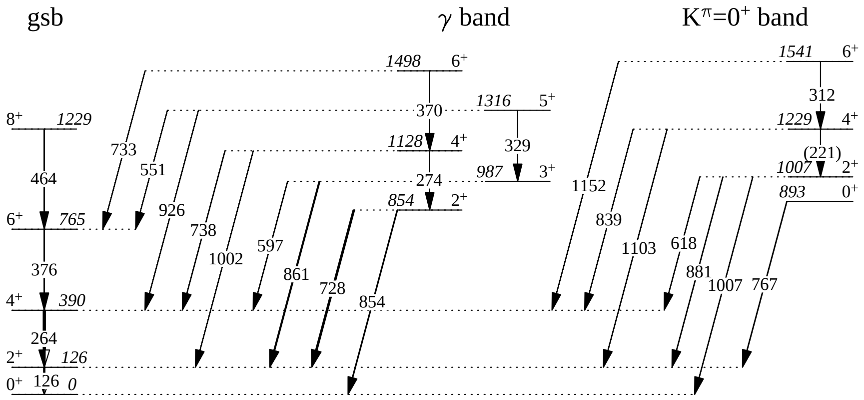

Fig. 4. Preliminary partial level scheme established from the mass 160 β decay study performed with the 8π spectrometer, highlighting the γ band and the first excited $K^\pi = 0^+$ band in ^{160}Er.

3. Nuclear structure with the TIGRESS spectrometer

Many experiments using accelerated radioactive beams will involve inverse kinematics, for which accurate Doppler corrections become critical. In order to improve the angular resolution of the γ rays emitted from nuclei in flight, segmentation of the detectors is necessary. The TRIUMF–ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS), a 12 detector array based on 8-fold segmented clover HPGe detectors, is currently being constructed for the ISAC-II facility at TRIUMF and will be completed in 2009. Each crystal in the clover detectors has approximately 40% relative efficiency, and the outer contacts are segmented 4-fold axially and 2-fold longitudinally [12]. A segmented BGO suppression shield consisting of 4 side plates and 4 front shields, and a CsI "back-plug" surround each clover detec-

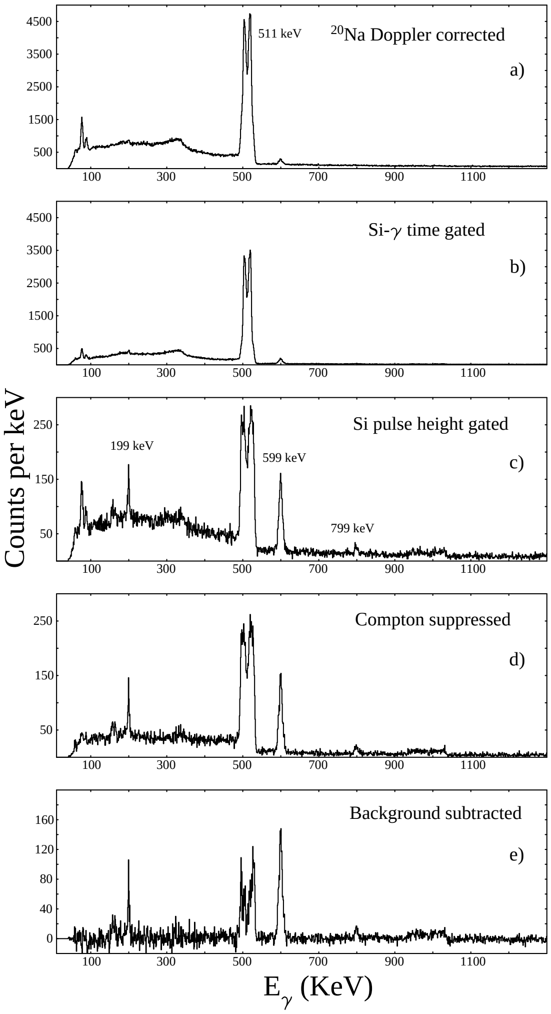

Fig. 5. Results obtained from the Coulomb excitation of a ^{20}Na beam on $^{\mathrm{nat}}$Ti target at 1.7 MeV/nucleon. Panel (a) displays the Doppler-corrected spectrum for the ^{20}Na scattered beam, panel (b) with a more restrictive condition on the Si-γ coincidence, panel (c) with a condition on the Si energy to exclude α particles from the decay of ^{20}Ne, panel (d) with Compton suppression applied, and panel (e) with background subtraction applied.

tor for Compton suppression. The eight outer contacts and one core contact are read out with 100 MHz waveform digitizers custom built for TIGRESS, and a waveform analysis demonstrates that position sensitivity of better than 2 mm can be achieved [13]. There are two standard configurations for the clover detectors in TIGRESS; a "fully-forward" high efficiency mode, in which the front BGO shields are pulled back to allow the Ge detectors to be moved forward, and "fully-suppressed" optimum peak-to-total mode. Detailed GEANT4 [14] simulations indicate that the full array will achieve a photo-peak efficiency of $\approx 17\%$ for a single γ ray at 1 MeV [15].

The first experiment using TIGRESS was the Coulomb excitation of ^{20,21}Na performed at ISAC-I. ^{21}Na is of interest because its valence nucleons exist in a five-particle ($5p$) state, so that information gained from a study of its low-energy structure will be relevant to the understanding of other $5p$ states, including an astrophysically-important $\frac{3}{2}^+$ state at 4.033 MeV in ^{19}Ne believed to have a $5p$–$2h$ configuration. In addition, the reported $B(E2 : \frac{5}{2}^+ \rightarrow \frac{3}{2}^+)$ transition strength in ^{21}Na is 14 ± 12 W.u. [16], the uncertainty being mainly due to a 40% uncertainty in the mixing ratio [17]. A Coulomb excitation measurement can improve the uncertainty significantly since the excitation process is insensitive to the $M1$ contribution. For this experiment, two TIGRESS detectors were used in conjunction with BAMBINO, which consists of 150 μm thick Si CD–S2 detectors from Micron Technology Inc., for light-ion detection. The BAMBINO detectors can be mounted 3 cm from the target for both forward and backward hemispheres, although in the present experiment only the forward detector was used covering a solid angle of $\approx 0.58\pi$ sr. The S2 detectors are segmented with 24 rings in θ for angles between 20° and 49° and 16 ϕ sectors. The beams had energies of 1.7 MeV/u and intensities of 2–6 $\times 10^6$ s^{-1}, and impinged on a target of $^{\mathrm{nat}}$Ti that was 450 μg/cm^2 thick. Fig. 5 displays a series of γ-ray spectra from the Coulomb excitation of ^{20}Na as a series of conditions are applied; with each condition the reduction of the 511-keV background line from e^+e^- annihilation is dramatic. The presence of the 199-keV and 799-keV γ rays in the spectra indicate that the second excited state in ^{20}Na is populated significantly in the process. Analyses of the yields are in progress, and preliminary results indicate that an uncertainty of $\leq 10\%$ is achievable for the ^{21}Na $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ $B(E2)$ value.

4. Summary

The 8π spectrometer at ISAC-I, with its auxiliary detector systems, offers a world-unique device for β-decay spectroscopy in that γ rays, β-particles, and conversion electrons can be detected simultaneously, along with the performance of fast lifetime measurements. A wide programme of nuclear structure research has been undertaken, with data from a mass 160 β-decay experiment highlighted here. The nuclear structure programme using the TIGRESS spectrometer with accelerated beams has commenced with the Coulomb excitation of ^{20,21}Na. Future work will involve additional Coulomb excitation studies, single-nucleon transfer reactions, and will expand into other areas as additional auxiliary detector systems come on-line. These include a CsI array for light-ion detection, a Si barrel detector to complement the Si CD detectors, a Bragg detector, a neutron-detector array based on deuterated scintillator, and a particularly powerful combination will be the EMMA recoil spectrometer [18] with TIGRESS positioned at the target location.

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