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P. E. Garrett
University of Guelph

C. E. Svensson
University of Guelph

G. C. Ball
TRIUMF

G. Hackman
TRIUMF

E. F. Zganjar
Louisiana State University

See next page for additional authors

Authors

P. E. Garrett, C. E. Svensson, G. C. Ball, G. Hackman, E. F. Zganjar, C. Andreoiu, A. Andreyev, S. F. Ashley, R. A.E. Austin, D. Bandyopadhyay, J. A. Becker, S. Chan, H. Coombes, R. Churchman, R. S. Chakrawarthy, P. Finlay, G. F. Grinyer, B. Hyland, E. Illes, G. A. Jones, W. D. Kulp, J. R. Leslie, C. Mattoon, A. C. Morton, C. J. Pearson, A. A. Phillips, P. H. Regan, J. J. Ressler, F. Sarazin, M. A. Schumaker, J. Schwarzenberg, M. B. Smith, and J. J. Valiente-dobón

Gamma-Ray Spectroscopy at TRIUMF-ISAC

P.E. Garrett[1], C.E. Svensson[1], G.C. Ball[2], G. Hackman[2], E.F. Zganjar[3], C. Andreoiu[1], A. Andreyev[2], S.F. Ashley[4], R.A.E. Austin[5], D. Bandyopadhyay[1], J.A. Becker[6], S. Chan[2], H. Coombes[2], R. Churchman[2], R.S. Chakrawarthy[2,10], P. Finlay[1], G.F. Grinyer[1], B. Hyland[1], E. Illes[1], G.A. Jones[4], W.D. Kulp[7], J.R. Leslie[8], C. Mattoon[9], A.C. Morton[2], C.J. Pearson[2], A.A. Phillips[1], P.H. Regan[4], J.J. Ressler[10], F. Sarazin[9], M.A. Schumaker[1], J. Schwarzenberg[11], M.B. Smith[2], J.J. Valiente-Dobón[1], P.M. Walker[4], S.J. Williams[4], J.C. Waddington[12], L.M. Watters[12], J. Wong[1], J.L. Wood[7]

1) Department of Physics, University of Guelph, Guelph, Ontario, N1G2W1, Canada
2) TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T 2A3, Canada
3) Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana, 70803-4001, United States
4) Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom
5) Department of Astronomy and Physics, Saint Mary's University, Halifax, Nova Scotia, B3H3C3, Canada
6) Lawrence Livermore National Laboratory, PO Box 808, Livermore, California, 94551, United States
7) School of Physics, Georgia Institute of Technology, Atlanta, Georgia, 30332-0430, United States
8) Department of Physics, Queen's University, Kingston, Ontario, K7L3N6, Canada
9) Department of Physics, Colorado School of Mines, Golden, Colorado, 80401, United States
10) Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, V5A1S6, Canada
11) Institut für Isotopenforschung und Kernphysik, Währinger Strasse 17, 1090 Wein, Austria
12) Department of Physics, McMaster University, Hamilton, Ontario, L8S4M11, Canada

Abstract. The 8π spectrometer at TRIUMF-ISAC consists of 20 Compton-suppressed germanium detectors and various auxiliary devices. The Ge array, once used for studies of nuclei at high angular momentum, has been transformed into the world's most powerful device dedicated to radioactive-decay studies. Many improvements in the spectrometer have been made, including a high-throughput data acquisition system, installation of a moving tape collector, incorporation of an array of 20 plastic scintillators for β-particle tagging, 5 Si(Li) detectors for conversion electrons, and 10 BaF_2 detectors for fast-lifetime measurements. Experiments can be performed where data from all detectors are collected simultaneously, resulting in a very detailed view of the nucleus through radioactive decay. A number of experimental programmes have been launched that take advantage of the versatility of the spectrometer, and the intense beams available at TRIUMF-ISAC.

Keywords: gamma-ray spectrometer, conversion electrons, lifetime measurements.
PACS: 23.20.-g, 23.20.Lv, 23.20.Nx, 23.40.-s, 23.40.Bw, 23.40.Hc

INTRODUCTION

With a new generation of radioactive beam facilities coming on-line, many researchers are re-visiting techniques pioneered decades ago in order to address the

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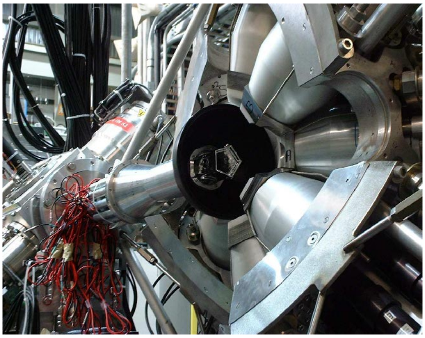
most pressing issues in nuclear physics research today. Radioactive-decay studies, eclipsed in the 1980's and 1990's by in-beam γ-ray spectroscopy and heavy-ion fusion-evaporation reactions, are enjoying a revitalization as one of the most important techniques to learn about nuclear structure, address questions in nuclear astrophysics, and explore physics beyond the current Standard Model. The advantages of modern β-decay studies over those performed even a decade ago are the tremendous increases in instrumental resolving powers, sensitivities, and data analysis with modern computers. In the present paper, work involving β-decay spectroscopy at the Isotope Separator and Accelerator (ISAC) facility of the TRI-University Meson Facility (TRIUMF) is reported. Much effort has been devoted in the past five years to build a highly sensitive and versatile device for decay studies centered on the 8π γ-ray spectrometer and its auxiliary detectors. A wide and varied programme of nuclear structure, nuclear astrophysics, and weak-interaction studies is being pursued.

INSTRUMENTAL CAPABILITIES

The 8π spectrometer and its associated auxiliary detectors currently comprises 4 different detector systems: Compton-suppressed Ge detectors (the 8π spectrometer) for γ-ray detection, plastic scintillators (named the SCintillating Electron Positron Tagging ARray – SCEPTAR) for detection of β particles, BaF_2 detectors (named the Dipentagonal Array for Nuclear Timing Experiments – DANTE) for γ-ray detection with fast-timing measurements, and Si(Li) detectors (named the Pentagonal Array for Conversion Electron Spectroscopy – PACES) for conversion electron studies. The ISAC low-energy beam is focused on a segment of ½″ wide tape at the center of these arrays. The Moving Tape Collector (MTC) can then be used to transport the deposited sample into a shielded tape box away from the detectors at predetermined time intervals using a computer-controlled stepping motor. The beam ON/OFF times, and tape movement intervals, frequencies, and dwell times are all variable limited only by the beam-pulsing response time («10 ms), and tape movement speed. The MTC system allows separation of parent/daughter/granddaughter/etc. decays of differing half-lives, an indispensable feature at an online isotope separator like the ISAC facility.

The 8π Spectrometer

The 8π spectrometer is based on a geometrical arrangement of 20 hexagonal and 12 pentagonal shapes. The 20 Ge detectors, Ortec HPGe with a nominal relative efficiency of ~25%, occupy the hexagonal positions, with 4 rings of 5 detectors at angles of $\pm37°$ and $\pm79°$ with respect to the beam direction. The target-to-front-face distance for the BGO suppression shields is 13 cm, and that for the Ge detectors is 14 cm. The absolute photopeak efficiency of the reconfigured array has been measured for the 1332-keV ^{60}Co line to be 1.5%, with a peak-to-total ratio of 0.41. To demonstrate the sensitivity of the reconfigured 8π array, shown in Fig. 1 are results from an experiment [1] using a ^{26}Na beam of 10^6 ions/s of 10-hour duration. A sensitivity on the relative β-decay branching on the order of 10^{-6} was achieved.



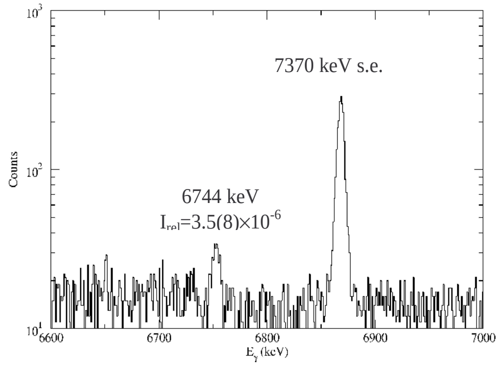


FIGURE 1. Photograph (left) of the upstream portion of the SCEPTAR plastic scintillator array (the pentagon shaped object in the center of the target chamber) and one hemisphere of the 8π array. The SCEPTAR array covers ~80% of the solid angle, and each plastic scintillator shadows a particular Ge detector. The partial spectrum (right) was obtained from a 10hr run with a beam of 10^6 ^{26}Na s^{-1} and displays the sensitivity of 10^{-6} for weak β branches achieved.

SCEPTAR

Complementing the Ge detectors are 20 plastic scintillators of SCEPTAR. Arranged into 2 rings of 5 trapezoidal pieces and 2 rings of 5 rectangular pieces, the positioning is such that one plastic scintillator overlaps the solid angle of one Ge detector. This permits the rejection of bremsstrahlung events in a Ge detector due to the stopping of the very-high-energy β particles often encountered in far-from-stability radioactive decays. The total solid angle coverage of SCEPTAR is approximately 80% of 4π. The plastic scintillators are BC410 of thickness 1.6 mm. Light is collected from the edge of the scintillators and transported via ~25 cm long light-guides to the phototubes located outside of the main frame of the array. Figure 1 contains a photo showing portions of the 8π and SCEPTAR arrays.

PACES

The most recent addition to the arsenal of detectors is PACES. An array of 5 Si(Li) detectors, PACES makes available both conversion-electron and internal-pair spectroscopy, the latter of which is advantageous far from stability where the Q-value is large. Inclusion of conversion-electron data provides not only multipolarity information, but also reveals electric monopole (E0) transitions indicative of shape coexistence. The Si(Li) detectors are approximately 5 mm in thickness and have a typical resolution of 2.5 keV at 1 MeV. A close-up view of the PACES array is shown in Fig. 2. A recent experiment [2] using PACES investigated the decay of a newly discovered isomer in ^{174}Tm. The 2.29(1) s isomer was first observed with the 8π spectrometer only [3]; based on X-ray yields, it was suggested that the 100-keV and 152-keV transitions observed were *M1* in nature. However, it was not known if the full decay intensity had been observed, making a spin assignment for the isomeric level uncertain. This experiment was recently repeated with the inclusion of PACES, where an *E3* multipolarity for the 152-keV transition was determined based on conversion-electron sub-shell ratios as shown in Fig. 2. The spin-parity for the isomeric level is now suggested to be 0^+ [2].

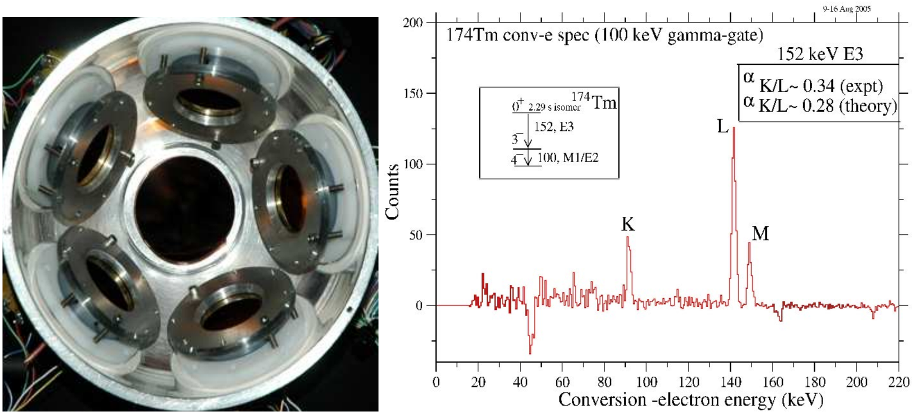


FIGURE 2. Photograph (left) of the PACES array of Si(Li) detectors for conversion electrons, and the low-energy portion of spectrum (right) collected with PACES gated on the 100-keV transition following the isomer decay in ^{174}Tm.

DANTE

The ten BaF_2 detectors of DANTE are being installed in the available open pentagonal positions of the spectrometer for fast timing measurements. The BaF_2 scintillator is the fastest known; one of its two scintillating-light components has a decay constant of 0.6 ns and emits light in the UV region. The detectors are coupled to very fast photomultiplier tubes, the Photonis XP2020/URQ, having a quartz entrance window for maximum transmission of the fast-component UV light. An initial test experiment [4] to accurately map the time response of the SCEPTAR plastic scintillators and test the feasibility of the DANTE array used 4 BaF_2 detectors from the University of Surrey. Using a ^{26}Na radioactive beam, it was found that the individual SCEPTAR detectors had timing resolutions (FWHM) in the range of 1–1.5 ns. With BaF_2-BaF_2 coincidences, on the other hand, the timing FWHM of ≈200 ps was ultimately achieved. In addition to determining the timing resolution, a novel Compton-rejection scheme for the BaF_2 detectors was also investigated. Since five BGO shields of neighbouring Ge detectors form a pentagonal ring around each BaF_2 detector, the BGO signals were used to form a BaF_2 Compton veto. This reduced the background significantly, even though the geometry was not optimum. This test may be the first time that such timing BaF_2 detectors have been Compton suppressed [4]. This will lead to a significant reduction in the systematic uncertainty assigned to the short level lifetimes, since one of the dominating contributions arises from the Compton distribution under the peak of interest.

EXPERIMENTAL PROGRAMMES

As the 8π spectrometer is such a versatile array, a widely varied set of experiments have been proposed addressing nuclear structure, nuclear astrophysics, and Standard Model tests. Studies to date have included: 1) the β decay of ^{11}Li, to study the possibility of neutron-halo "survival" during the β decay process [5], 2) ^{18}Ne [6], 3) ^{35}Ar [7], and 4) ^{62}Ga [8], as part of the super-allowed Fermi β-decay programme, 5) ^{26}Na [1], (our workhorse test beam), 6) ^{32}Na to investigate the structure of ^{32}Mg and the island of inversion, 7) ^{156}Ho and 8) ^{158}Tm decay as part of the programme to study shape-phase transitions in the $N=90$ isotones, and isomeric states in 9) ^{174}Tm [2–3], 10) ^{178}Hf [9], and 11) ^{178,179}Lu [10]. There are a number of other accepted experiments: search for seniority isomers in the mass 80 and 100 regions, structure of neutron-rich Cd and Pd isotopes in connection with *r*-process nucleosynthesis in the mass 120 region, additional experiments in the $N=90$ region, studies of ^{14}Be, a study of the possible *s*-process branch point ^{115}Cd, etc. This list will continue to grow as ISAC develops more production targets and ion sources to provide a richer variety of radioactive beams.

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