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ABSTRACT

The Isotope Separator and Accelerator (ISAC) facility located at the TRIUMF laboratory in Vancouver, Canada, is one of the world's most advanced ISOL-type radioactive ion beam facilities. An extensive γ-ray spectroscopy programme at ISAC is centred around two major research facilities: i) the 8π γ-ray spectrometer for β-delayed γ-ray spectroscopy experiments with the low-energy beams from ISAC-I, and ii) the next-generation TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) for in-beam experiments with the accelerated radioactive ion beams. An overview of these facilities and recent results from the diverse programme of nuclear structure and fundamental interaction studies they support is presented.

I. 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), which is 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 on targets ranging from SiC to Ta. Some of the most notable achievements are beams of ^{11}Li up to 5×10^{4} 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 $t_{½}$=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 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 spectrometer at ISAC-I and the TIGRESS spectrometer that will be located at ISAC-II.

II. NUCLEAR STRUCTURE AT ISAC-I

The nuclear structure programme at ISAC-I is centred (although not exclusively) on the 8π spectrometer and its auxiliary detectors. The 8π spectrometer consists of twenty HPGe detectors with a relative efficiency of 20–25% surrounded by annular BGO shields for Compton suppression and a BGO “back-plug” detector. The detectors are positioned at the hexagon positions of a truncated icosahedron. 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 target-to-detector distance is approximately 14 cm, and the array efficiency is ~1.5% at 1.33 MeV. The tape of the MTC forms a continuous loop, typically 120 m in length, and has its movement governed by the programming of a controller unit.

A number of auxiliary detectors systems have been implemented in the 8π spectrometer; SCEPTAR – the SCintillating Electron Positron Tagging ARray, PACES – the Pentagonal Array for Conversion Electron Spectroscopy, and DANTE – the Dipentagonal Array for Nuclear

Timing Experiments. SCEPTAR consists of twenty pieces of 1.6 mm thick plastic scintillator surrounding the target position, arranged so that there is a one-to-one match with the Ge detectors. Being relatively thin, SCEPTAR acts as a ΔE detector for electrons and positrons, and is useful to indicate that a β decay has occurred. PACES incorporates five Si(Li) detectors 5 mm thick that replace the upstream half of SCEPTAR, and is most useful for conversion electron spectroscopy. DANTE consists of ten BaF_2 detectors positioned in the open pentagonal positions of the truncated icosahedron and is used for fast-timing measurements. This combination of detector systems is unique in the world, and provides for comprehensive spectroscopy of nuclei following β decay.

The 8π nuclear structure program has examined nuclei from ^{11}Li to ^{179}Lu. An initial study [1] with the 8π array to observe the β decay of a beam of 10^3 ^{11}Li s^{-1} suggested that the theoretical prediction of a β decay occurring in the core and leaving intact the halo neutrons could be realized. Further studies [2] with greatly increased sensitivity using 8π+SCEPTAR and a beam of >10^4 ^{11}Li s^{-1} have been performed that will yield a much more detailed picture. Figure 1 shows portions of spectra obtained from the two ^{11}Li experiments. The improvement in quality and statistics of the data is obvious, and the detailed γ-ray lines-shapes now available allow for precise determination of the level life-times and neutron decay braches. Future studies in this direction are planned, such as the heavier halo system ^{14}Be.

A number of theoretical calculations predict that the familiar shell gaps that give rise to the “magic” numbers, or closed major shells, may change drastically in neutron-rich nuclei, and thus a major line of research is the mapping of the nuclear shells as one proceeds away from stability. The investigation of shell structure in the neutron-rich Mg and O isotopes is particularly interesting due to the “island of inversion” where the changes in the shell structure cause the disappearance of the *N=20* neutron shell with the consequence that nuclei become deformed rather than retain a spherical shape, and other nuclei that would normally be predicted to be bound are unbound. An initial experiment [3] examining the decay of ^{32}Na demonstrated that spectroscopy is possible with beam intensities as low as 1 s^{-1}. More detailed studies must await the development of the actinide target for an expected 2–3 orders-of-magnitude boost in beam intensity. The very-neutron rich Cd and Pd isotopes are of interest in order to probe the quenching of the *N=82* shell below ^{132}Sn. This has an important consequence on observed elemental abundances, particularly on the abundance of nuclei in the mass 120 region [4-6]. This programme will soon commence now that Ag beams have been developed. A further region of interest, due to predicted shell closures at *N=32* and *N=34*, is the neutron-rich Ca isotopes and an experiment was recently performed to observe the β decay of the ^{52}K. The ^{52}K beam intensity was ~10 s^{-1}, and sufficient data were collected to permit $\gamma\gamma$ coincidences, analysis of which is ongoing [7].

For many years it has been known that nuclei near *N=90* exhibit a rapid change in the shape of the ground state as the neutron number increases from *N=88* to *N=92*. The excited-state spectrum also undergoes a rapid evolution from that resembling a vibrational system to a rotational one. Very recently [8,9], based on improved spectroscopy through ^{152}Eu decay and IBM calculations, it was suggested that nuclei at *N=90* are at a critical point of a shape phase transition. A new model, based on a solution of the Bohr Hamiltonian with a square-well potential in the β shape degree of freedom, has been developed centred on this idea [10]. It has been claimed [11] that the new model successfully describes the level structures of a series of *N=90* isotones; however, the lack of precision data prevents a definitive conclusion.

Studies to date using the 8π spectrometer to investigate *N=90* nuclei include ^{156}Ho, ^{158}Tm, and ^{160}Lu decay. Beam intensities for these experiments can reach >10^7 s^{-1}, and typically data on the order of 1 TB are collected. New *E0* transitions have been observed that are critical in the determination of shape coexistence in these nuclei, but analysis of the data is not complete thus $\rho^2(E0)$ values are not yet available. Figure 2 displays portions of the γ-ray and conversion electron spectrum collected with one 8π Ge detector and one of the PACES Si detectors. Comparison of the intensities of the electron lines to those in the γ-ray spectrum allows the determination of the multipolarity of the transition.

III. NUCLEAR STRUCTURE WITH TIGRESS

Many of the experiments performed at ISAC-II, with its ability of accelerating the radioactive beams beyond the Coulomb barrier for a wide variety of targets, will involve inverse kinematics reactions. For γ-ray detection, it is important to have very-high photo-peak efficiency while incorporating the ability to locate the first interaction point precisely so that a proper Doppler shift correction can be applied. It is for this purpose that the TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is being constructed.

TIGRESS, when fully completed in 2009, will incorporate twelve highly segmented clover detectors mounted in a frame with the geometry of a rhombicuboctahedron. Each crystal in a clover detector 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 detector 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 2mm 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 simulations [14] indicate that the full array will achieve a photo-peak efficiency of 17% for a single γ-ray at 1 MeV.

A number of auxiliary detectors are planned for TIGRESS. The first to be commissioned is BAMBINO, which consists of 150-μm thick Si CD-S2 detectors from Micron Technology Inc. that will be used for light-ion Coulomb excitation. Two such detectors can be mounted 3 cm from the target for both forward and backward hemispheres, covering a solid angle of ~1.15π sr, and each have 24 rings in θ for angles between 20° and 49° and between 131° and 160°, and 16 sectors in ϕ for 360° coverage. Figure 3 shows a photograph of BAMBINO in its target chamber during a commissioning experiment. Also planned is a Si ΔE-E detector in a box-like geometry to be used for Coulomb excitation studies, single-nucleon transfer, and inelastic scattering, a segmented Bragg detector to be able to identify ions on an event-by-event basis, a CsI detector for light-ion identification for Coulomb excitation and fusion-evaporation studies, and a neutron detector employing deuterated liquid scintillator. A very powerful complement is the ElectroMagnetic Mass Analyzer (EMMA), a recoil spectrometer of the electric-dipole – magnetic-dipole – electric-dipole type [15], that is expected to be available in 2009.

The first experiment, performed at ISAC-I, conducted using TIGRESS and BAMBINO was the Coulomb excitation of ^{20,21}Na. The system was commissioned with a beam of stable ^{21}Ne. The beams had energies of 1.7 MeV/nucleon and intensities of 2–6 $\times$ 10^6 s^{-1}, and impinged on a target of ^{nat}Ti that was 450 μg/cm^2 thick. The resulting γ-ray spectra for ^{21}Ne and ^{21}Na beams (with a preliminary Doppler correction and without background subtraction) obtained in coincidence with particles detected in BAMBINO are shown in Fig. 4. Of particular interest is the appearance of the 511-keV annihilation line that arises from the β^+ decay of ^{21}Na beam particles; the weakness of the peak indicates that the amount of scattered beam in the target chamber is well under control and will not interfere with the extraction of the matrix elements. By analyzing the particle-γ coincidence yield as a function of scattering angle, the matrix element for Coulomb excitation can be uniquely determined.

IV. CONCLUSIONS

Highlights of the nuclear structure studies at the TRIUMF ISAC facility were outlined. The 8π spectrometer and its associated auxiliary detectors is a world unique facility for nuclear physics utilizing β decay, in that γ-ray singles, coincidences, conversion electrons, β-particle tagging, and lifetime measurements can be performed simultaneously. A broad programme of nuclear structure, nuclear astrophysics, and Standard Model tests is underway. Nuclear structure investigations with TIGRESS have just commenced with the Coulomb excitation of radioactive ^{21}Na, and preliminary spectra from the experiment have been presented.

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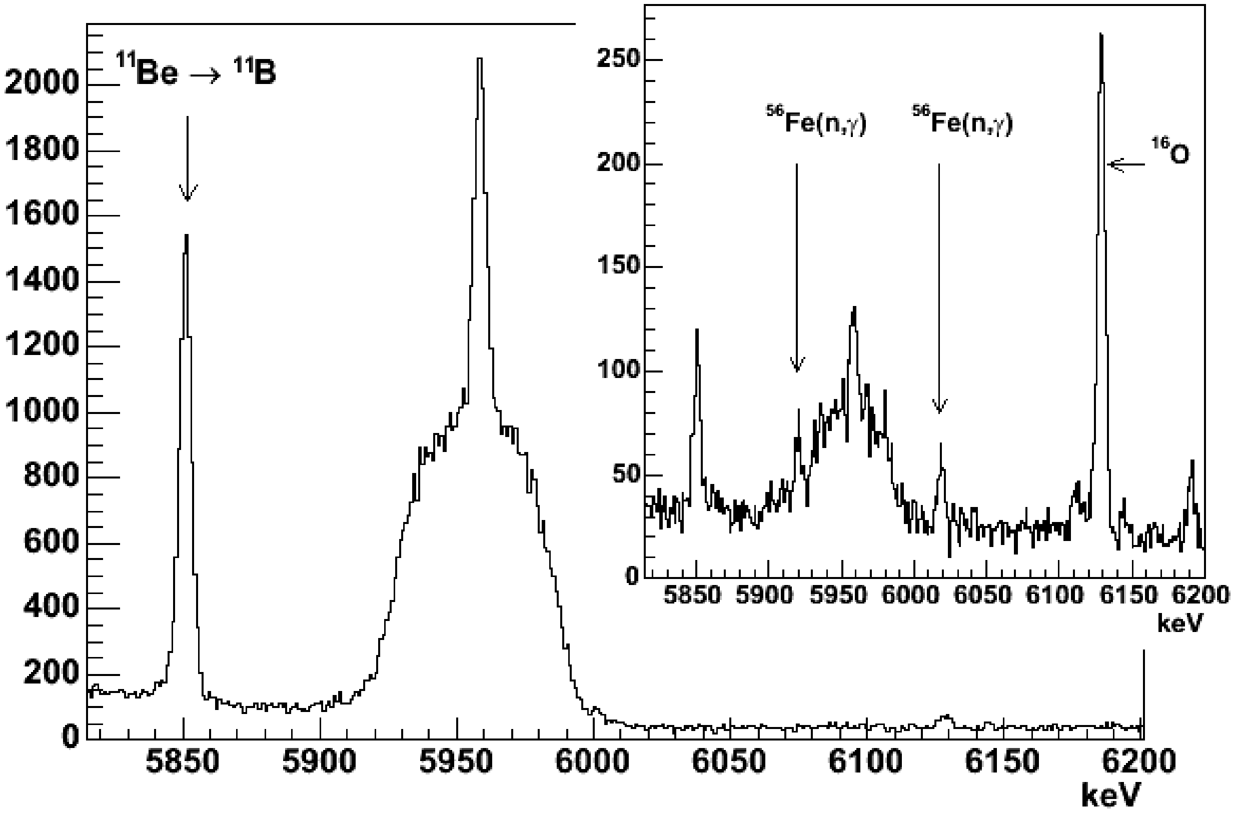

Figure 1. Comparison of data obtained from two ^{11}Li decay experiments. In the first experiment (inset), the ^{11}Li beam intensity was ~10^3 s^{-1}, and only the 8π Ge detectors were used. In the second experiment, the ^{11}Li beam intensity was ~1.5×10^4 s^{-1}, and coincidences with β particles detected with SCEPTAR was employed.

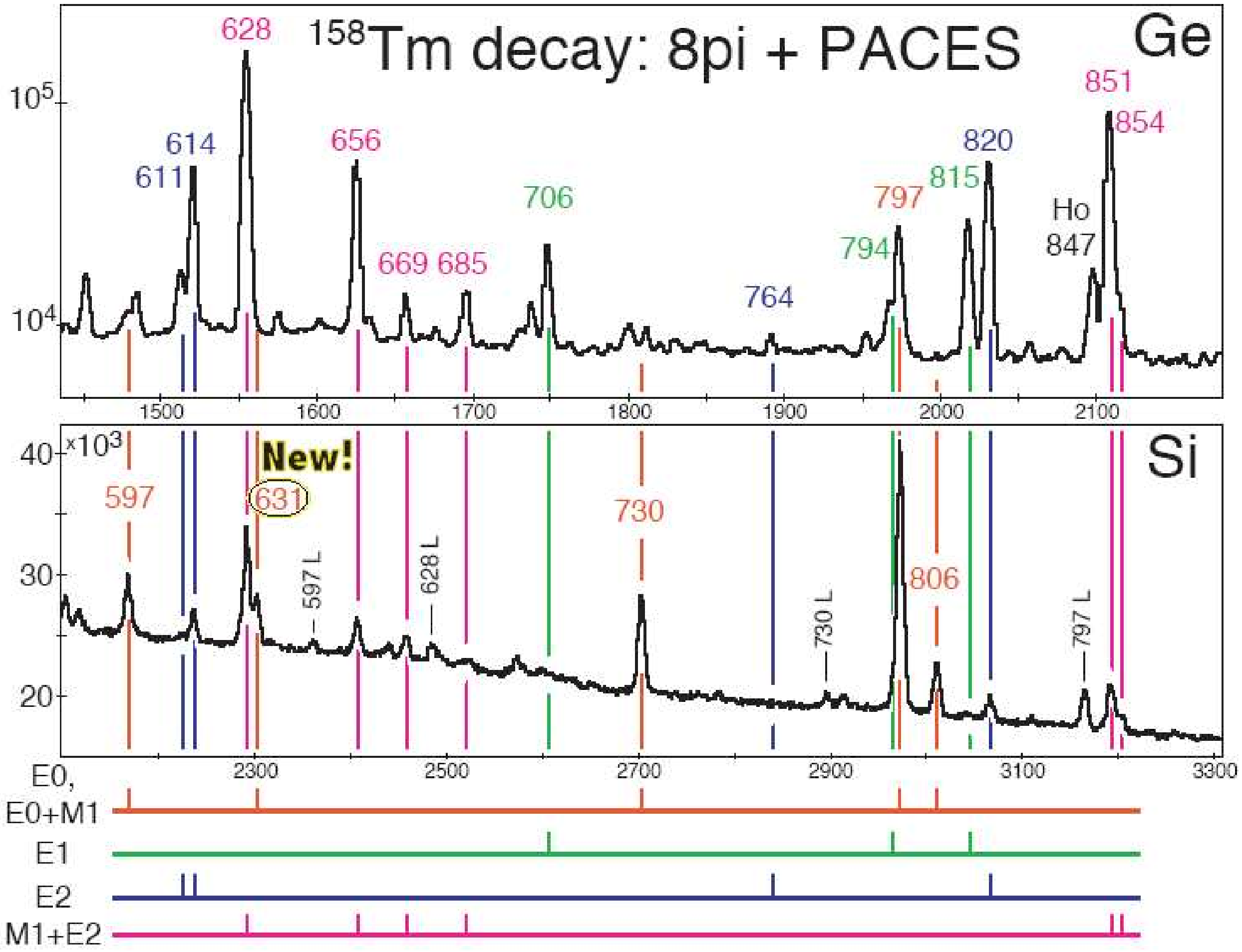

Figure 2. Portions of the γ-ray (top) and electron (bottom) spectra obtained with one of the 8π Ge detectors and one of the PACES Si detectors in the decay of ^{158}Tm. Peaks that are intense on the electron spectrum but moderate or missing in the γ-ray spectrum are identified as *E0* transitions.

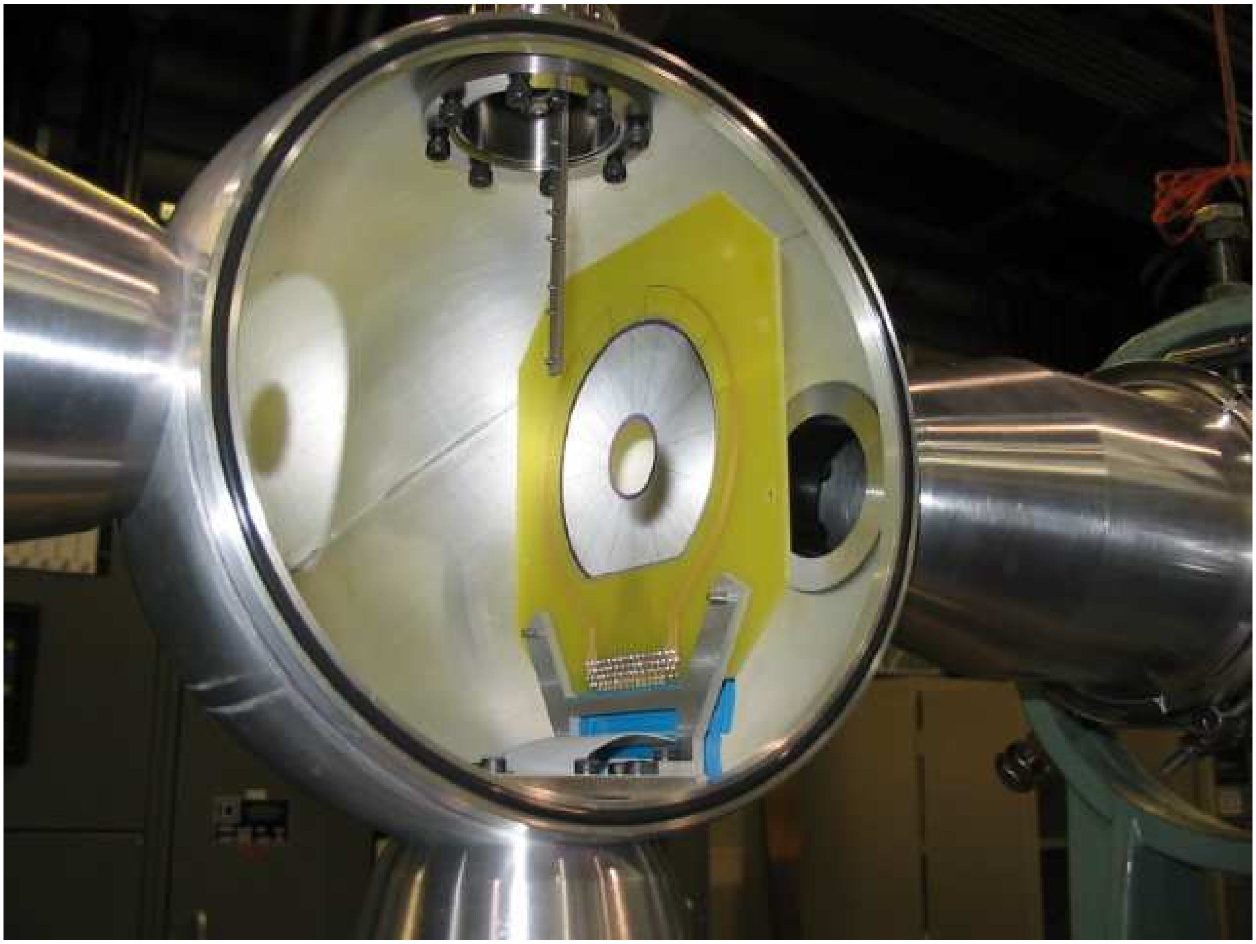

Figure 3. Photograph of one BAMBINO Si CD-S2 detector mounted in its target chamber. The beam enters from the left, impinges on the Ti target (not shown) and passes through the hole in the centre of the CD detector.

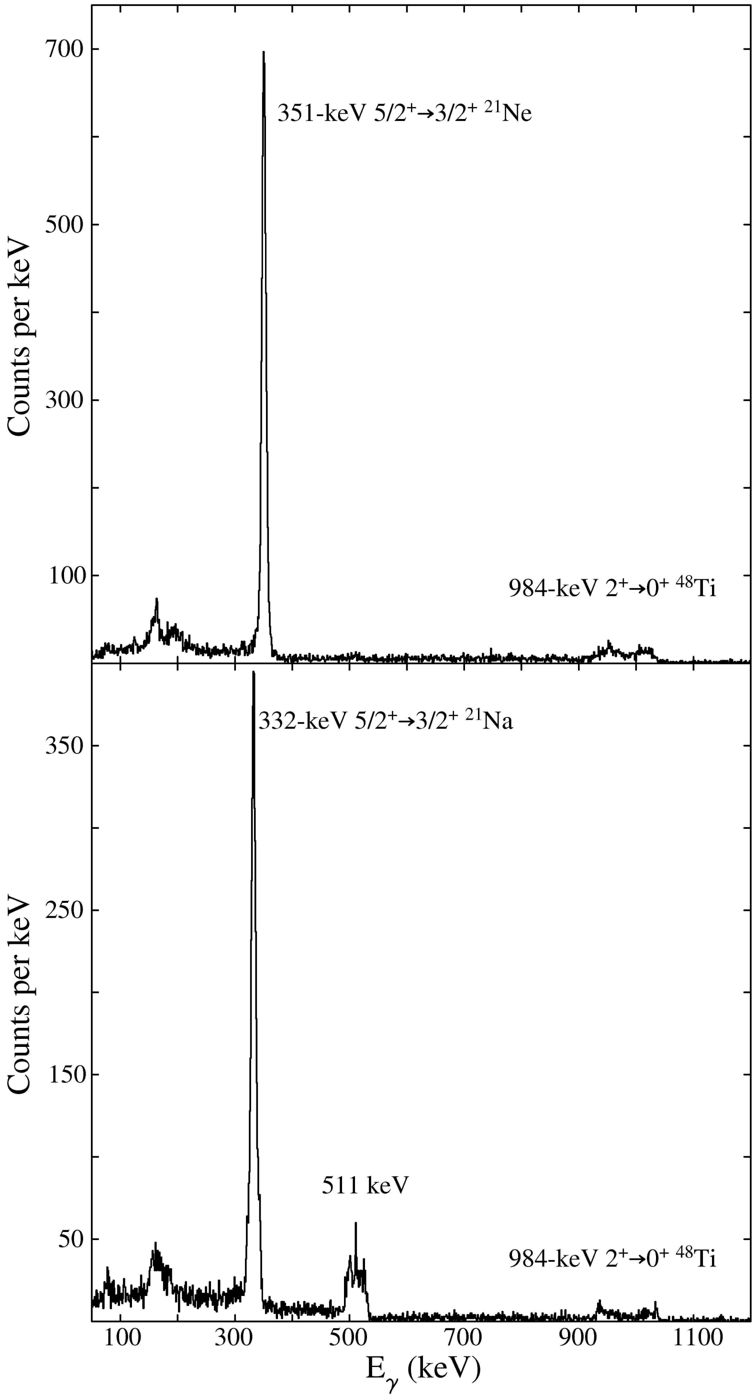

Figure 4. Portions of the γ-ray spectrum obtained from the Coulomb excitation of ^{21}Ne (top) and ^{21}Na (bottom) on a target of ^{nat}Ti using BAMBINO and TIGRESS. A coincidence condition with particles detected in BAMBINO has been applied, without background subtraction and a preliminary Doppler correction for the scattered beam particles has been used.