NEW DEVELOPMENTS IN ELECTRON AND RECOIL DECAY SPECTROSCOPY FOR STUDIES OF EXOTIC AND HEAVY NUCLEI*

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New developments in arrays of Ge and Si detectors to observe prompt γ-ray and conversion electron emission at the target are described. To study the structure of nuclei lying far-from stability which are produced with sub μb cross-sections, the target arrays will be used in conjunction with recoil separators, employing the method of Recoil Decay Tagging. A new focal plane spectrometer, GREAT, will be constructed which will give increased sensitivity to the studies of rare nuclei either using the RDT technique for identification of the prompt emission or by recoil decay spectroscopy in the focal plane of the recoil separator.

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1. Introduction

The route to achieving better understanding of the effective nuclear interaction lies in testing the predictions and limits of applicability of nuclear models by probing nuclei under extreme conditions. One approach, which has been actively pursued by many research groups world-wide over the last fifteen years, is to measure the properties of nuclei having very large angular momentum, up to their fission limit. Both macroscopic-microscopic and microscopic descriptions of nuclear behaviour have had considerable success in reproducing the kaleidoscope of different shapes that the nucleus is observed to assume as its angular momentum is varied. Another avenue is to examine the quantal behaviour of nuclei having either extremes in overall mass (heavy and superheavy nuclei) or extreme values of the ratio of neutrons to protons (exotic nuclei). The application to superheavy and exotic nuclei is a severe

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test of candidate theoretical models and demands a rigorous derivation of the nuclear Hamiltonian if the theories are to be applied globally. At present, the predictions of different state-of-the-art models, using the Strutinsky approach and the Skyme-Hartree-Fock method, give very different positions of the next spherical shell closure for protons beyond $Z = 82$ [1].

Thus experimental research is being directed towards the measurement of observables of exotic and very heavy quantal systems. There are essentially two methodologies. One is the use of radioactive beams to produce nuclei far-from-stability in nuclear reactions in sufficient quantities to carry out in-beam experiments. New accelerators such as the SPIRAL facility at GANIL, Caen, France, will achieve this by post-acceleration of the products of an initial reaction induced by a primary beam of stable nuclei. The other technique is to observe the nuclei of interest as the products of the primary reaction directly. This latter requires high incident beam intensities and extremely sensitive instrumentation in order to isolate the channel of interest. In either case, studies of the most rare nuclear species will require their separation from a large background of other products, their identification, and the detection of their decay processes.

2. Recoil decay tagging

The separation of the nuclei of interest, which are usually weakly populated products of compound nucleus reactions, can be achieved using a variety of recoil separators *e.g.* the gas-filled separator RITU [2] at Jyväskylä, the electromagnetic separator SHIP at GSI [3], the CAMEL at Legnaro [4], the FMA at Argonne [5] or the RMS at Oak Ridge [6]. The prompt γ radiation (or conversion electron emission) at the target is tagged with its isotopic character by measuring the radioactive decay properties of the nucleus at the focal plane of the recoil separator [7–9]. Since the decay lifetime is long compared with the average time between recorded events, it is important first to associate temporally the prompt radiation with the detection of a heavy recoil (the time variation is typically hundreds of nanoseconds) and then associate both temporally and spatially the recoil detection with its radioactive decay. The nuclear identification is then made on the basis of the characteristics of the decay process, *e.g.* the unique energy of α-emission. The latter association of the recoil and its decay is possible provided that the nuclear lifetime is shorter than the average time between events in each detector pixel defined by the detector position resolution. Figure 1 shows the relationship between lifetime and *total* rate in the detector for different granularities, which give real/random ratios of either 1/100 (minimum value necessary for α-decay tagging) or 1/10 (minimum value expected for β-decay tagging if the average β energy is also measured). It is assumed that the rate of detected evaporation residues is 2 per minute for the channel of interest.

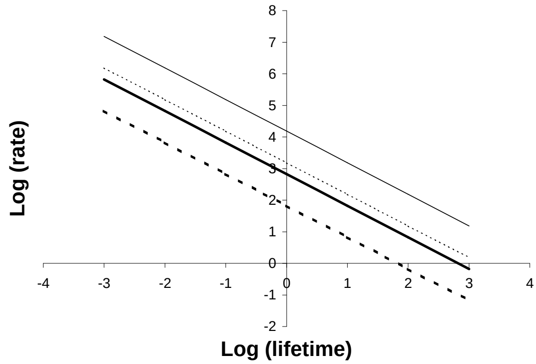

Fig. 1. The figure shows the allowed rate (per second) in the implantation detector as a function of decay lifetime (s) to give peak to total random background of either 1/100 (solid lines: typical of α-decay RDT) or 1/10 (dashed: expected for β-decay RDT) for a granularity of 200 (thick lines) and 4500 (thin lines). The GREAT implantation Si detector will have 5000 pixels. It is assumed that the rate of detected evaporation residues is 2 per minute for the channel of interest.

3. Target spectrometers

The operation of a large escape suppressed germanium array in conjunction with a recoil spectrometer was achieved with the coupling first of the TESSA [10] arrays and then with EUROGAM [11] to the Daresbury recoil separator [12,13]. More recently arrays such as JUROSPHERE and SARI have been used with the gas-filled separator RITU at Jyväskylä [14,15], and GASP has been coupled to the CAMEL recoil separator at Legnaro [16], AYEball [17] and Gammasphere [18] have been coupled to the FMA at Argonne, and the CLARION array has been coupled to the RMS at Oak Ridge. In order to improve the sensitivity for in-beam spectroscopy new target arrays are being developed.

3.1. The VEGA spectrometer

The GSI project VEGA [19] will comprise 4 very high efficiency segmented Clover germanium detectors. The crystals in each Clover have a diameter of 7 cm and length of 14 cm (before shaping). The total volume of germanium considerably exceeds all other detector designs. Each detector has an intrinsic photopeak efficiency of $\varepsilon_p = 0.38$ at 1.3 MeV. In a box geometry, these detectors can be positioned 7 cm from the target, giving a total efficiency of $\varepsilon_p \Omega = 20\%$ at 1.3 MeV. Each crystal is electrically segmented on its outer contact in 4 ways to give effectively 16 active segments. An escape suppression shield will surround each segmented Clover germanium detector. The flexibility of the VEGA array allows different detector configurations to be used for different experiments in order to minimise pile-up and Doppler broadening. For example, the detectors can be pulled back from the target position if a high multiplicity reaction is being used.

3.2. The SACRED spectrometer

The Liverpool-Jyväskylä SACRED silicon detector array [20] is designed to detect multiple conversion electron emission from the target. It employs a solenoidal magnetic field to transport the electrons from the target to the detector. The detector itself is segmented so as to form 24 or 25 independent elements, which have individual amplification and timing channels. An important component of the spectrometer is the electrostatic barrier, which suppresses the high flux of low energy electrons produced in atomic processes. The typical peak efficiency of the array is about 10% for electrons with incident energy between 100 and 300 keV. Recently this array has been used, in transverse geometry, to observe conversion in-beam electron emission from ^{232}U. The $e^{-}-e^{-}$ coincidence spectrum is shown in figure 2, similar in quality in terms of resolution and efficiency to that achieved by the best γ-ray arrays [21]. For RDT experiments where the prompt conversion electrons are tagged by recoil decay processes, the solenoid will have its axis parallel with the beam direction, in a collinear geometry. The annular silicon detector will be placed upstream of the target, which has the advantage that the atomic electron flux is smaller in this direction and the kinematic broadening of the electrons is a minimum.

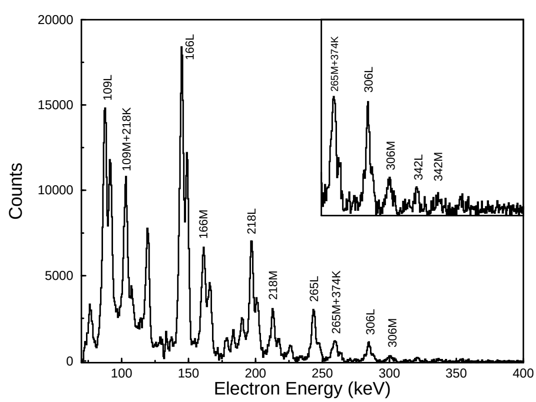

Fig. 2. Projection of electron-electron matrix taken using the SACRED array, for the reaction 42 MeV α + ^{232}Th, demanding that at least one electron has an energy corresponding to the $109_{\mathrm{L,M}}$, or 165_{L}, or $219_{\mathrm{K,L}}$ keV transition in ^{232}U. Contamination lines arise from the reaction α + ^{181}Ta.

4. The GREAT spectrometer

In order to achieve the necessary level of sensitivity, a tagging detection system deployed at the focal planes of the high-transmission recoil separators must be highly segmented, provide excellent energy resolution and have the highest possible efficiency. Furthermore, the large number of detector signals must be read out at high rates and the events of interest selected according to the temporal and spatial associations dictated by the physics of the experiment, without incurring unacceptable data losses. A new focal plane spectrometer, GREAT (Gamma, Recoil, Electron, Alpha, Time/ Tagging), and its associated electronics and data acquisition system will be constructed to satisfy these criteria.

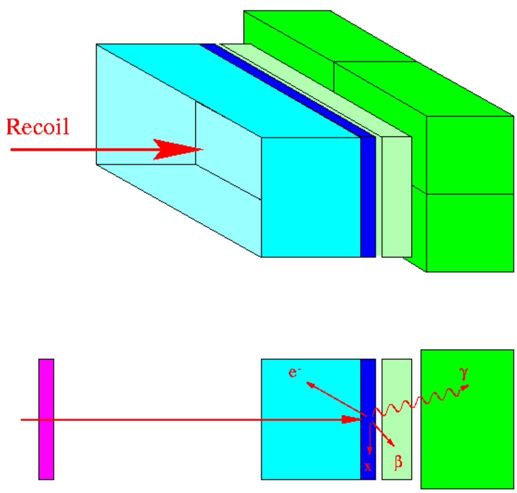

Fig. 3. Scheme of the GREAT spectrometer. The recoils pass through, in order, the multiwire proportional counter (not shown in the upper figure), the PIN Si box, the implantation Si detector, the planar Ge detector and the large volume Ge Clover detector.

The GREAT spectrometer (see figure 3) is designed to measure the properties of reaction products transported to the focal planes of recoil separators. GREAT comprises five distinct components:

(1) double-sided silicon strip detectors into which the reaction products are implanted and used to measure subsequent α particle, β particle or proton emission;

(2) an array of silicon PIN photodiode detectors to measure conversion electron energies with good ($\sim$ 2 keV) energy resolution;

(3) a double-sided planar germanium strip detector to measure the energies of X rays, low energy γ rays and β particles;

(4) a high efficiency segmented germanium Clover detector to measure the energies of higher energy γ rays;

(5) a multiwire proportional counter in front of the silicon strip detectors to act as an active recoil discriminator.

The silicon strip detectors and the germanium detectors are segmented in order to enable position correlations to be made with associated decays in the particle detectors of GREAT, while the separation of the photon energy range into two types of germanium detector gives the greatest flexibility and performance. GREAT provides the capability to measure all of the decays from the radioactive reaction products for both in-beam tagging and radioactive decay studies.

4.1. α-decay and proton decay

For α-decay measurements the energy resolution is limited by the pulse height defect. A FWHM of 10 keV at 5 MeV is the design aim and will ensure that in most cases the a lines of interest can be cleanly used for tagging. This is particularly important in the actinide region where neighbouring nuclei possess similar α-decay energies. High granularity is required when the α-decay lifetime is long. As well as measuring the energies of conversion electrons, the PIN silicon detectors surrounding the implantation detector will be used to detect ionising radiations that are emitted by nuclei within the strip detectors but escape without depositing their full energy. This will increase the efficiency for determining the full energy of α- particles from $\sim$ 55% to $\sim$ 80% using add-back techniques. It will therefore reduce the background in the low-energy region of the spectrum, which is particularly important for proton decay, where the sensitivity of the measurement is further improved by looking for α-proton correlations.

4.2. $\beta - \gamma$ tagging

Nuclei near the proton drip line with mass < 150 prefer to decay by β emission, and the general principle of RDT can be applied using this mode of decay. In this case, identification of the nucleus of interest requires association of the β particle with the heavy recoil by time and position correlation and association of the β particle with γ emission in the daughter nucleus. As typical β decay lifetimes are long ($0.1 \to 1$ s), and the total recoil rate in the implantation detector is high ($\sim 10^3 \to 10^4$), high granularity is required. The energy loss in silicon for the high-energy β particles is typically 30 keV/100 μm, which means that the electronic noise on each channel has to be kept to a minimum. The position and energy of the β particles are also measured in a planar germanium detector adjacent to the silicon detector. Their range in germanium is a few mm which determines the granularity and thickness of this detector. Division into pixels is required for two reasons: *(i)* to define the trajectory of the electrons between the silicon detector and the planar germanium detector so that the position uncertainty in the former detector matches its granularity; *(ii)* to reduce the counting rate in individual electronic channels. Measurement of the β-ray energy will also help remove background from more stable nuclei that have lower energy β end-points. Unique identification will rely on the detection of subsequent γ emission in the large germanium Clover detector, in prompt coincidence with the detection of the β particle.

4.3. Isomer decay

Measurement of the decay properties of isomeric states in the focal plane of the recoil separator will allow their prompt precursors be selected with excellent signal to noise. In this case the position of the delayed photon (X ray or γ ray) is determined using the planar germanium detector and higher energy γ rays measured using the Clover detector. The granularity of the planar detector has to match the mean free path of low energy photons in germanium: 90% of 50 keV and 100 keV photons will undergo energy loss in respectively 1.3 mm and 7 mm of germanium. Alternatively, conversion electron emission associated with the isomeric decay can be readily detected in the silicon detector array.

4.4. Electronics and data acquisition

The electronics and associated data acquisition system for GREAT will embody a different concept to most existing systems. Usually, data aquisition systems employ hardware gates to generate the master coincident condition, which cannot be triggered until the heavy recoil is detected in the focal plane of the recoil separator. This requires that the signals from the target array have to be stretched by up to several μs, allowing the data stream to be cluttered with additional signals of random origin which are not related to the triggering event. This can introduce unacceptable dead time in the data acquisition process. A more severe limitation arises when most of the reaction products are detected at the focal plane, as would be the case for reactions leading to medium mass compound nuclei. A decision has to be made as to which events are interesting, which in the case of RDT cannot be made until the radioactive decay has happened. As this process may not occur until several ms or even seconds after the initial reaction, the hardware master gate method becomes untenable. These difficulties will be overcome by building a Total Data Readout (TDR) system where all the electronics channels run independently and are associated in software to reconstruct events. The TDR system is triggerless and will allow all the data from both the target position and the focal plane to be collected. The advantage of this system is that there are virtually no system dead time losses. Each data word is associated with a timestamp generated from a common 100 MHz clock. The data are then reconstructed in the event builder using temporal and spatial associations defined by the physics of the experiment. In a simple example this could mean that all target position data will be rejected unless they have a corresponding recoil detected in GREAT with a timestamp $T \pm\Delta t$ (T is typically a few μs and Δt about 200 ns) later than the target data, corresponding to the flight time through the separator. In the experiments which exploit the β-γ tagging method, the prompt γ-ray data would only be written to tape if they were accompanied by a recoil ion signal, followed by a position-correlated high-energy β particle and accompanying (delayed) γ-ray within a certain time range. In the TDR system the only deadtime would be that introduced in the channel itself by the analogue shaping and conversion time (typically 10 μs). Data selection is carried out by the event builder and the selected subset of events are written to data tape.

5. Applications

The following experiments will become possible with the GREAT spectrometer and its associated target spectrometers. These few examples illustrate the new opportunities afforded by the high resolution, granularity and efficiency of GREAT.

5.1. Coulomb excitation of ^{254}No

The energy resolution of the silicon PIN photodiode array will allow the observation of low-lying collective states that decay by the emission of conversion electrons. For example, it is possible to measure both excitation energy of the first excited state in ^{254}No and the B(E2: $0^+ \to 2^+$) value following secondary Coulomb excitation which takes place after transmission through the recoil separator. Spectroscopic measurements of this nature will provide vitally important information on collective properties of the deformed superheavy mass region and provide clues as to the location of the next spherical shell gap for protons. According to the N_pN_n systematics of reference [22], the value of B(E2: $0^+ \to 2^+$) for ^{254}No, assuming no hexadecupole moment, should be 320 W.u. if the next proton magic number is 114 or 510 W.u. if it is 126 (with an accuracy of 15%). The value estimated from the known energy of the $2^+ \rightarrow 0^+$ transition [23, 24] and the Raman systematics [25] is 350 ± 140 W.u., insufficient to distinguish between the two possibilities. Collective excitation of the 2^+ state in ^{254}No is achieved by passing the recoiling ion through a degrader foil placed upstream of the silicon detectors. The probability for this process is about 10^{-3}. The detection rate of conversion electrons emitted in the decay of the 2^+ state, following production of the No recoil by the inverse reaction ^{48}Ca(^{208}Pb, 2n)^{254}No, will be sufficient to determinine the B(E2) to an accuracy of 20% or better.

5.2. Spectroscopy of ^{224}U

The nucleus ^{224}U is predicted to have the deepest octupole minimum in its ground state [26]. The cross section for its production is less than 1μb, which implies that RDT measurements of prompt γ-ray emission will allow the measurement of the decay scheme of ^{224}U in a few days running time using the new instrumentation described here. This estimate is based on previous experiments which measured the low-lying structure of ^{226}U ($\sigma \sim 6\mu$b) in an experiment using JUROSPHERE+RITU [27]. In the case of ^{224}U high-resolution measurements of its α-decay are also essential because the energy of this decay is similar to that found in the decay chain of a strong contaminant reaction. The RDT measurements are not capable of measuring the positions of the low-lying 2^+ and 1^- states in ^{224}U, which are crucial to the determination of octupole collectivity in this nucleus. The transitions from these states can be observed in GREAT following production of the parent nucleus ^{228}Pu, a nucleus that can be produced with a cross section of about 100 nb. Here $\alpha - e^-$ coincident measurements are made using the silicon detectors, for which only a few events are required.

5.3. β-γ tagging measurements of ^{80}Zr

The high granularity of the silicon strip detectors and the innovation of the double-sided planar germanium strip detector will open up important new regions of nuclei for study. In addition to α-decay studies of heavy nuclei, the GREAT spectrometer is designed to observe β decay and thus tag prompt radiation from lighter mass nuclei that lie far from stability. In this way the physics of nuclear systems with $N \sim Z$ can be investigated, including neutron-proton pairing, Coulomb energy differences of mirror nuclei and isospin mixing. One example that illustrates this is the study of the $N = Z$ nucleus ^{80}Zr, which decays by β^+ emission with a half-life of a few seconds [28]. Since most of the open channels lead to evaporation residues detected with high probability at the focal plane of the recoil separator, high granularity is required to remove the random background (see figure 1). This background is further removed by demanding a high-energy deposition in the planar germanium detector, and by requiring that this β-particle detection is accompanied by the detection of the known transitions [28] in the daughter nucleus ^{80}Y.

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