The SAGE spectrometer:
A tool for combined in-beam $\gamma$-ray and conversion electron spectroscopy.

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Abstract. The SAGE spectrometer allows simultaneous in-beam $\gamma$-ray and internal conversion electron measurements, by combining a germanium detector array with a highly segmented silicon detector and an electron transport system. SAGE is coupled with the ritu gas-filled recoil separator and the GREAT focal-plane spectrometer for recoil-decay tagging studies. Digital electronics are used both for the $\gamma$ ray and the electron parts of the spectrometer. SAGE was commissioned in the Accelerator Laboratory of the University of Jyväskylä in the beginning of 2010.

1. Theoretical motivation
One important but yet unanswered question in physics is the location of the next closed spherical proton and neutron shells. The increased stability due to these shells should lead to the formation of the predicted “island of stability” [1, 2] in the region of superheavy nuclei. The location of this region of increased stability is not yet specified as different theoretical approaches make conflicting predictions about the next spherical magic numbers. Microscopic-macroscopic models predict $Z=114$ and $N=184$ for the next doubly magic nucleus. On the contrary non-relativistic mean-field models predict these numbers at $Z=124$ and 126 and $N=184$ and relativistic ones at $Z=120$ and $N=172$ [3, 4, 5, 6, 7, 8, 9].

To get firm experimental evidence on the existence and exact location of the “island of stability” in-beam and decay spectroscopy studies of superheavy elements are required. So far elements with up to 118 protons have been produced ($^{294}_{118}$ [10]). The extremely low production cross sections, of 1 pb or less [11], of such heavy elements restricts the number of nuclei one can approach experimentally with the more neutron rich nuclei out of reach with current production methods.

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The Silicon And GErmanium (SAGE) spectrometer [12, 13] aims to provide a direct insight to the stability of elements with Z=114 and higher by performing in-beam γ-ray and internal conversion electron spectroscopic studies of lighter nuclei. This approach is driven by theoretical predictions which indicate that the single-particle Nilsson orbitals near the Fermi surface in deformed nuclei with proton number around 100 originate from spherical single-particle levels above the possible shell gap at Z=114 [14].

Studies of single-particle excitations in odd-mass nuclei or multiparticle-multihole excitations in even-even nuclei, where states involving the 2f5/2 orbital are populated, will provide information regarding the predicted closed spherical shells. The configurations of the experimentally observed bands can be deduced from the B(M1)/B(E2) reduced transition probabilities ratios. These are sensitive to the g-factors of the orbitals involved and according to the geometric model are [15]:

$$\frac{B(M1)}{B(E2)} \propto \frac{K^2(g_K - g_R)^2}{Q_0^2},$$

where $g_K$ and $g_R$ are the gyromagnetic ratios of the rotating core and the single-particle respectively, $K$ is the projection of the total angular momentum on the nuclear symmetry axis and $Q_0$ is the intrinsic electrical quadrupole moment.

From independent γ-ray and conversion electron experiments performed in transfermium nuclei [14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29] it was observed that the highly converted M1 transitions were present mainly in the conversion electron spectra, whereas the E2 transitions where most prominent in the γ-ray spectra. This implies that B(M1)/B(E2) are easily measured if the electrons and γ rays are observed in the same experiment in order to provide accurate branching ratios. The SAGE spectrometer was built in order to make efficient simultaneous conversion electron and γ-ray measurements in superheavy nuclei possible.

In addition to superheavy nuclei studies SAGE can be employed in the research of shape coexistence in the light lead and mercury region. In these cases a triplet of low-lying 0+ states associated with different macroscopic shapes is observed. The properties of the low-lying 0+ states and the inter-band transitions between the same spin-parity states of rotational oblate and prolate bands can be investigated through simultaneous conversion electron and γ-ray spectroscopy [30, 31]. These experiments will measure the conversion electron strengths of the inter-band transitions (oblate to prolate) and the location and feeding of the low-lying 0+ states. The measurements of the E0 matrix elements in neutron mid-shell isotopes of lead and mercury will provide direct information on configuration mixing and shape changes in these nuclei.

2. Description of the spectrometer

The SAGE spectrometer combines the JUROGAM II germanium-detector array for the detection of γ rays with a highly segmented silicon detector for the detection of electrons. SAGE can be coupled with the RITU gas-filled recoil separator [32] and the GREAT focal-plane spectrometer [33], as shown in Figure 1. The main parts of the spectrometer can be seen in Figure 2 which shows a design drawing of the setup and are explained in the following paragraphs.

SAGE is built on experience gained from designing and operating the SACRED spectrometer [34, 35]. SACRED employed a solenoid coil electron transport system to transfer conversion electrons from the target region to a segmented silicon detector. The knowledge and experience obtained from SACRED was necessary in order to optimise the resolving power and transmission efficiency of SAGE.

JUROGAM II consists of 15 so-called Phase I Compton-suppressed germanium detectors [36, 37] and 24 fourfold segmented Clover detectors [38]. The version of the array used as part of SAGE uses only 10 of the Phase I detectors and has a total γ-ray detection efficiency of 5.5% at 1332 keV.
Figure 1. A schematic representation of the SAGE spectrometer coupled with RITU and GREAT [13].

Figure 2. A design drawing of SAGE. The different parts of the setup are as follows: “A” the target position, “B” the silicon detector, ”C” the carbon foil unit and “D” the high-voltage barrier. Surrounding the target region are the JUROGAM II germanium detectors and around the beam pipe are the solenoid coils. The beam is represented by a cone [13].

The silicon detector is annular and segmented into 90 individual segments of varying size as shown in Figure 3. The detector is 1 mm thick with its active part having a diameter of 48 mm and the total diameter of the silicon being 50 mm. Even though the detector is highly segmented its total active area is approximately 96%.

A high-gain charge sensitive preamplifier is connected to each pixel of the silicon detector. A modified version of the CAEN A1422 hybrid preamplifier with 50 µs decay time constant and 400 mV/MeV gain is used.

The silicon detector is positioned 95.5 cm upstream of the target as shown in Figure 2. This is required because the silicon detector is sensitive to all types of radiation so if it was placed...
Figure 3. A photograph of the silicon detector used with SAGE. The individual segments are clearly visible with the signal tracks running across the surface of the detector connecting each pixel with one of the bonding pads situated on the outside part of the silicon.

near the target region not only conversion electrons but also other charged particles, like delta electrons, protons and α particles would be detected, creating a significant background. A solenoid coil system is used to transport the conversion electrons towards the silicon detector, as shown in Figure 2. The maximum magnetic field produced on the solenoid axis is 0.8 T downstream of the target with the field having an average value of 0.6 T upstream of the target. Magnetic shielding is used to reduce the effect of the magnetic field on the photomultiplier tubes of Jurogam II as explained in [12].

The electron transmission efficiency of SAGE is approximately 7% between 200 keV and 400 keV. At higher energies the efficiency gradually decreases and if the detection efficiency of the detector is taken into account it drops to about 3% at 600 keV. At lower energies the efficiency drops rapidly as most of the electrons are reflected by the electromagnetic fields.

The adopted near collinear geometry between the beam and solenoid axes illustrated in Figure 2 helps to reduce Doppler broadening and additionally decrease the flux of delta electrons reaching the detector. Delta electrons are low energy electrons produced during the collisions of beam and target particles and are emitted primarily at forward angles [39, 40].

To further reduce the delta electron background a high-voltage barrier is positioned in the region between the target and the silicon detector. Voltages of up to -50 kV can be applied to the high-voltage barrier and high vacuum conditions are required for its safe operation.

The required vacuum conditions of $10^{-7}$ mbar are obtained with the use of a carbon foil unit as shown in Figure 2. The carbon foil unit consists of two 50 μg/cm² carbon foils with intermediate pumping. This unit is necessary in order to separate the high vacuum region from the helium gas under which RITU operates. RITU is a QDQQ type separator using helium at 1 mbar or less as filling gas and is used for transporting to the focal plane reaction products recoiling out of a thin target and separating them in-flight from the accelerator beam. From Figure 2 it can be seen that the target region is in helium and so the targets are gas cooled. For experiments where higher beam intensities are required, a rotating target may be used for additional cooling.

Combining SAGE with RITU and GREAT allows the use of the recoil-decay tagging method [41, 42] which greatly enhances the background subtraction.

GREAT is positioned at the focal plane of RITU and utilises two double-sided silicon strip detectors for the detection of recoils and their subsequent α decays. The focal plane spectrometer additionally allows the measurement of other decay types. This includes X-rays and γ rays using a planar double-sided germanium detector and Clover germanium detectors. An array of PIN
detectors is used for the detection of conversion electrons. A multiwire proportional chamber at the entrance of GREAT is responsible along with the DSSDs, for distinguishing fusion reaction products from their subsequent decays and from scattered beam particles.

SAGE employs digital electronics to instrument both the electron and the γ-ray readout. Lyrytech 16-channel VHS-ADC cards are used to provide the 196 channels of electronics required, 90 for the silicon and 106 for the germanium detectors. In the ADC cards the outputs of the preamplifiers are directly digitised and then processed using the method of Moving Window Deconvolution [43, 44]. The digital data acquisition system can handle higher count rates than the previously used analogue system. Count rates of 30 kHz per detector should cause no problems to the system and rates of up to 45 kHz were observed in the Phase I detectors without energy resolution deterioration. Additionally the digital system shows linear behaviour throughout the energy range in contrast with the analogue system used previously with JUROGAM which showed non-linear behaviour at the low energy range.

The triggerless Total Data Readout (TDR) method [45] is used in SAGE. In this system no common hardware trigger is applied to start the data collection but all the channels run independently and are associated in software to reconstruct the events. This virtually eliminates the dead time issues arising when a common hardware trigger is used and when wide time gates are applied at the electronics employed for the focal plane detectors.

The Grain data analysis system [46] is used for both the online and the offline data analysis in SAGE experiments. Grain allows sorting of the TDR data using an experiment specific sort code written in Java by the user. Time, energy, energy loss or other gates can be defined in the sort code thus allowing the use of many powerful analysis techniques such as recoil-decay tagging. Multi-dimensional analysis of the sorted data can be performed with Grain. For example using two-dimensional histograms, γ-ray and conversion electron cross-coincidence analysis can be performed.

3. Summary and conclusions
The SAGE spectrometer was designed and built by a collaboration between the University of Liverpool, the University of Jyväskylä and STFC Daresbury Laboratory. SAGE combines the JUROGAM II germanium-detector array with a highly segmented silicon detector allowing efficient γ-ray and internal conversion electron cross-coincidence measurements. By coupling SAGE with the RITU gas-filled recoil separator and the GREAT focal-plane spectrometer the detection of recoils and their subsequent decays at the focal plane is made possible allowing the use of the powerful recoil-decay tagging technique.

The spectrometer has been successfully commissioned in the beginning of 2010 in the Accelerator Laboratory of the University of Jyväskylä. The commissioning runs showed that the spectrometer works within the design criteria but further work is required in order to optimise the behaviour of the silicon detector.

The first two experiments were performed at the beginning of 2010 studying shape coexistence in mercury and radon isotopes. The analysis performed on the data obtained from these experiments is yet to be finalised but proves that SAGE can efficiently measure γ rays and conversion electrons simultaneously and can be also employed for the detection of E0 transitions. Here γ-ray and conversion electron spectra (Figure 4) obtained using a $^{133}$Ba source are presented as proof of principle.

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Figure 4. Total $\gamma$-ray (left) and conversion electron (right) spectra obtained with the SAGE spectrometer using a $^{133}$Ba source. The labels over the peaks denote transition energies in keV. The inset in the conversion electron spectrum shows the said spectrum on a different scale.

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