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A study of the suitability of the LISE2000 spectrometer for SIRIUS commissioning experiments

R. Chakma and J. Piot on behalf of the SIRIUS collaborators

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Abstract

SIRIUS is a focal-plane detection system aimed to conduct decay spectroscopic studies on heavy and superheavy nuclei. For commissioning the setup, the LISE2000 spectrometer at GANIL was selected due to its availability. Simulations with the LISE++ code showed that the transmission efficiency of the spectrometer is rather small $\simeq 0.5\%$. This study has confirmed this result and also reports why this facility is not suitable for commissioning SIRIUS.

Introduction

Superheavy nuclei research has gained momentum with the development of new accelerators. In the coming years, the SPIRAL2 at GANIL will deliver very intense heavy ion beams making it possible to study exotic elements with low production probability. The nuclei of interest will be selected by the S^3 spectrometer and can be studied through decay spectroscopy. The detection system that will be installed at the focal plane of S^3 [1] is called SIRIUS (Spectroscopy and Identification of Rare Isotopes Using S^3)[2]. SIRIUS will be composed of a highly segmented double-sided silicon strip detector (DSSD) where the produced nuclei will be implanted, silicon pad detectors (Tunnel detectors), and Germanium detectors around the DSSD in a compact geometry. The tunnel detectors will measure charged particles such as alpha, electrons, fission fragments, and protons that would escape from the implantation detector following the decay of implanted ions. These ions will be identified using a time-of-flight measuring device based on the detection of secondary electrons released during the passage of ions through an emissive foil.

To commission this new detection setup, some standard reactions such as $^{170}\text{Hf}(^{40}\text{Ar}, 3-4n)^{216,217}\text{Th}$ and $^{174}\text{Yb}(^{40}\text{Ar}, 4-5n)^{209,210}\text{Ra}$ are foreseen. These experiments will verify the operation of the SIRIUS and test the data acquisition system in real conditions. The LISE2000 spectrometer[3] at GANIL is available to perform these experiments. Simulations of $^{174}\text{Yb}(^{40}\text{Ar}, 4-5n)^{210-209}\text{Ra}$ in the LISE2000 spectrometer using the LISE++[4] code showed that the transmission efficiency of the spectrometer is about 0.5% for $^{210-209}\text{Ra}$ nuclei in the 20^+ charge state. On the 21st of April 2021, this experiment was performed to check its suitability for the commissioning purpose of SIRIUS. This report presents the setup used and discusses the results obtained in the experiment.

Experiment

To produce $^{209,210}\text{Ra}$ nuclei, a ^{40}Ar beam was delivered in $17-18^+$ charge state from the CIME cyclotron of SPIRAL1 on a ^{174}Yb target. The target was $0.252(39) \text{ mg/cm}^2$ thick, and the beam had average energy of 4.62 MeV/u at the middle of the target. The evaporation residues (ERs) produced in the reaction were then separated by the first achromatic part of the LISE (Ligne d'Ions Super Epluches) spectrometer[5]. The ERs went through a multiwire proportional counter (MWPC) and got implanted into a double-sided stripped detector (DSSD) placed at the focal plane of the separator. A schematic diagram of the experimental setup is shown in fig 1. The MWPC held 15 mm isobutane (C_4H_{10}) at $\approx 4-6 \text{ mbars}$ with $0.9 \mu\text{m}$ thick Mylar windows on both sides. The DSSD had a dimension of $5 \times 5 \times 0.03 \text{ cm}^3$ and had 16 front and 16 back strips forming 256 pixels for position and time correlations.

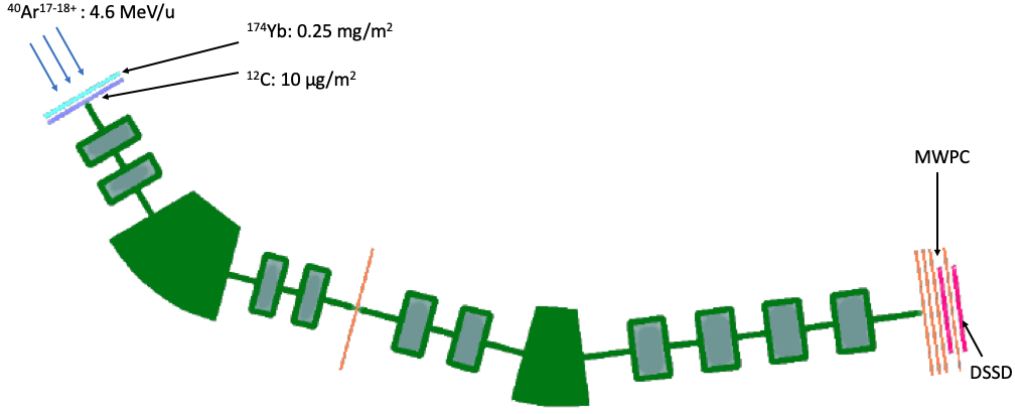


Figure 1: A schematic of the experimental setup.

The distance between the DSSD and the MWPC was $\simeq 43$ cm. A time-to-amplitude-converter (TAC), ORTEC-566 was used to measure the time of flight of the ERs. The TAC was started using an OR signal from the 16 front strips of the DSSD and stopped by a delayed signal from the MWPC. The MWPC signal was delayed by ~ 180 ns to operate in the 200 ns range. The TAC was not calibrated in this experiment and calibration parameters of a similar TAC with the same settings were used. The DSSD was calibrated using a standard 3- α source (^{239}Pu , ^{241}Am , ^{244}Cm). The calibration of the front and back strips are shown in fig. 2a and 2b respectively. The resolutions (FWHM) of the front and backside at 5.8 MeV of ^{244}Cm were found to be 66 keV and 75 keV respectively, sufficient for the purpose of this study.

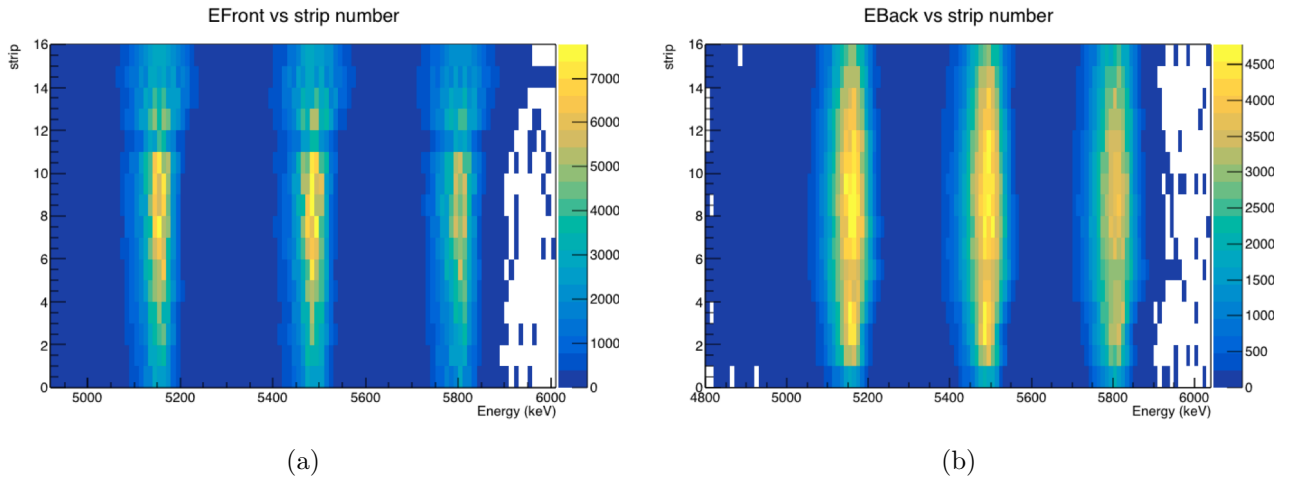


Figure 2: Calibration of the a) front and b) backside of the DSSD using a standard 3- α source. The horizontal axis gives the calibrated energy, and the vertical axis represents the strip number on each side.

Results and Discussions

Several runs were performed to investigate the transmission and the rejection capability of the spectrometer for three charge states (Q): 18^+ , 20^+ , and 21^+ . For each charge state, the runs have been added and analyzed. Because of better statistics, only the summed spectra corresponding to the 20^+ charge state are presented here.

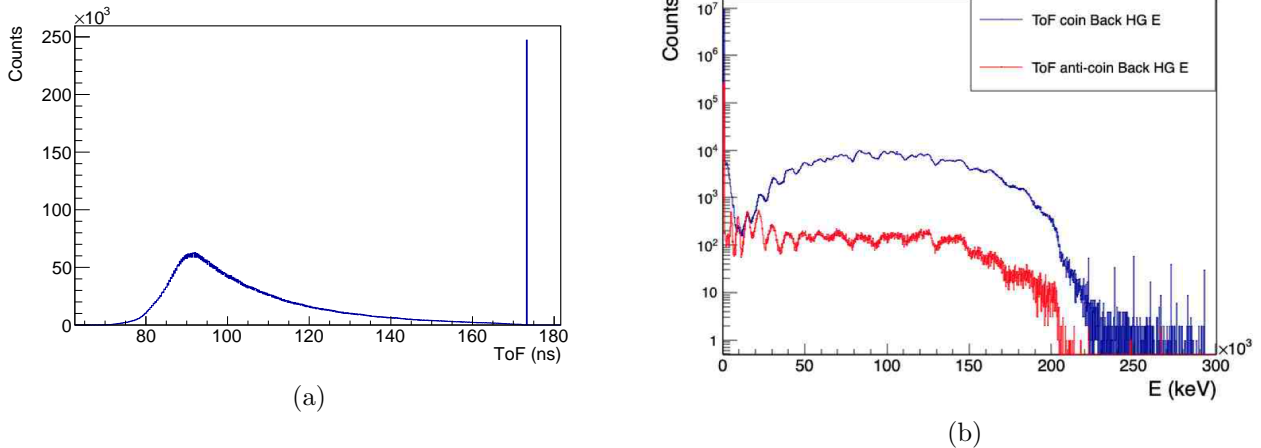


Figure 3: a) The calibrated ToF spectrum and b) the energy spectra recorded in the Si detector in coincidence and anti-coincidence with ToF signals. The low energy peaks correspond to the pedestal values.

The spectra of energies¹ of the particles recorded in the DSSD in coincidence (recoil-type DSSD signal) and no/anti (decay-type DSSD signal) coincidence with a ToF signal are shown in fig. 3b. The ToF spectrum of the reaction products is shown in fig. 3a. Note that because the TAC was started by a signal from the DSSD and stopped by a delayed signal from the MWPC, $\text{ToF} = \text{delay} - \text{TAC amplitude}$. Overwhelmingly large peaks on the lower value side in the energy spectra and the peak towards the end of the time spectrum are related to their respective pedestal values. In the ToF spectrum, the peak around 90 ns corresponds to the time of flights of the fusion products with ≈ 33 MeV kinetic energies. The ERs lose about 10 MeV in the Mylar foils of the MWPC, and their velocities can be calculated using eq. 1:

$$v = \sqrt{\frac{2 \times KE[\text{MeV}]}{M \times 931.5[\text{MeV}]}} \times 30 \text{ [cm/ns]} \quad (1)$$

where KE is the kinetic energy, M is the mass of the recoils. So, for ^{210}Ra , eq. 1 gives $v \sim 0.46$ cm/ns, and hence, $\text{ToF} \sim 92$ ns.

This is indeed what is seen in the ToF spectrum. Furthermore, in the anti-ToF-coincident plot of the DSSD, a peak around 7 MeV is in agreement with the energies of the alpha particles from the decay of $^{209-210}\text{Ra}$ (see fig. 4a).

The energies and ToFs of the recoils correlated in position with the decay-type signals ranging from 6.9-7.15 MeV are overlaid (red dots) on the Energy-ToF matrix of the recoils (see fig. 4b). One can see that the recoils of interest have more than the expected energies. This irregularity is perhaps a manifestation of the summing of energies of multiple recoils since a very high recoil rate was observed in the DSSD. The recoil rate and decay rate [per sec] in each pixel of the DSSD are shown in fig.5. One can notice that the recoil rate is nearly twenty folds larger than its counterpart decay rate in every pixel. From the temporal correlations of decay signals with the preceding ones in the same pixel, the lifetime of a nuclear species is usually determined. The half-lives of ^{209}Ra and ^{210}Ra nuclei are 4.7(2) s and 3.8(2) s respectively[6]. Considering these relatively long lifetimes and the observed recoil rate, it is not surprising to find wrong time correlations of the decay signals to their parent signals. If the recoil rate is very high, the information of the parent recoil is erased by the successive recoils leading to wrong correlations. Fig. 6 shows the energy of the decay signals on the horizontal axis, and the vertical axis gives their time difference ΔT in the Log_2 scale relative to the last recoil in the same pixel. In the figure, the lifetime of the ^{209}Ra has been marked with a dotted line for reference. The lifetime of the supposed alpha decays of $^{209-210}\text{Ra}$ (encircled with a rectangle) appears

¹Since the calibration of the DSSD was carried out in the 5-6 MeV range only, the calibrated energies of many recoil-type and decay-type events appear to be larger than the beam energy of 184 MeV.

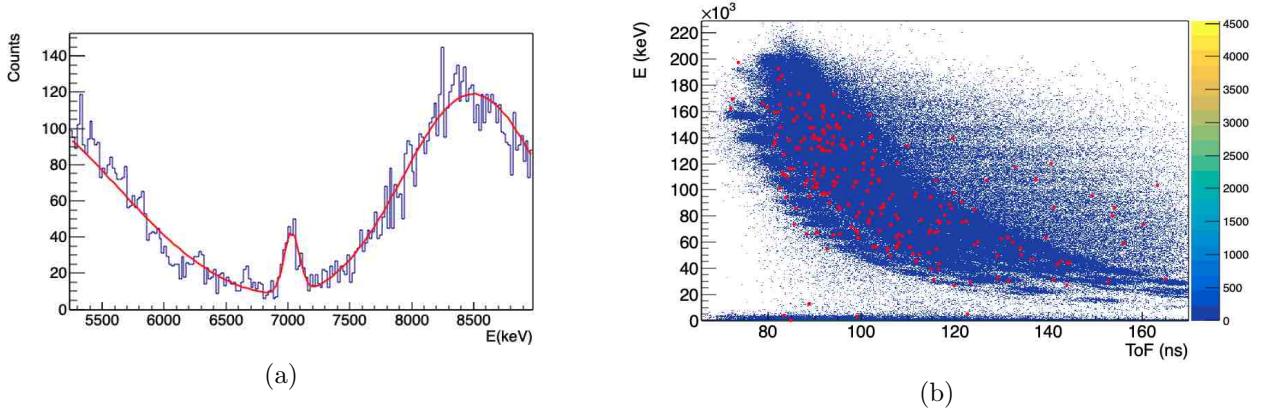


Figure 4: a) The spectrum of energies of decay-type (anti-ToF-coincident) signals recorded in the DSSD. b) The Energy-ToF matrix of the recoil-type signals. The red dots represent the energies and the ToFs of the recoils correlated with the decay-type signals in the range (6.9 - 7.15 MeV).

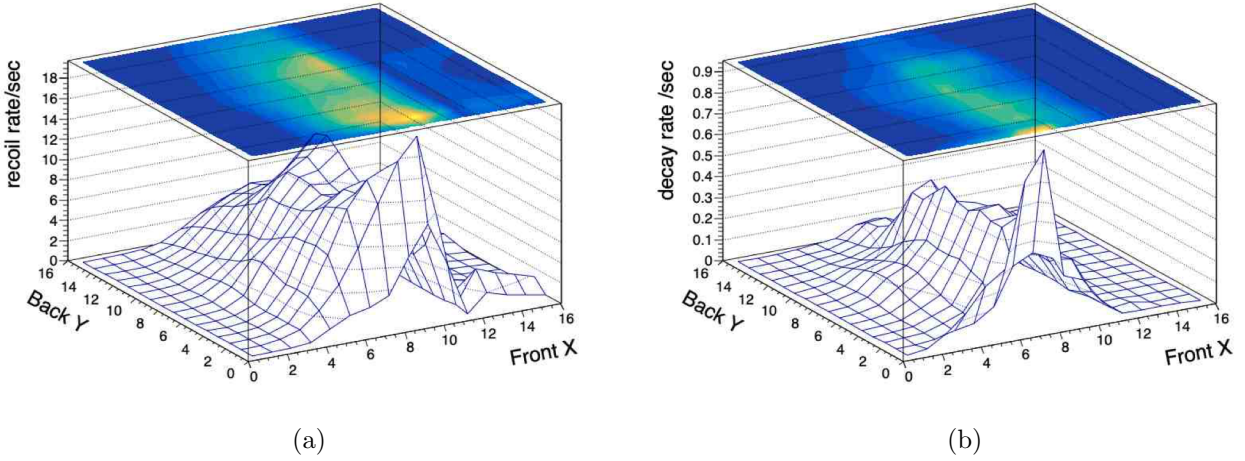


Figure 5: Rate [s^{-1}] of a) recoil-type and b) decay-type signals registered in the DSSD.

much lower than the expected value because of the high recoil rate. Besides energy measurement, lifetime measurement serves as a reliable probe in identifying the nuclear species. Hence in this study, the identification of $^{209-210}\text{Ra}$ nuclei expected to be produced in the reaction remains inconclusive. By assuming that the peak around 7 MeV is due to full-energy deposition of the alpha particles from the decay of $^{209-210}\text{Ra}$ nuclei produced in the reaction, the transmission factor (T_Q) and the rejection factor (R_Q) of the separator were estimated.

The rejection factor is the ratio of the number of particles not detected in the DSSD over the number of particles entering the separator (Dose). Here one-to-one collision of beam particles and target nuclei is assumed, i.e., no two or more ions come out of the target when a projectile collides with the atoms in the target material.

$$R_Q = 1 - \frac{N_{\text{detected in the DSSD}}}{\text{Dose}}$$

where,

$$\text{Dose} = \frac{\text{beam intensity} \times \text{time}}{\text{charge state} \times 1.6 \times 10^{-19}}$$

R_Q is not very useful quantity as $N_{\text{detected in the DSSD}} \ll \text{Dose}$, hence, $\frac{\text{Dose}}{N_{\text{detected in the DSSD}}}$ is used to reflect the rejection capability of the separator.

The transmission factor can similarly be defined as the ratio of $^{209-210}\text{Ra}$ nuclei detected in the

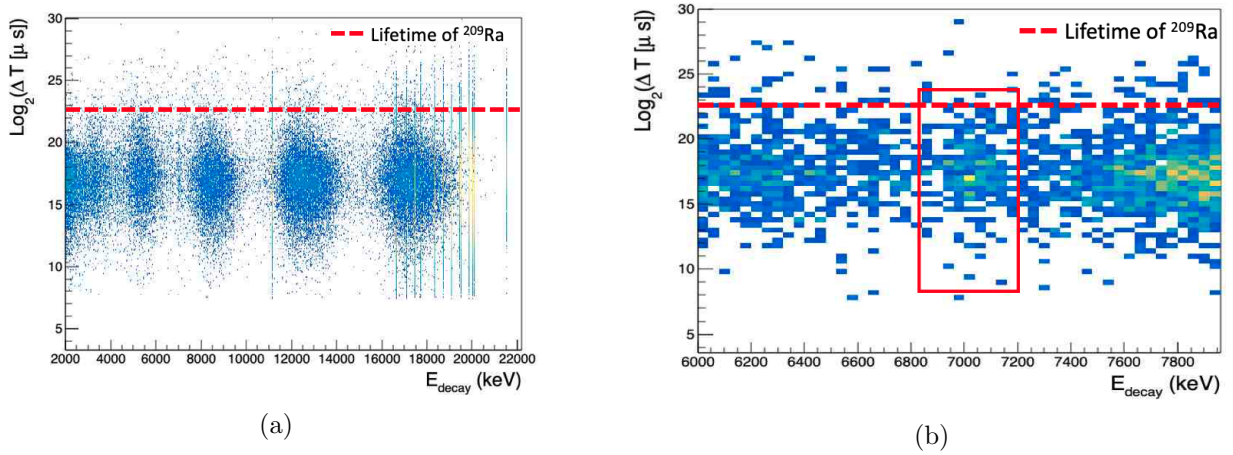


Figure 6: a) Energy and time correlation plot of the decay signals occurring in the same pixel. The horizontal axis gives the energies of the decay-type signals, while the vertical axis gives their time differences relative to the corresponding last recoil-type signals. b) A zoomed section of a) to highlight the full-energy depositing alpha particles from $^{209-210}\text{Ra}$ nuclei.

DSSD out of the number produced in the reaction:

$$T_Q = \frac{N_{\text{detected}}}{N_{\text{produced}}}$$

The number of $^{209-210}\text{Ra}$ produced in the reaction can be estimated using the following equation:

$$N_{\text{produced}} = \text{Dose} \times \sigma \times \text{number of target nuclei per unit area}(N) \times \text{target thickness}$$

where σ is the cross-section ($\sigma = 1.4$ mbarn for the reaction of interest). The number of target nuclei per unit area is given by:

$$N = \rho \times N_A / M$$

where N_A is the Avogadro constant (6.022×10^{23} particles per mole), ρ is the density and M is the molar mass of the target.

$$N_{\text{produced}} = \text{Dose} \times \sigma \times \rho_A \times N_A / M \quad (2)$$

where ρ_A is the mass thickness / the surface density / density thickness defined as:

$$\rho_A = \frac{\text{total mass}}{\text{total area}} = \rho \times \text{average thickness}$$

In this study, the signal-to-noise ratio (S/N) is defined as the ratio of the number of $^{209-210}\text{Ra}$ full-energy-depositing alpha particles to the remaining number of the decay-type signals. The results obtained using the above relations are given in table 1. The transmission efficiency of the spectrometer is small for all three charge states. In addition to a very high recoil rate in the DSSD, the ToF system was not 100 % efficient, resulting in smaller S/N ratios and a loss of time correlations. A tiny fraction of the dose identified as decay-type signals can easily eclipse the number of $^{209-210}\text{Ra}$ nuclei produced in the reaction. Hence the real recoil rate is slightly higher, and the decay rate is much lower than the measured ones reducing the correlation time window even more than the limit imposed by the recoil rate. It is evident from fig. 6, only time correlations up to a few hundredths μs are possible, this limit is far lower than the lifetimes of the ^{209}Ra and ^{210}Ra nuclei.

Conclusion

This study confirmed the simulated transmission efficiency of the LISE2000 spectrometer obtained using the LISE++ code and demonstrated that the spectrometer is not suitable for commissioning the SIRIUS detection setup due to poor selection of nuclei of interest, low transmission, and rejection capabilities.

Charge state	18 ⁺	20 ⁺	21 ⁺
Run time (s)	3635	12149	1686
Avg beam intensity (μA)	0.023544	0.020645	0.027125
$B\rho$ (T.m)	0.5746	0.5171	0.4925
Dose	2.97×10^{13}	7.828×10^{13}	1.36×10^{13}
Number of recoils in the DSSD	389264	9.2×10^6	1.2×10^6
1/(1 - Rejection factor)	7.8×10^7	8.5×10^6	1.13×10^7
ToF efficiency (%)	96.3	97.3	98.03
Number of $^{209-210}\text{Ra}$ produced	36235 ± 5608	95575 ± 14791	16597 ± 2569
$N_{\alpha-full}(^{209-210}\text{Ra})$	8(5)	291(39)	27(14)
Transmission factor (%)*	0.044(28)	0.61(12)	0.33(18)
Number of decay-type signals in the DSSD	14089	252668	23791
S/N (%)	0.05(2)	0.115(7)	0.11(2)

Table 1: The transmission factor and the rejection capability of the LISE2000 facility are given for the three charge states: 18⁺, 20⁺, and 21⁺. $N_{\alpha-full}$ is the number of alpha particles that deposited full energy from $^{209-210}\text{Ra}$ decays. * The transmission factor was calculated assuming 50% of the alpha particles escape the DSSD, hence the number of $^{209-210}\text{Ra}$ detected is $2N_{\alpha-full}$. The errors in the numbers of $^{209-210}\text{Ra}$ produced were computed only from the uncertainty in the thickness of the target.

Acknowledgment

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