Delta-ray simulations for the SAMURAI-Si project at RIKEN

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I. Introduction

The Superconducting Analyzer for Multi-particle from RAdio Isotope beams (SAMURAI) is a large acceptance spectrometer currently under construction at the RIBF facility at RIKEN, Japan [1]. It will consist of a large-gap superconducting magnet with 7 Tm of bending power. Among the experiments planned with this new device are proton breakup reactions with proton-rich exotic beams, exciting proton unbound states in these nuclei with (γ,p) reactions induced by virtual photons. These are of interest to nuclear astrophysics as they play an important role in nucleosynthesis processes, such as the rp-process.

The invariant mass method will be used. In this method, the kinetic energies and scattering angles of the breakup products must be measured to high precision in order to obtain information about the relative angle and energy (E_{rel}) between the particles, and relate to the reaction mechanism. A resolution of ~0.2 MeV at E_{rel} = 1.0 MeV is desired, and this can be obtained if the resolution of the opening angle between the proton and the heavy-ion residual has a resolution of □θ_{open}~2 mrad. However, this precision is difficult to reconstruct after the breakup reaction products have been separated by SAMURAI and detected in the focal plane detectors. A more precise measurement of the opening angle is possible if silicon strip detectors are placed after the reaction target, but before the SAMURAI spectrometer.

Simulations with the GEANT4 package [2] were conducted in order to determine a possible arrangement for placing silicon detectors in the setup for the (γ,p) reaction measurements. In these calculations, the detection efficiencies and resolutions were compared for two types of silicon strip detectors: the GLAST single-sided strip detector (SSSD), manufactured by Hamamatsu, and the TTT double-sided strip detector (DSSD), manufactured by Micron Semiconductor Ltd. In addition, possible experimental difficulties, such as the effect of delta-ray electrons on the measurement, were investigated with these simulations.

II. Simulations of the detection efficiency and resolution

The design specifications for the silicon detectors associated with the (γ,p) reaction setup for SAMURAI require that the silicon detector setup should have close to 100% efficiency for detection of proton-Heavy Ion (p-HI) pairs with E_{rel} < 1 MeV. This corresponds to having an angular coverage of about 3.6° in the lab for most experiments with secondary beams at 250 MeV/u. For a hypothetical Si detector with 10 cm × 10 cm of surface coverage, a simple calculation shows that the Si detectors can be placed up to 80 cm away from the breakup reaction target and still satisfy the efficiency requirement. The TTT-DSSD detectors have 9.73 cm × 9.73 cm of surface coverage, while the GLAST-SSSD detectors have 8.75 cm × 8.75 cm of surface coverage. The 100% detection efficiency requirement can be still be satisfied by the GLAST-SSSD detectors if they are placed up to 70 cm away from the target.

To verify the assumptions of the simple calculations mentioned above, a simulation of the proposed Si-detector setup was conducted with GEANT4. In the simulation, the breakup reactions $^{9}C \rightarrow {}^{8}B+p$ and $^{57}Cu \rightarrow {}^{56}Ni+p$ at 250 MeV/u were investigated. A target of ^{208}Pb with areal density of 10 mg/cm^2 was assumed. Two Si detectors of each type were placed at 50 cm and 80 cm from the ^{208}Pb target. The detection efficiency was simulated with the requirement that both the proton and heavy ion should be detected by both detectors in each event, and thus the detection efficiency was limited by the detector that was placed the farthest downstream from the reaction target. The results of these simulations for the two reactions and two detector types are shown in Figure 1. Both detectors satisfy the efficiency requirement for the $^{57}Cu \rightarrow {}^{56}Ni+p$ reaction, but a larger opening angle in the case of the $^{9}C \rightarrow {}^{8}B+p$ reaction leads to lower detection efficiency (the "simple" calculation above assumed that $M_{HI} >> M_{proton}$). This problem can be corrected if the detectors are simply moved closer to the target as required by the experiment.

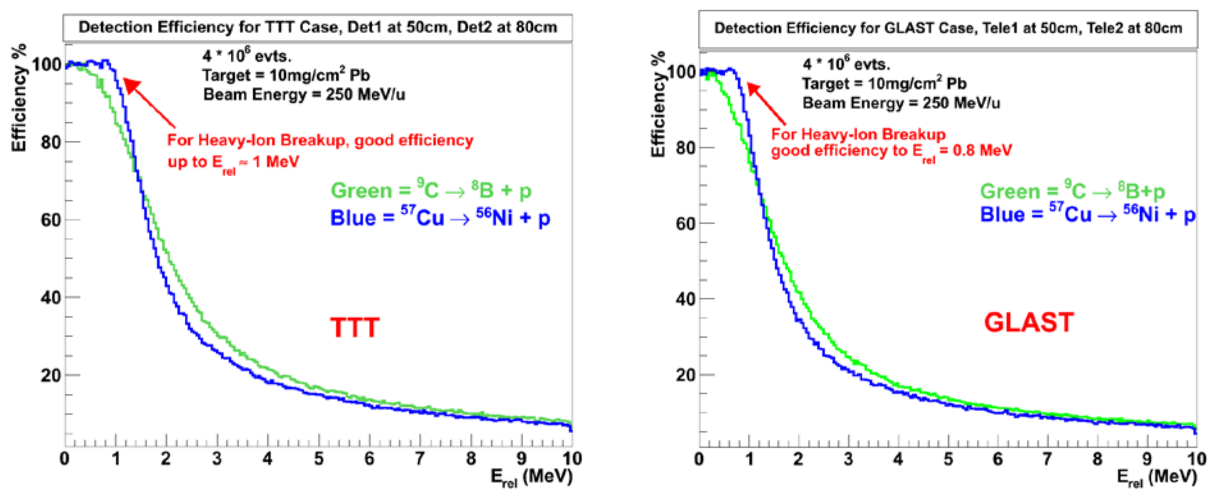

FIG. 1. Results of the breakup reaction detection efficiency simulations for the case where the TTT-DSSD or GLAST-SSSD detectors were placed at 50 cm and 80 cm downstream of the reaction target. Both types of detectors had close to 100% efficiency for the heavy-ion (^{57}Cu) breakup, whereas the efficiency was reduced for light-ion (^{9}C) breakup case.

GEANT4 simulations were also carried out to investigate if the detectors satisfied the design specifications for the resolution of E_{rel}. Since both detectors have strip pitches of < 1 mm, the 2 mrad angular resolution is possible. In practice, the simulations show that for both types of detectors, the resolution of E_{rel} is mainly limited by the thickness of the reaction target and not by the strip pitch of the detectors.

III. The Effect of Delta Electrons

In order to maximize the detection efficiency for the breakup reactions at $E_{rel} < 1$ MeV, the silicon detectors should be placed along the beam axis after the reaction target. This implies that the unreacted beam and the reaction products from the breakup reactions will interact with the silicon detectors. As these charged ions pass through the reaction target and silicon detectors, they will scatter atomic electrons from the material, creating delta-rays (δ-rays). At 250 MeV/u, the maximum kinetic energy of elastically scattered electrons is $(4m_e/M_{beam})*E_{beam}$, corresponding to $E_e \approx 550$ keV. Electrons passing through silicon deposit 1.66 MeV/(g/cm^2) [3]. Thus, δ-rays with $E_e = 550$ keV passing though 300 μm of silicon, the proposed thickness of the Si detectors for the (γ,p) experiments, would deposit about 116 keV, not including the electron angle of incidence or the multiple scattering in the silicon. For comparsion, a 250 MeV proton from the breakup reaction deposits around ≈ 200 keV as it passes through a detector with that thickness. Since the energy deposits for the δ-rays and the protons are both relatively low in energy, the δ-rays could cause "cross-talk" and false proton events in the silicon detectors.

Simulations of the δ-ray energy and production were also carried out with GEANT4 using the standard EM models for ionization and electron multiple scattering. In these simulations, the number of δ-rays scattered from the first silicon detector downstream of the reaction target and detected in the second silicon detector was investigated. First, the distance between the two detectors was varied. This distance is important because for the GLAST-SSSD solution, silicon detector telescopes with two detectors that are close together (within 2 cm) are needed to give simultaneous x and y position measurements for the reaction products (the TTT-DSSD detectors give x and y position measurements within one detector). Summaries of the results of these simulations are given in table 1 and figure 2. In figure 2, it is seen that the number of δ-rays detected in the second Si detector decreases roughly exponentially with distance. For this reason, having the Si detectors close together, such as would be the case with the GLAST-SSSD telescopes, should be avoided as there will be too many false events generated by the δ-rays.

Table I. Summary of the simulation results for the δ-rays

Distance between dets.	δ-rays/1000 evts.	$\langle n_\delta \rangle$/event	$\langle E_\delta \rangle$/event
2 cm	26513	27	115 keV
10 cm	8894	8.9	113 keV
25 cm	1856	1.9	110 keV
50 cm	474	0.47	115 keV

Other solutions for reducing δ-rays were tried in the simulations. One solution was to modify the silicon detector by making a hole in the middle of the detector for the beam to pass through. While this solution would reduce the number of δ-rays produced, it was also found to reduce the detection efficiency for the breakup reactions, especially for the heavy-ion cases of interest like ^{57}Cu → ^{56}Ni+p where the θ_{open} would be within the detector hole for small E_{rel}. Another solution was to place a material in between the Si detectors to absorb or deflect the δ-rays. Thin (15μm) sheets of materials like Ta were effective in reducing the δ-rays that triggered the second Si detector, but these sheets also degraded the resolution of the E_{rel}. So, maximizing the distance between the Si detectors seems to be the best way to minimize the effect of δ-rays on the breakup reaction measurement while not sacrificing detector efficiency and/or resolution.

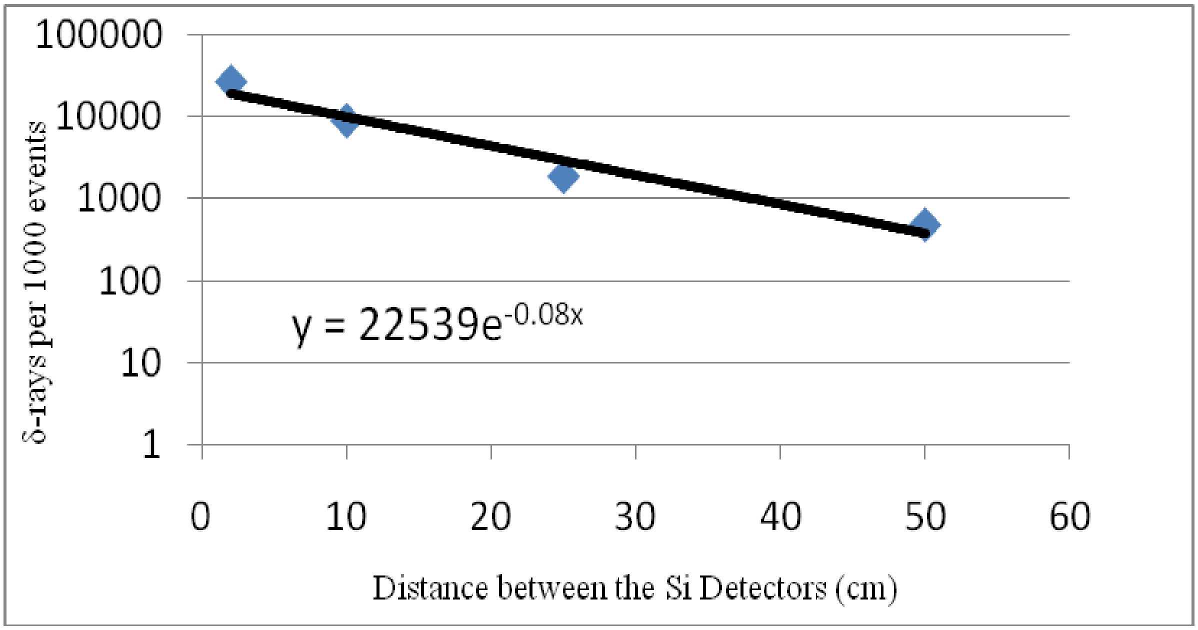

FIG. 2. Variation of the number of δ-rays seen in the second, downstream Si detector generated from the interaction of the beam with the first silicon detector. The number of δ-rays detected decreases roughly exponentially with distance.

IV. Conclusion

In conclusion, a GEANT4 simulation for the (γ,p) reaction setup with the SAMURAI spectrometer at RIKEN has been developed to investigate the properties of the proposed silicon detector setup. With this simulation, the setup was found to satisfy the design specifications for detection efficiency and resolution for the breakup reactions. However, significant numbers of δ-rays with kinetic energies large enough to impact the quality of the measurement were also produced as the ions interacted with the detectors in the simulation. While several methods for reducing the effect of the δ-rays on the measurement were tried, the best way found so far has been to keep the detectors some distance apart, such as, for example 30 cm. Given this constraint, the silicon detector setup with SSSD telescopes is not a valid solution. In general, to provide x-y position measurements, while allowing that a reasonable distance is also needed between the detectors, double sided silicon strip detectors (DSSSD) should be used.

[1] Large-Acceptance Multi-Particle Spectrometer SAMURAI Construction Proposal, version 2010.
[2] GEANT4 version 4.9.4, S. Agonstinelli *et al.*, Nucl. Instrum. Methods Phys. Res. **A506**, 250 (2003).
[3] M. Pindo, Nucl. Instrum. Methods Phys. Res. **A395**, 360 (1997).