Design of a segmented high purity germanium detector for muonic X-ray spectroscopy and imaging at a pulsed muon source

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Background & Introduction

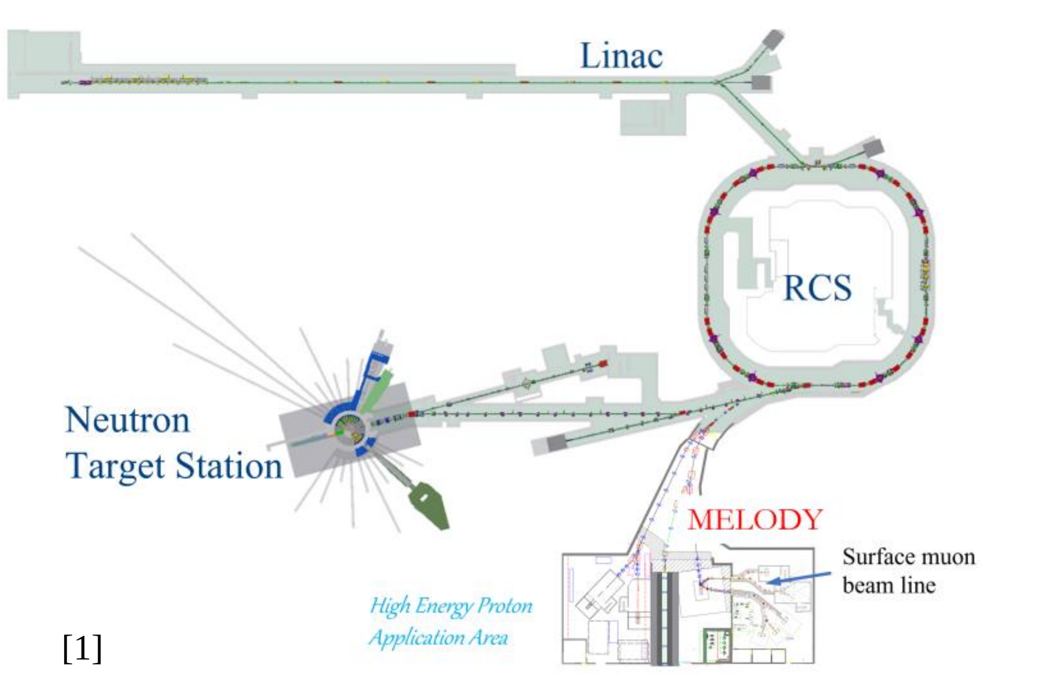
The muon is a lepton with a mass of 105.7 MeV/c^2 and charge of ±1. As a elementary particle, muons has been widely studied in various areas since its discovery, such as particle physics, material science, and nuclear physics. Muons are a fascinating probe to study material properties because muonic atoms can easily be formed by stopping negative muons inside a material after a substantially determined transport distance at a specific energy. The muon is subsequently captured by the nucleus and orbits the nucleus at very small distances, followed by emitting characteristic X-rays during its cascade down to the ground state. Elemental analysis based on muonic X-rays provides information about bulk material (~10 µm to ~1cm scale) composition without causing damage.

The muons are mainly produced by π decay, which is derived from cosmic rays and accelerators. The accelerator muons are classified as surface muons, cloud muons, and decay muon. The surface muon is produced by the decay of a π^+ near the target surface and has only a positive charge because the π^- is trapped before the decay. The cloud muon is generated between the target and the first deflection magnet. The decay muon is produced by the π meson during flight with both charge. Partial formula for π and µ are as follows:

$$p + n \rightarrow p + p + \pi^-$$

$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

$$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$$



Currently, there are 5 muon facilities or muon sources in the world: CMMS, SµS, ISIS, J-PARC, and MuSIC. A muon station for science, technology and industry (MELODY) based on China Spallation Neutron Source (CSNS) is designed and on deployment. The MELODY and CSNS II project are expected to welcome the first group of users by 2029[1].

Which detector is needed for muonic atom X-rays?

- different elements & different energy levels of muonic atom
- about 1Hz frequency of µ pulse & up to 10^5µ with time width of 410ns

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- fine energy resolution to distinguish peaks
- multi electrode detector for higher count rate

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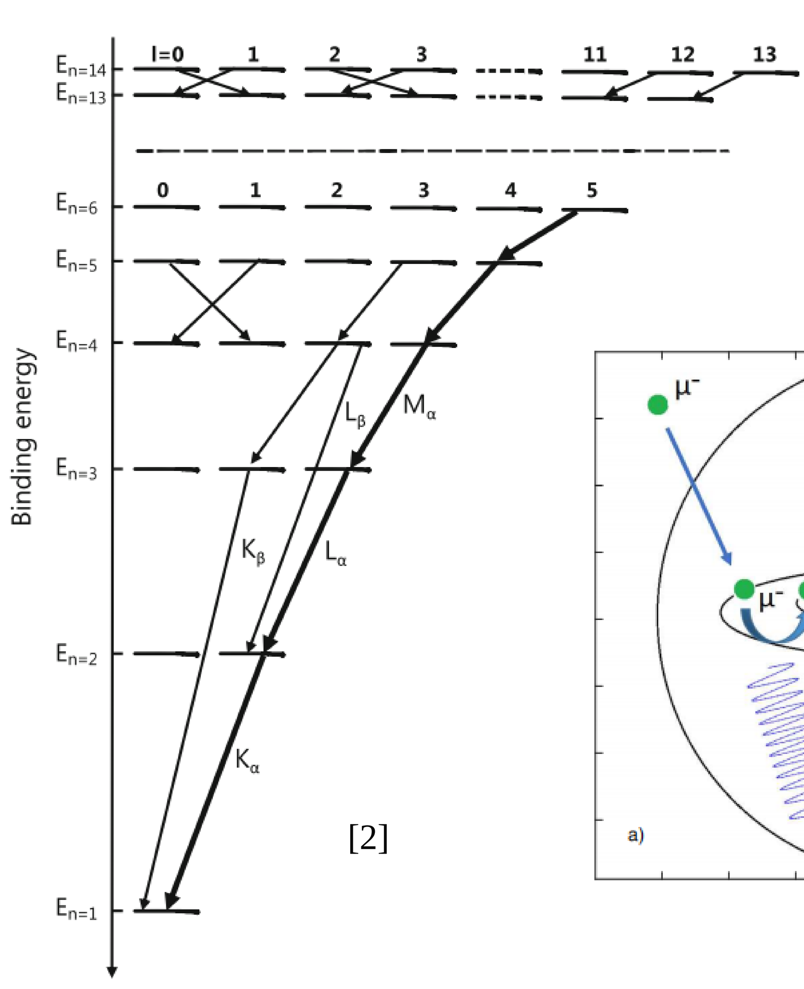
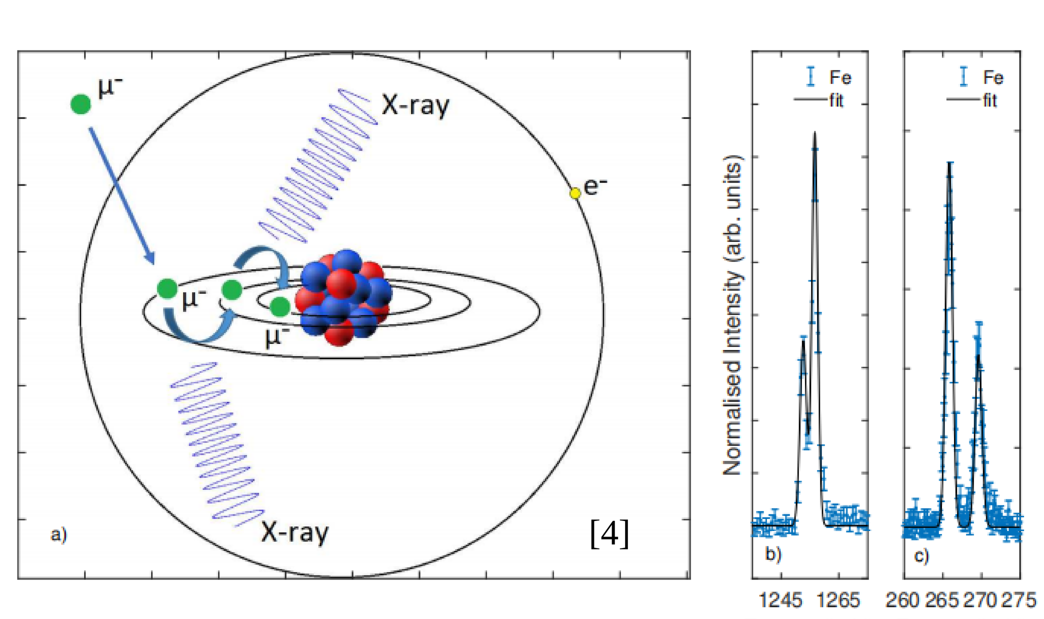
- Semiconductor detector especially HPGe
- double-sided cross-strip segmented HPGe

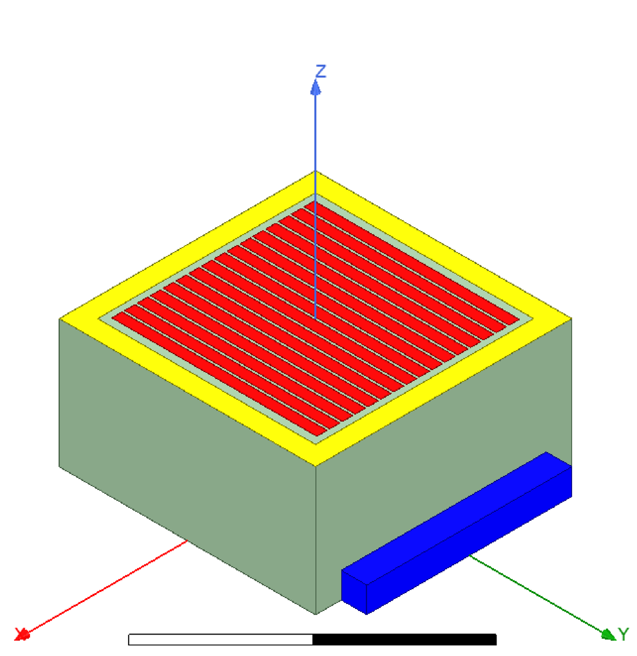


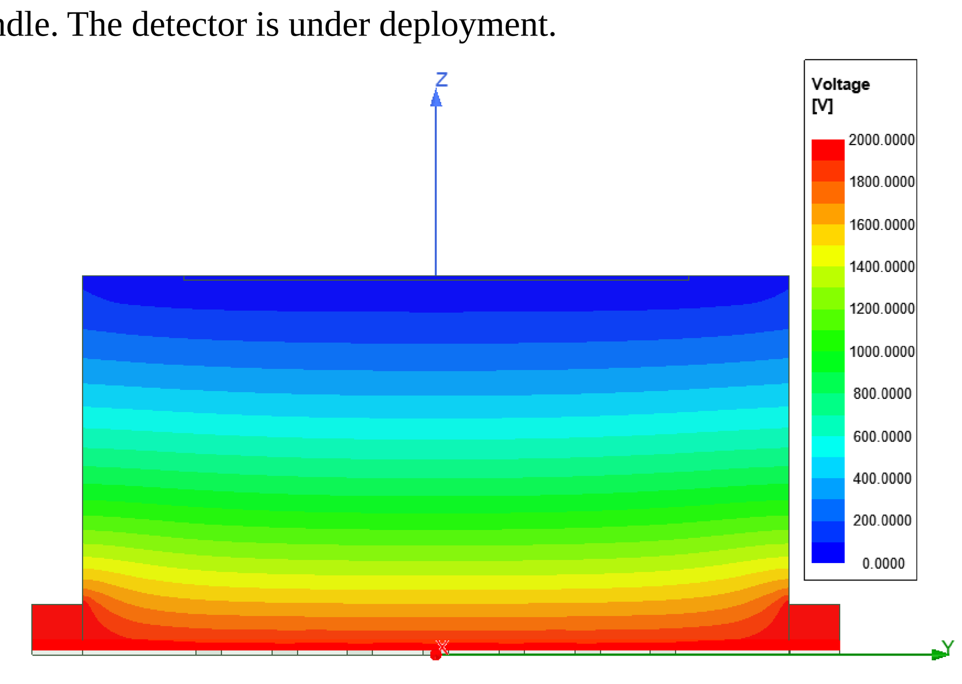
Other advantages of segmented HPGe:

- ✓ 2-D position resolution for imaging
- ✓ excellent energy resolution even to distinguish the chemical structure states of atoms



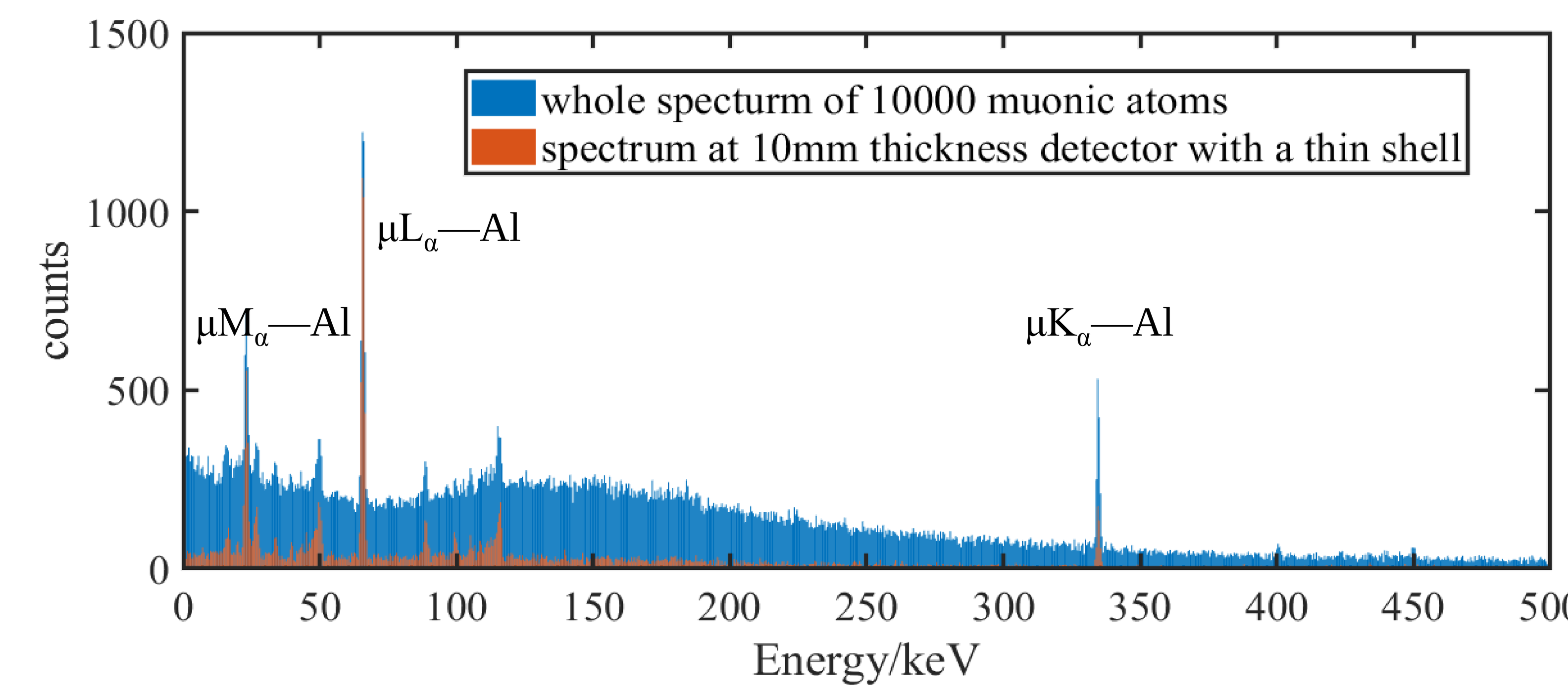
Detector design: a box-like p-type HPGe detector, with length of 2cm and height of 1cm, 16 strips with width of 0.8mm on each side, around protect electrodes on each side, all fabricated with amorphous Ge and Al, and 2 Li diffusion electrode for mechanical fixation and handle. The detector is under deployment.





Simulation results and analysis

Maxwell, Geant4, and Garfield++, and Matlab are used for simulation of 10^5 µ with E_k of 4MeV towards Al target .

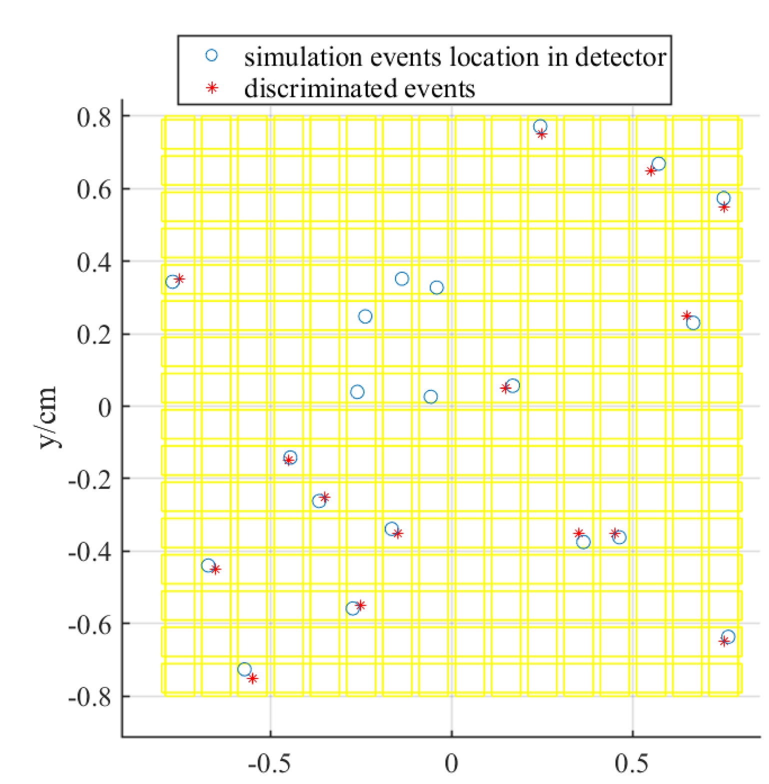


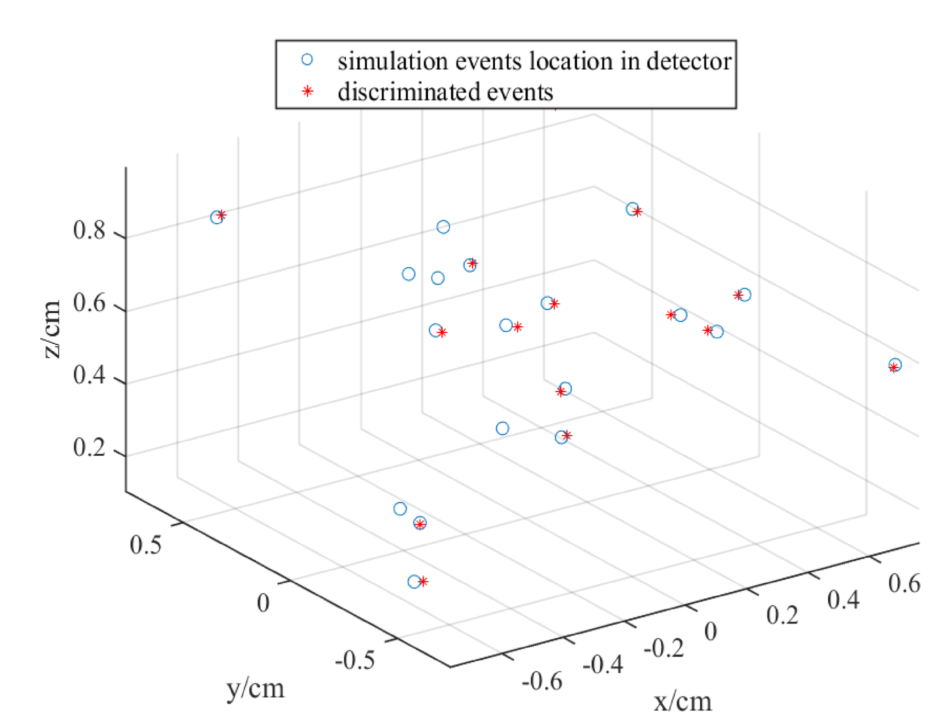
1 unit of µ produces:

- >3000% secondary particles,
- ~400% events deposited in surrounding HPGe detector of 10mm-thickness,
- 40% full energy peak of muonic atom X-rays

The detector is set to different distances from the Al target with different count rates and discrimination rates. After completing a run of simulation to obtain the energy and time information of each electrode strip, an algorithm is written to reconstruct the position and energy of the event in the detector. With the increase of energy deposition points in the detector, the discrimination rate of double-sided cross-strip readout method for events decreases, and the maximum number of events discriminated is about 13 at a distance of 45cm, that is, 13 times increase of effective count rate than single-electrode detectors. So that the muonic atom X-ray detection efficiency of MELODY can be improved to the level of other muon devices which has µ pulse frequency of about 25Hz.

distance/cm	64	58	54	51	48	45	43	41
events in detector	10	12	14	16	18	20	22	24
discriminated events	9.4	10.2	11.6	12.2	12.8	13.2	12	11.2
discriminate rates	94%	85%	83%	76%	71%	66%	55%	47%





Conclusion & future work

- ✓ A HPGe detector with double-sided cross-strip electrode design is proposed, and is under deployment currently.
- ✓ It can be operated at high count rate and measure multiple low-energy X-ray events.
- ☐ Electrode fabrication, bounding, and electronic design are the key issues to limit the number of channels.
- ➢ Detectors with more strips or pixel-like HPGe are under research, which may further improve the detection efficiency

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