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Deep Subthreshold Pion Production

in $^{12}C+^{12}C$ at 25 to 80 MeV/nucleon

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SUPER

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(Deep) Subthreshold Pion Production

Pion Production in Nuclear Collisions at Subthreshold Energy

- In pp collisions, the threshold energy required for a projectile to produce a π^0 meson is 279.4 MeV.
- For the AA collisions, the single NN collision model predicts threshold energies for π^0 production to be approximately 50 MeV/nucleon.
- For $AA \to AA\pi^0$ reactions, the absolute threshold energy is approximately 10 MeV/nucleon for large mass numbers.

Deep Subthreshold

- Close to absolute threshold to $\sim$ 50 MeV/nucleon
- Clusters at play

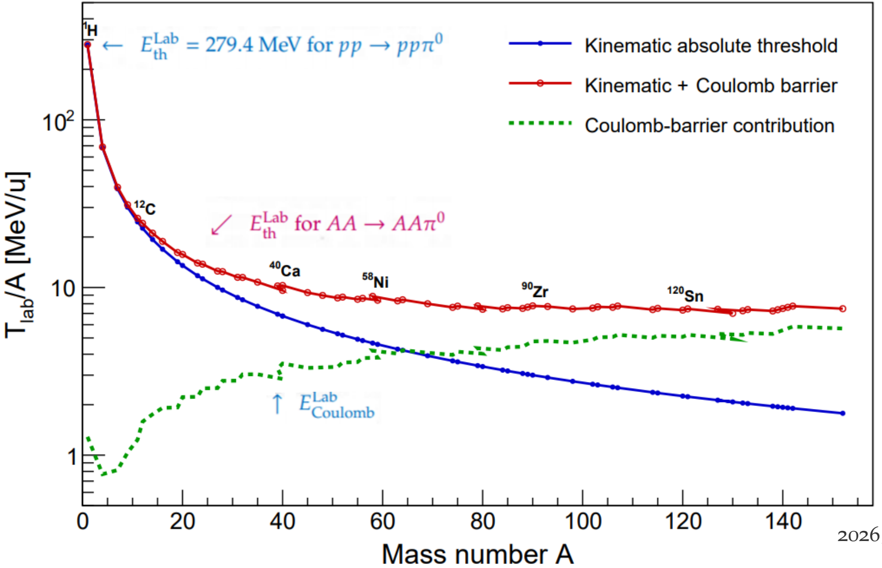
Subthreshold

- Below threshold for pp collisions
- Binary NN collisions at play

Above Threshold

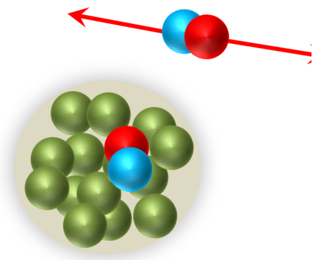
- Above threshold for pp collisions
- Various production processes

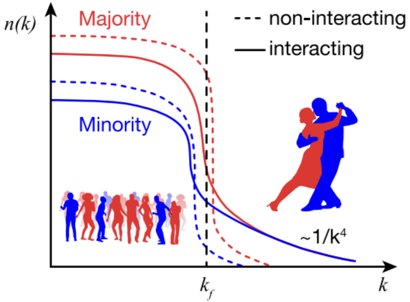
Absolute Thresholds For Pion Production in AA Collisions



How are Pions Produced at Deep Subthreshold Energy?

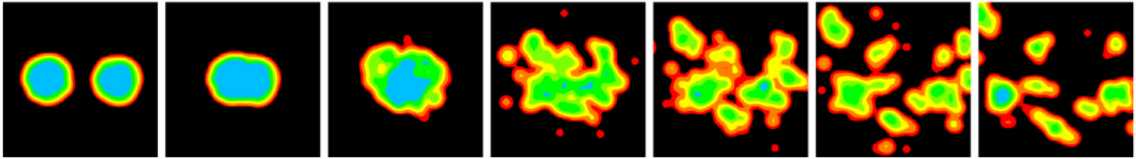
- At these deeply subthreshold energies, short-range correlated (SRC) nucleon pairs can play a significant role in π^0 production.
- As a result, the π^0 production cross section may exhibit a notable change in slope near the Fermi-model threshold.
- Protons or neutrons originating from SRC pairs can provide valuable insights into the underlying π^0 production mechanisms.





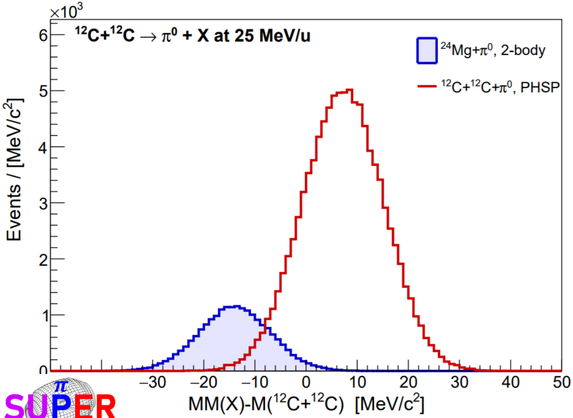
How are Pions Produced at Deep Subthreshold Energy?

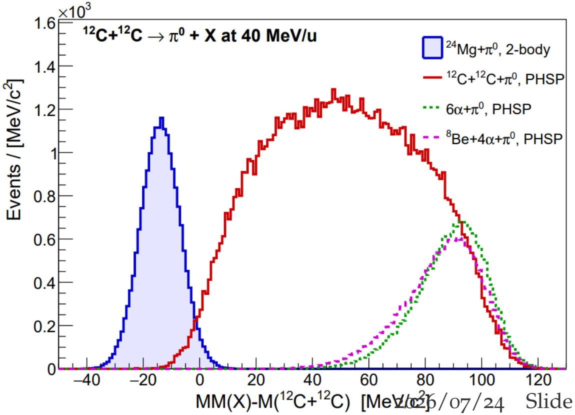
- Near the absolute threshold, one must invoke the presence of collective effects.
- Pion production close to the absolute threshold requires that many nucleons in the projectile and the target act cooperatively to convert their energy into the pion mass.
- However, the detailed physics related to the coorperative effects is not yet well understood: clustered structures such as α clusters in colliding nuclei.



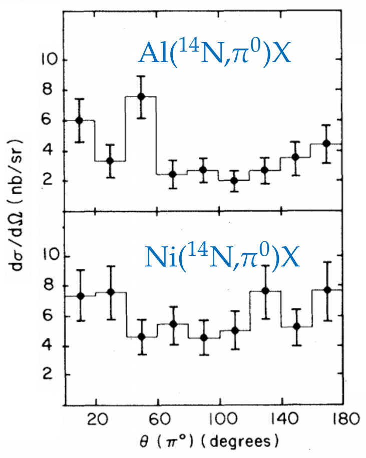
Subthreshold Pion Production in $^{12}C+^{12}C$ Collisions

- Lowest threshold for $^{12}C+^{12}C \rightarrow ^{24}Mg+\pi^0$: (20.23 MeV/nucleon)
- $^{12}C+^{12}C \rightarrow ^{12}C+^{12}C+\pi^0$: (22.56 MeV/nucleon)
- $^{12}C+^{12}C \rightarrow 6\alpha + \pi^0$ and other reactions with more smaller fragments

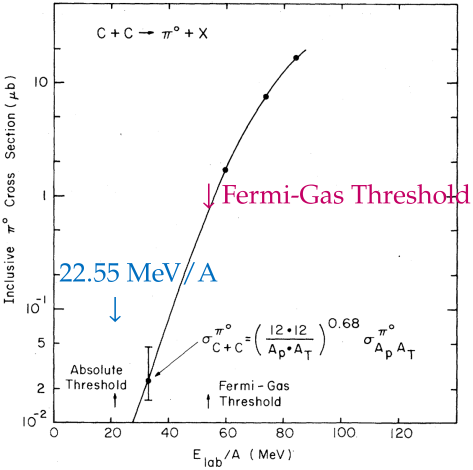


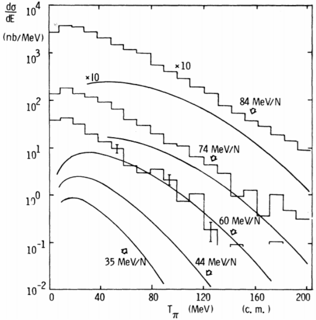


Subthreshold π^0 Production



C+C$\longrightarrow$ π^0+X

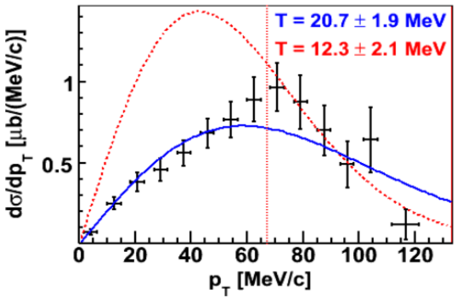




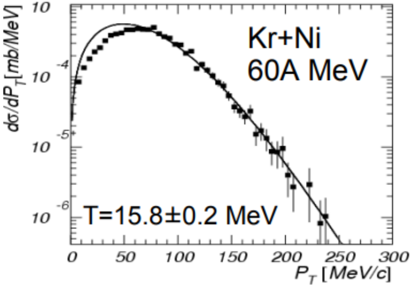
T_π

Transverse Momentum and Temperature

Ta+Au at 40 AMeV



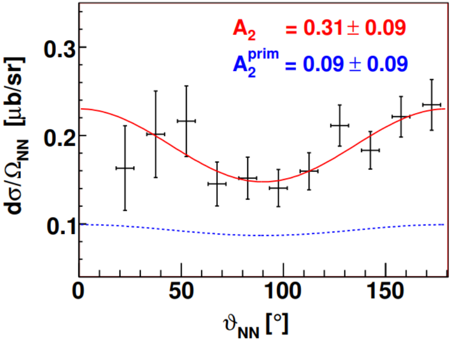
Y. Schutz et al., NPA 622, 404 (1997)

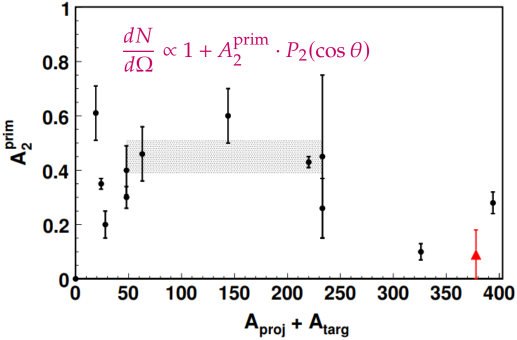


- Assuming a source in thermal equilibrium, the transverse momentum should exhibit a Boltzmann distribution with a slope parameter related to an apparent temperature of the source:

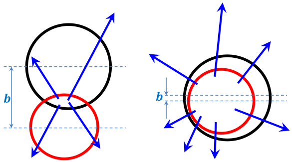
$$\frac{d\sigma}{dp_T} \propto p_T \sqrt{E_T} \exp\left(-\frac{E_T}{T_0}\right), \qquad E_T = \sqrt{m_{\pi^0}^2 + p_T^2}$$

Polar Anisotropy and Pion Absorption



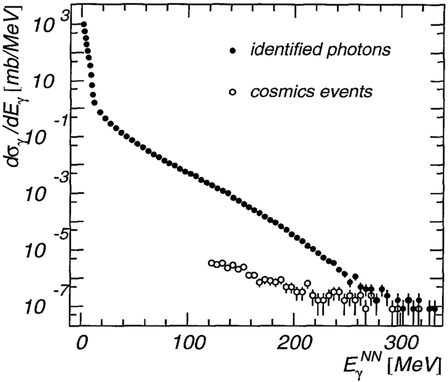


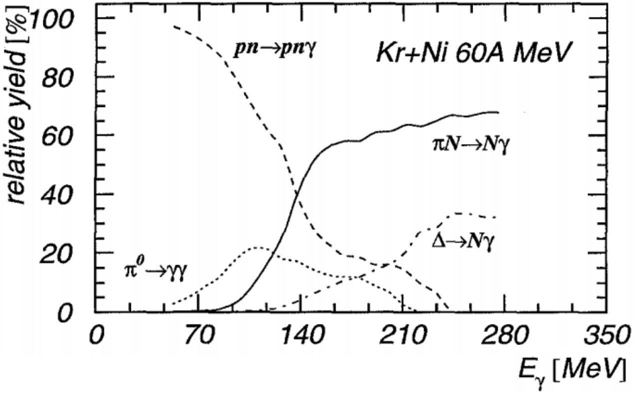
- The angular distribution of primordial π^0 from Ta+Au collisions at 40 AMeV might be almost isotropic. [a]



[a] K. Piasecki and T. Matulewicz, Acta Physica Polonica B **41**, 393 (2010).

Hard Photon Production





- For the Kr+Ni system at 60 AMeV this energy is equal to 194 MeV.

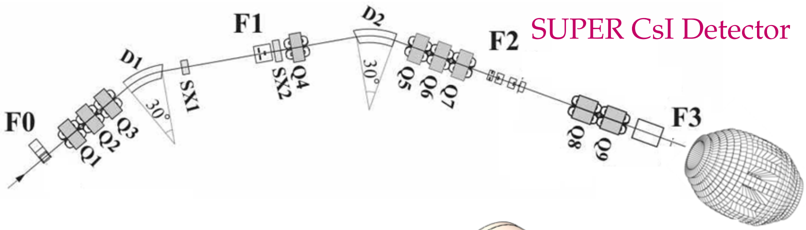
$$E_\gamma^{\max} = \frac{s_{\max} - 4m_N^2}{2\sqrt{s_{\max}}}, \quad s_{\max} = \frac{2[E_F(m_N + E_L) + p_F p_L]^2}{m_N(m_N + E_L)}.$$

SUPER Campaign

SUbthreshold Pion production Experiment at RI Beam Facilities

- The SUPER campaign with the CsI(Tl) array has just started with the **SUPER-C** (at RCNP). The following experiments will be the **SUPER-B** (at RIBF) and the **SUPER-A** (at RAON).
- The SUPER+ campaign with the superconducting magnet and the TPC is now under consideration.

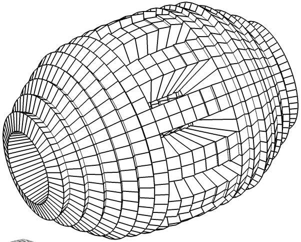
SUPER Detector in the EN Course of RCNP

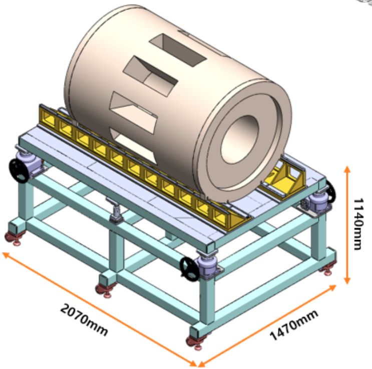


SUPER CsI Detector

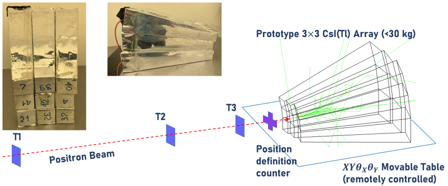
- The CsI detector will be mounted on the movable structure in a space of 2×3 m^2.

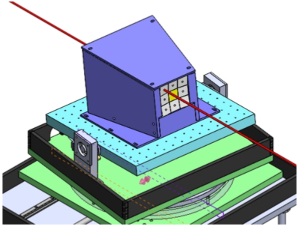
768 CsI(Tl) crystals

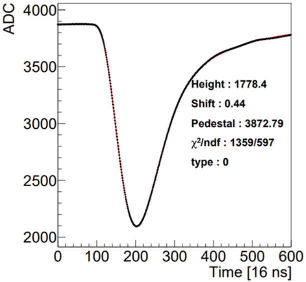


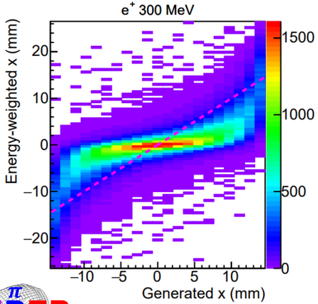


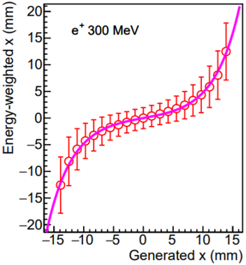
Beam Commissioning of the 3×3 CsI(Tl) Array

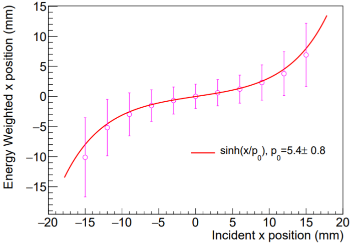




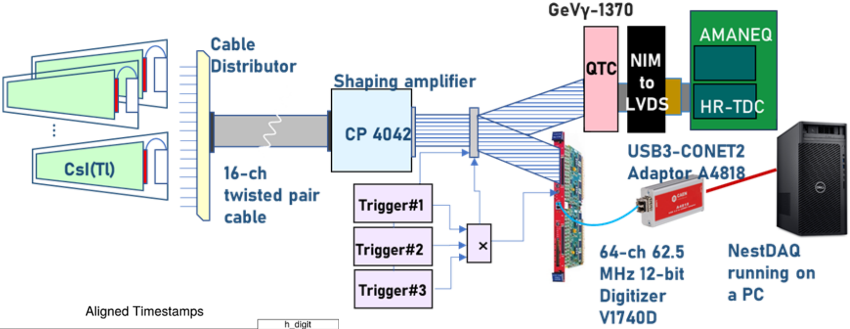


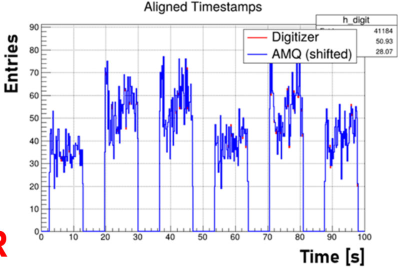


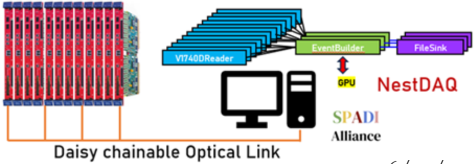




Beam Commissioning of Data Acquisition System







Yield Estimation

- Yield estimates was based on the total cross sections for inclusive π^0 production by ^{12}C beam on ^{12}C target, which ranges from 20 nb to 10 μb for 30 to 80 MeV/nucleon.
- For the beam intensity of 10^{11} pps (I = 16 pnA) and $\sigma = 1\ \mu$b, the π^0 production yield can be obtained as

$$Y_{\pi^0} = 10^{11}/\mathrm{s} \cdot 1 \times 10^{-1}\mathrm{g/cm^2} \cdot \frac{6.02 \times 10^{23}/\mathrm{mol}}{12\ \mathrm{g/mol}} \cdot 1 \times 10^{-30}\mathrm{cm^2} \approx 500/\mathrm{s}$$

- Using the proposed CsI(pure) detector, the number of π^0 events collected in a day is expected to be

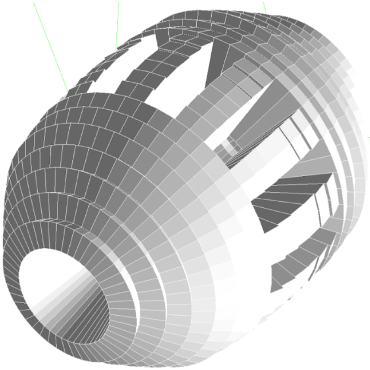
$$N_{\pi^0} \quad = \quad 500/\mathrm{s} \cdot \frac{3\pi\ \mathrm{sr}}{4\pi\ \mathrm{sr}} \cdot (\varepsilon_{\mathrm{recon}} = 0.6) \cdot 10^5\ \mathrm{s}\ \approx 2.0 \times 10^7$$

Run Plan

- During the 80 MeV/nucleon run, the trigger rate will reach 300 kHz due to bremsstrahlung photon emission in nuclear collisions. We will optimize the threshold level to achieve a manageable trigger rate of 30-50 kHz.
- We will also study the trigger rate by varying the beam intensity.

Beam energy (MeV/nucleon)	Beam time (hour)	Expected yield (π^0)
80	3	DAQ study
80	6	1×10^7
60	6	5×10^6
40	15	5×10^5
30	18	6×10^4
25	24	a few hundreds

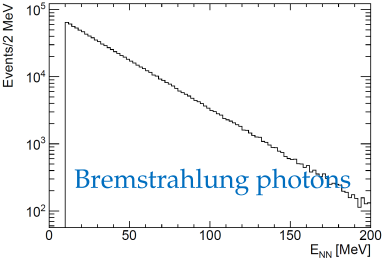
High-Statistics Measurements

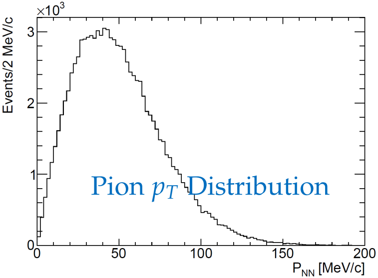


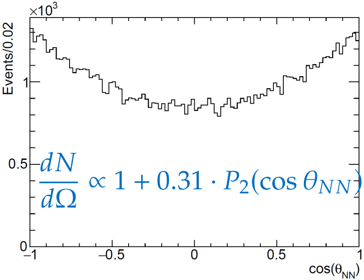
- High-precision measurements of the cross section, angular distribution, and p_T/T_π spectra for subthreshold π^0 production reactions and hard photon bremsstrahlung processes.
- Acurate determination of the true threshold energy for π^0 production in C+C collisions, along with precise evaluation of temperature and primordial asymmetry parameters.
- Simultaneous detection of nuclear fragments—including p, d, t, ^{3}He, and ^{4}He—to provide deeper insight into the effects of cluster structures in C+C collisions.

Simulation Study (Event Generation)

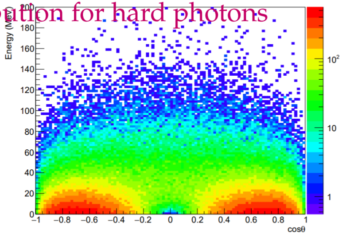
- Geant4 simulation for subthreshold π^0 production and hard photon emission at deep subthreshold energies.

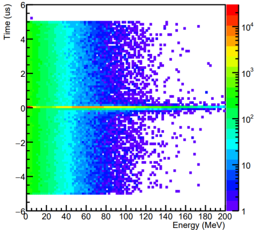






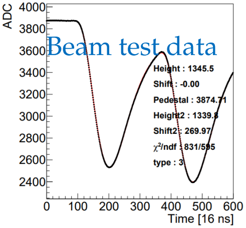
Angular distribution for hard photons

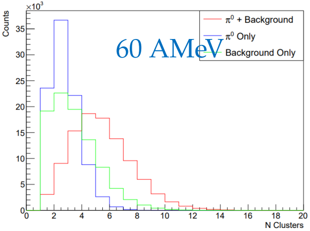


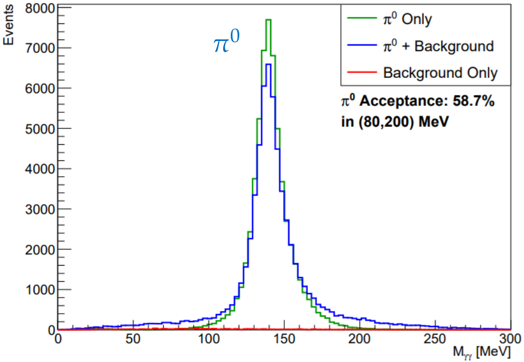


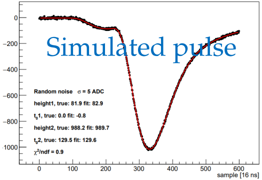
E_γ vs T_{pulse}

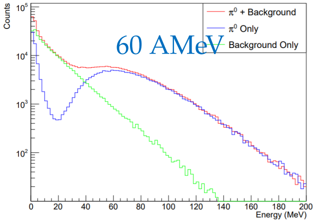
Simulation Results on Reconstructed $\gamma\gamma$ Mass Distribution







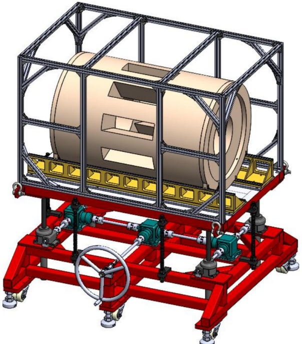




- A machine learning algorithm (XGBoost) with 10^5 training samples predicts π^0 signals that yields $E_{\text{cluster}} > 20$ MeV in 1 μs time window.

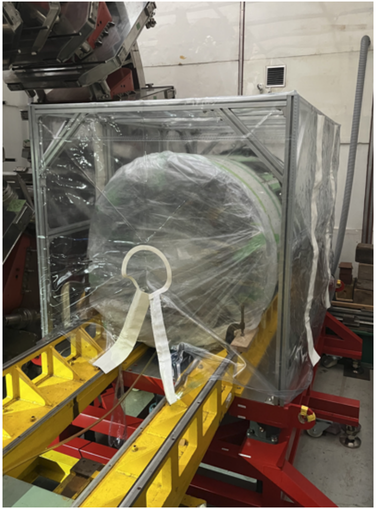
SUPER Timeline

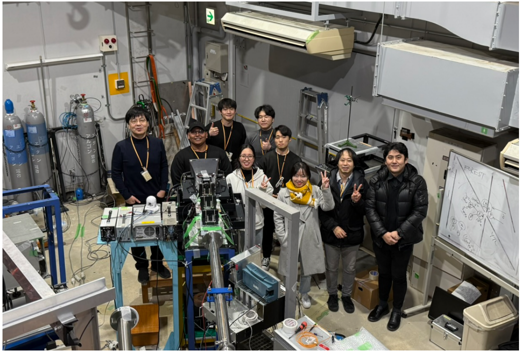
2025	May – June	SUPER proposal submission and approved (RCNP-E610)
	June – December	SUPER data acquisition tests at KU and RCNP.
2026	July	Replacement of the support structure at KEK
2027	June	SUPER prototype test at RAON
	(November)	SUPER detector assembly at RCNP.
2028	Spring	SUPER (E610) anticipates beam time.



- Cable connection board (40-pin to 32-pin to 64-pin)
- Cosmic-ray tests with the entire system
- Design of the beam pipe and the target system
- Consideration of beam-induced backgrounds such as X-rays and neutrons
- Beam degrader with a 80 MeV/nucleon ^{12}C beam

Current Status of SUPER





- We have a large-acceptance CsI(Tl) array.
- We successfully commissioned the detector prototype using a new DAQ system.

Summary

- We aim to conduct extensive studies on subthreshold π^0 production and hard photon ($E_\gamma > 30$ MeV) emission in ^{12}C+^{12}C collisions at energies ranging from 25 to 80 MeV/nucleon at RCNP.
- High-statistics subthreshold π^0 experiments using the SUPER detector will provide new insights into the collective dynamics of nucleons in nuclei.

SUbthreshold Pion production Experiment at RI Beam Facilities

Thanks to Y.J. Kim, S.Y. Ryu, G.Y. Lim
(KU/RCNP/KEK/RIKEN/IBS/Tohoku/Kobe)