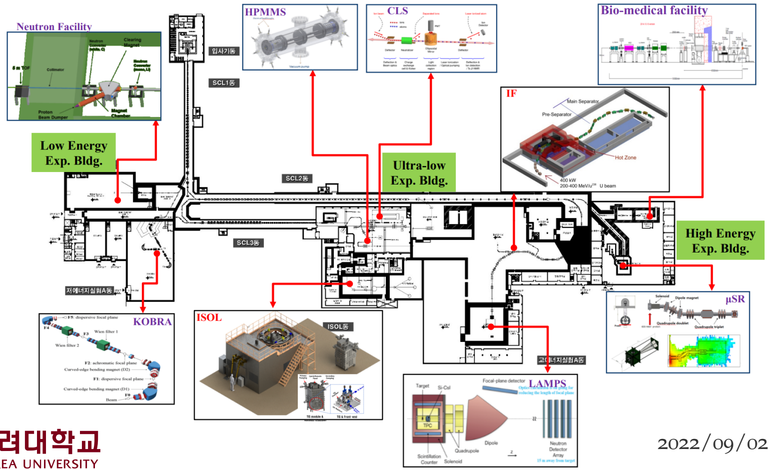
Subthreshold Pion Production in AA Collisions with SUPER

Subthreshold π^0 production at RAON

Jung Keun Ahn
(Korea University)

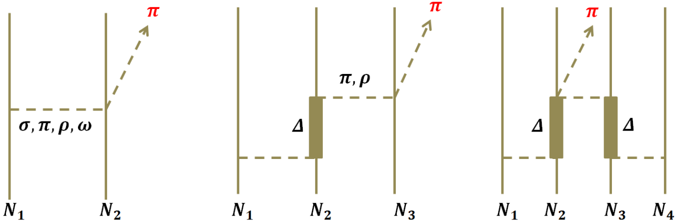
RI Accelerator Facility (RAON)

- Rare Isotope Accelerator Facility has a beam energy of 2-200 AMeV. The first section will deliver stable ion beams of 20 AMeV in 2023 and RI beams in 2024.
- KOBRA beam line delivers $^{14}N^{6+}$ beam at 43 AMeV and $^{16}O^{6+}$ beam at 41 AMeV. The beam intensity will be the order of 10^{12} pps.



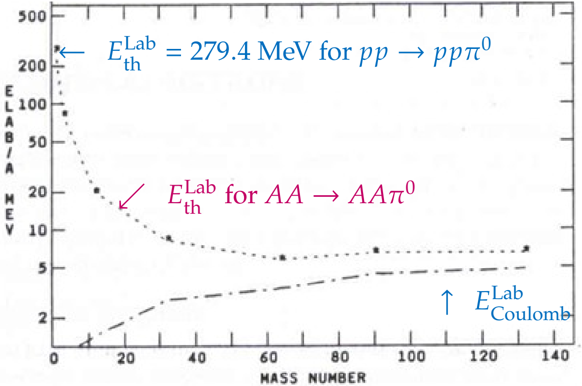
Pion Production below 100 AMeV

- In AA collisions, Fermi energy domain is the transition region between a dynamics driven by the mean-field, below 15–20 AMeV, and one where the NN collisions play a central role, above 100 AMeV.



- First explanations of subthreshold pion production were given in terms of coupling Fermi momentum to the momentum of relative motion between two nuclei.
- At lower energies and very close to the absolute threshold, one must invoke the presence of collective effects. However, the detailed physics related to the coorperative effects is not yet well understood.
- In the low energy limit, close to the absolute threshold, the process of pion creation requires the transfer of most the projectile's kinetic energy into a single degree of freedom (creation of a new particle).

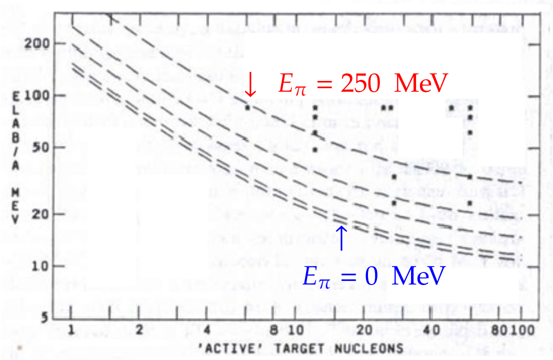
Absolute Threshold For Pion Production



A(Target)	$pA \to pA\pi^0$
^{12}C	147.0 MeV
Al	140.3 MeV
Cu	137.2 MeV
Sn	136.1 MeV
Pb	135.6 MeV

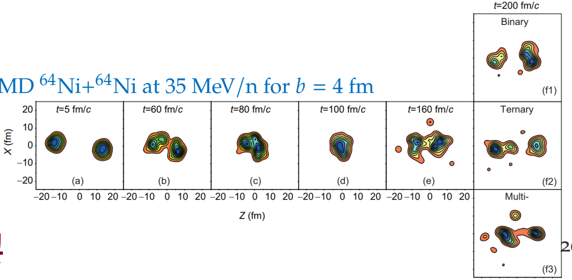
- The absolute threshold for pion production in symmetric heavy ion collisions vs mass number of the two nuclei.
- Coupling Fermi momentum to the momentum of relative motion between two nuclei is not expected to work for very low beam energies. On the basis of single NN collision model, threshold energies around 50 AMeV can be predicted.
- 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.

Target Nucleons involved in Pion Production



- How many nucleons must cooperate to produce a pion of a given kinetic energy?
- Minimum number of target nucleons required in a ^{14}N-induced reaction to produce pions of different kinetic energies.

ImQMD ^{64}Ni+^{64}Ni at 35 MeV/n for $b = 4$ fm



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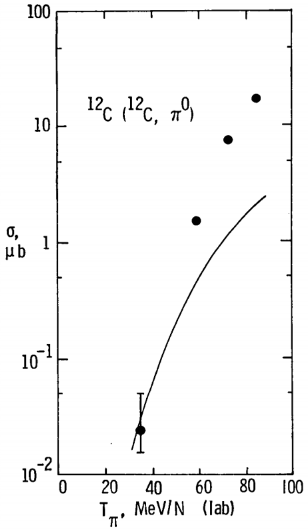
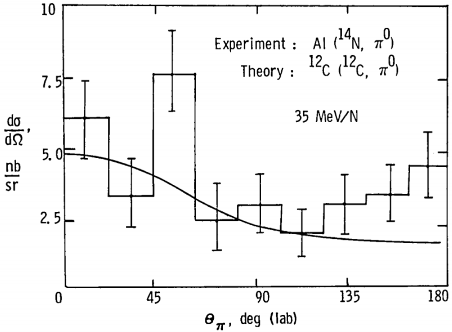
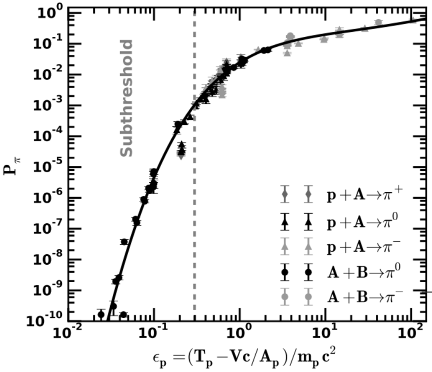
Subthreshold π^0 Production





Subthreshold π^0 Production



- P_π is the in-medium pion production probability per participant as a function of ε_p. The fitting curve is the parametrization given by [a]

$$\frac{P_\pi}{I_\pi \cdot \zeta} = \varepsilon_p^{-1/4} \cdot \exp[\varepsilon_p^{-1/4}$$

$$(0.0057x^4 + 0.019x^3 - 0.19x^2 + 1.07x - 3.7)],$$

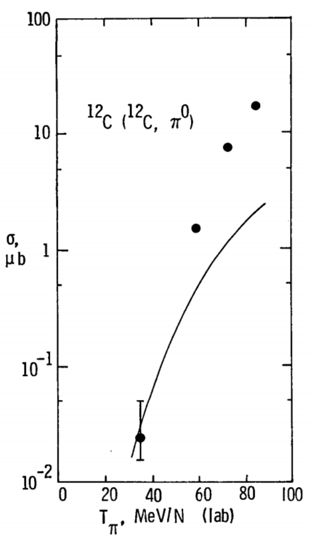
where $x = \log(\varepsilon_p)$.

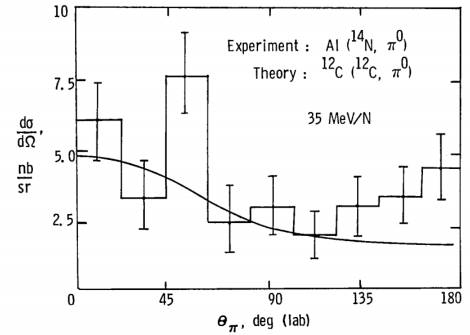
[a] E. Kafexhiu, Phys. Rev. C **94**, 064603 (2016).

- A common parametrization of the meson production cross section in AA collisions is $\sigma_\pi = \sigma_R \langle A_{part} \rangle P_\pi$, where the reaction cross section

$$\sigma_R = 10\pi r_0^2 \left(A_p^{1/3} + A_t^{1/3} + b\right)^2 \left(1 - \frac{V_c}{A_p T_p}\right), \qquad \langle A_{part} \rangle_b = \frac{A_p A_t^{2/3} + A_t A_p^{2/3}}{\left(A_p^{1/3} + A_t^{1/3}\right)^2}$$

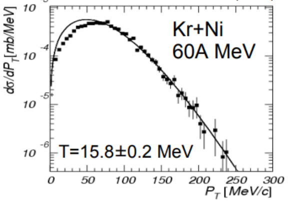
Subthreshold π^0 Production



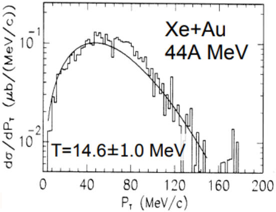


Transverse Momentum and Temperature

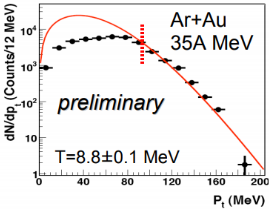
Y. Schutz et al., NPA 622, 404 (1997)



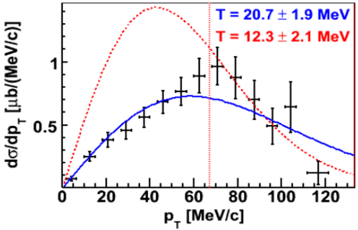
R. Mayer et al., PRL 70, 904 (1993)



N. Yahlali for TAPS



Ta+Au at 40 AMeV

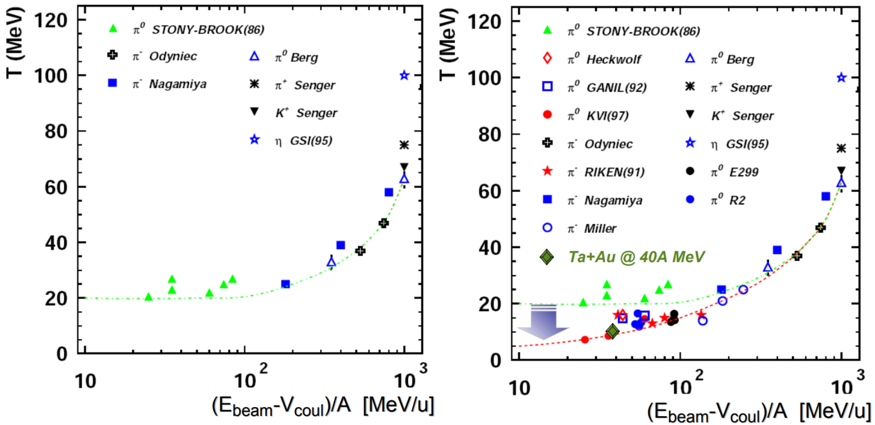


- Assuming a source in thermal equilibrium, the transverse momentum should exhibit a Boltzmann distribution with a slope parameter related to an apparent temperature of the source:

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

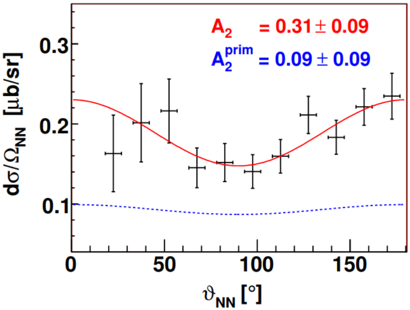
- The transverse momentum spectrum of primordial neutral pions, corrected for the reabsorption effects, does not show the thermal behavior.

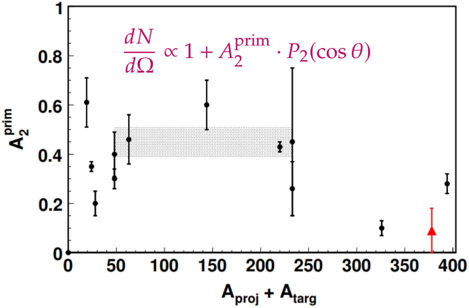
Temperature Parameter



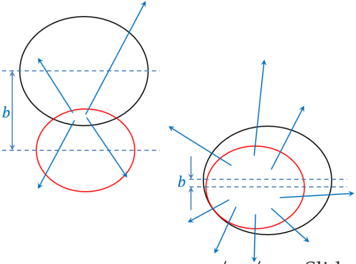
- The transverse momentum distribution of pions ~~is independent of~~ the bombarding energy below 200 AMeV.
- New experimental results point to the continuous rise of the temperature parameter with increasing beam energy.

Polar Anisotropy and Pion Absorption



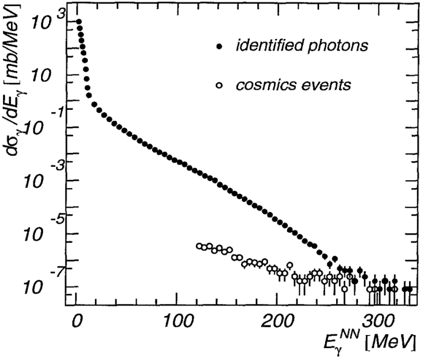


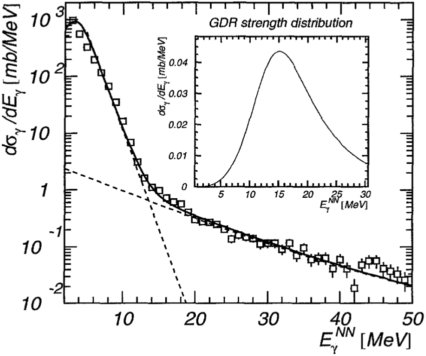
- The correction of the data by the simple reabsorption model (p_{π^0}- dependent mean-free-path λ_{π^0}) based on static geometrical considerations indicates, that the angular distribution of primordial π^0 from Ta+Au collisions at 40 AMeV might be almost isotropic [a]

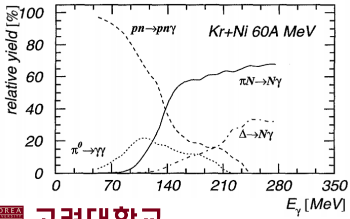


[a] K. Piasecki and T. Matulewicz, Acta Polonica B **41**, 393 (2010).

Hard Photon Production







- Hard photons originate from the bremsstrahlung radiated in individual NN collisions.
- The bremsstrahlung spectrum exploits the energy available in each NN collision and builds up by adding to the beam momentum p_L the Fermi momentum p_F.
- For the Kr+Ni system at 60 AMeV this energy is equal to 194 MeV.

π^0 Reconstruction

- The invariant mass of two gammas from the $\pi^0 \to \gamma\gamma$ decay is given by

$$m_{\gamma\gamma} = 2\sqrt{E_1 E_2}\sin\left(\frac{\theta_{12}}{2}\right)$$

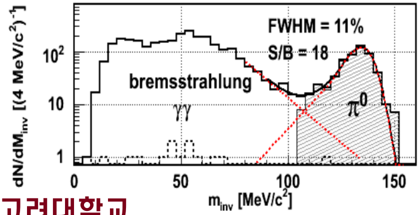
- The π^0 energy can be calculated from

$$E^2_{\pi^0} = \frac{2m^2_{\pi^0}}{(1-\cos\theta_{12})(1-X^2)}, \qquad X = \frac{E_1 - E_2}{E_1 + E_2}$$

.

- The kinetic energy and pion emission angle are obtained from

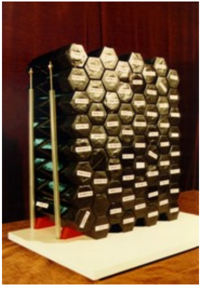
$$T_{\pi^0} = E_{\pi^0} - m_{\pi^0}, \qquad \cos\theta_{\pi^0} = \frac{p_{\parallel}}{p_{\text{tot}}} = \frac{E_1\cos\theta_1 + E_2\cos\theta_2}{(E_1^2 + E_2^2 + E_1E_2\cos\theta_{12})^{1/2}}$$

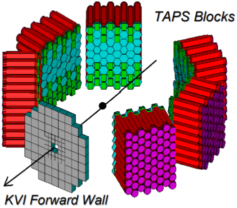


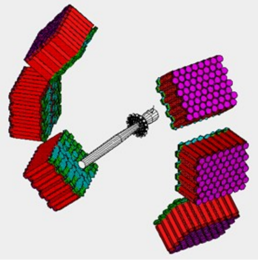
- ^{181}Ta+^{197}Au$\to \pi^0 + X$ at 40 AMeV, GANIL.
- S/B= 18 in the invariant mass spectrum measured using BaF_2 arrays.

MEDEA and TAPS

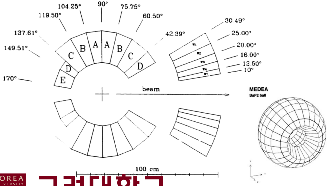
- TAPS consists of 384 BaF_2 and 384 CPV and the KVI forward wall is made up with 92 $\Delta E - E$ detectors.

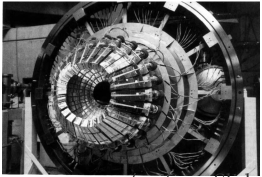






- MEDEA consists of 180 BaF_2 crystals at the LNS-Catania. This geometry allows for the covering of $3.7\ \pi$.





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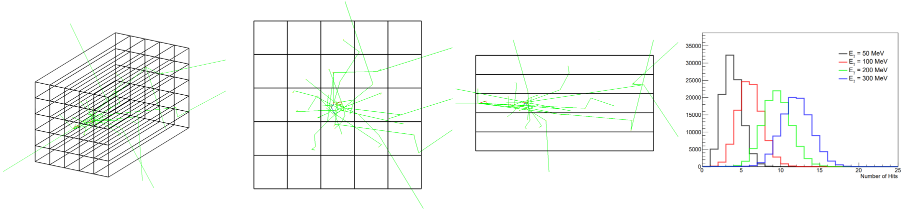
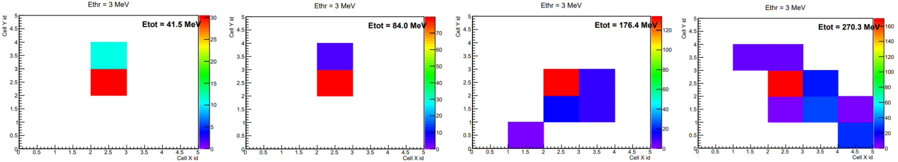
Candidate Scintillation Crystals

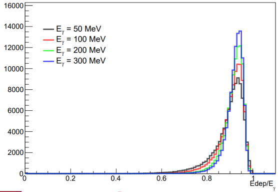
- Photon energies up to 300 MeV.
- High density, short radiation length (X_0) and Moliere radius (R_M).
- Fast decay time, high light yield, and wavelength matching between scintillator and photon sensor.
- Maximum size in crystal growth and cost performance.

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LYSO	GAGG
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.13	8.28	7.10	6.63
X_0 (cm)	2.59	1.85	1.85	2.03	1.68	1.12	0.89	1.14	1.56
R_M (cm)	4.8	3.5	3.5	3.4	2.6	2.3	2.0	2.07	2.1
Wavelength (nm)	410	560	420 310	310 195,210	330	480	420	420	520
Decay time (ns)	230	1300	35 6	620 0.6	30	300	5–15	36	90
Light output	1	0.45	0.06 0.02	0.21 0.03	0.10	0.09	0.01	0.66	1.0
Cost			$2200			$1600		$8600	$9000

First Phase Simulation Study







- Geant4 simulation on the detector response to photons hitting the center of the 5×5 array of CsI(pure) crystals ($3 \times 3 \times 30$ cm^3 each) in energies: 50, 100, 200, and 300 MeV [a].

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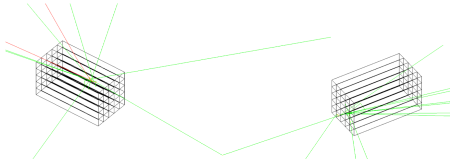
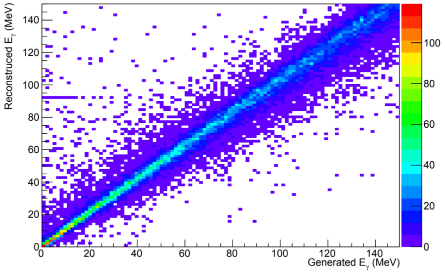
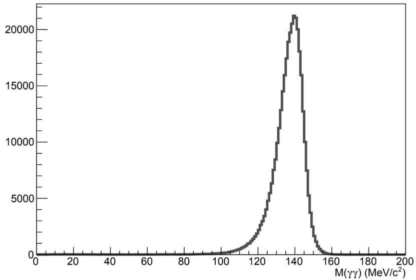
[a] Y.J. Kim (KU)

First Phase Simulation Study



- We generated π^0 decays with energies centered at 30 MeV using Geant4 simulation and two 5×5 CsI arrays separated by 110°.





- We reconstructed incident photon energies and angles using a XGBoost model with boosted decision trees $(E_i, E_{\text{tot}} \rightarrow \theta_{12}, E_1, E_2)$. [a].

[a] Y.J. Kim (KU)

Yield Estimate for N+Al Collisions at 35 AMeV

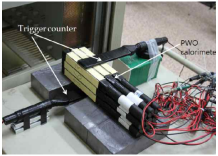
- Yield estimate was based on the total cross section for inclusive π^0 production by 35-AMeV ^{14}N beam on Al target: $I = 3$ pnA, $\rho = 62$ mg/cm^2, and $\sigma_{\pi^0} = 50$ nb.
- For the beam intensity of 10^{12} ppp ($I = 62.5$ pnA), the π^0 production yield can be obtained as

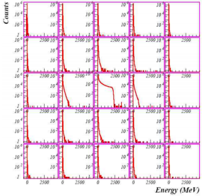
$$Y_{\pi^0} = 10^{12}/\mathrm{s} \cdot 6 \times 10^{-2}\mathrm{g/cm}^2 \cdot \frac{6.02 \times 10^{23}/\mathrm{mol}}{27\ \mathrm{g/mol}} \cdot 5 \times 10^{-32}\mathrm{cm}^2 \approx 10/\mathrm{s}$$

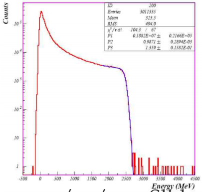
- Using the proposed CsI(pure) detector covering $\Delta\Omega = 0.72$ sr, the number of π^0 events collected in 10 days is expected to be

$$N_{\pi^0} = 10/\mathrm{s} \cdot \frac{0.72\ \mathrm{sr}}{4\pi\ \mathrm{sr}} \cdot (\varepsilon_{\mathrm{recon}} = 0.7) \cdot 10^6\ \mathrm{s} \approx 4 \times 10^4,$$

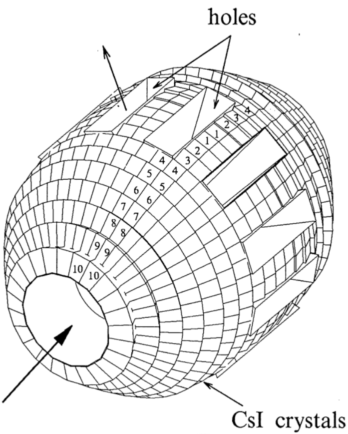
$$\Longrightarrow \quad \downarrow \quad \cdot \quad \uparrow \quad \cdot \quad \uparrow \quad \approx (10^4 \sim 10^6)$$

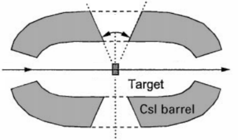




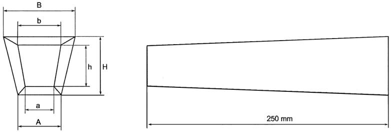


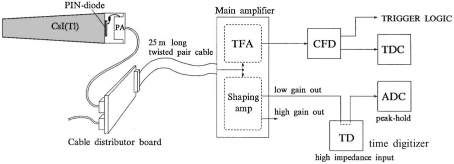
SUPER with the KEK CsI(Tl) Detector





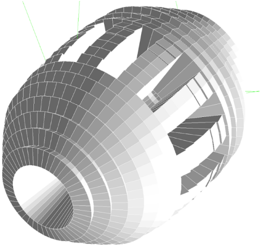
- The CsI(Tl) calorimeter of the KEK E246 is an excellent candidate for SUPER. It consists of 768 CsI(Tl) crystals covering 75% of 4π solid angle. [a]
- An individual crystal covers 7.5° in θ and ϕ angles, except for 48 crystals near the beam axis. The crystals are of 10 different dimensions and are shaped like pyramidal sectors with trapezoidal basis.
- The length of crystal is 25 cm ($13.5X_0$) and the average transverse dimensions are 3×3 cm^2 for front end and 6×6 cm^2 for rear end.

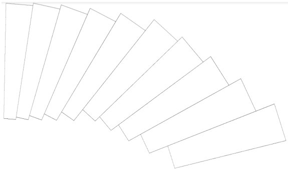




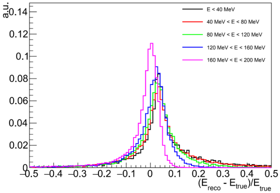
[a] Dementyev *et al.*, NIMA 440, 151 (2000)

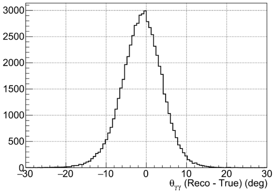
Simulation Study with the TREK CsI Array

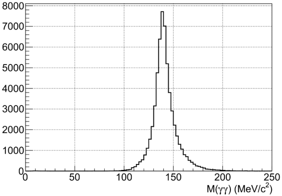




- We generated π^0 decays according to the p_T distribution and boosted for N+Al collisions at 40 AMeV. and reconstructed incident photon energies and angles using a XGBoost model with boosted decision trees.







Competing with Upcoming J-PARC Experiments

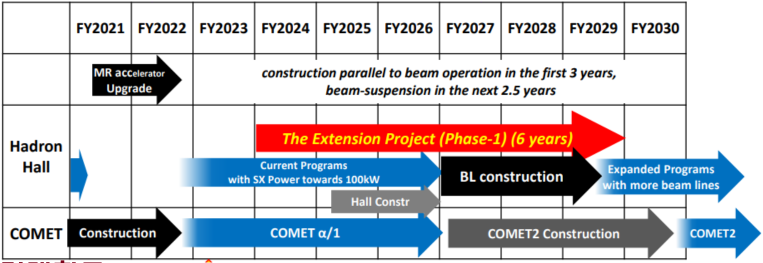
Director Naohito Saito
Institute of Particle and
Nuclear Studies
KEK

Prof. Jung Keun Ahn
Department of Physics
Korea University
Seoul, 02841, Korea email:
ahnjk@korea.ac.kr

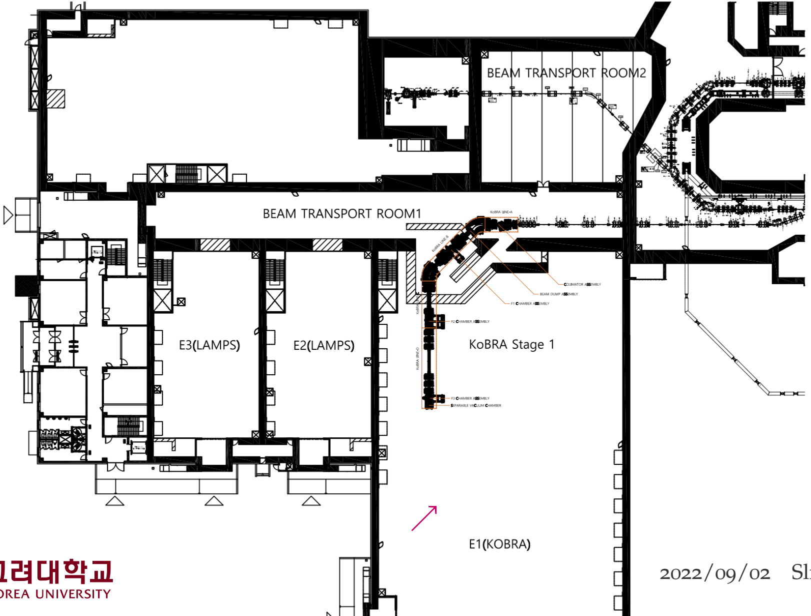
July 13, 2022

Letter of Request to Borrow Equipment
CsI(Tl) Calorimeter of the TREK Collaboration

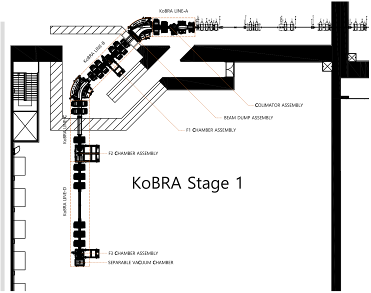
Dear IPNS Director Prof. Naohito Saito,



Candidate Beam Line (KoBRA) at RAON



KoBRA Beam Line

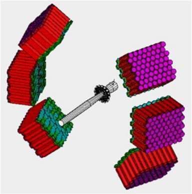


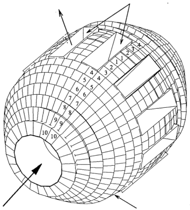
Summary

- We propose extensive studies on subthreshold π^0 production and hard photon ($E_\gamma > 30$ MeV) emission at RAON;

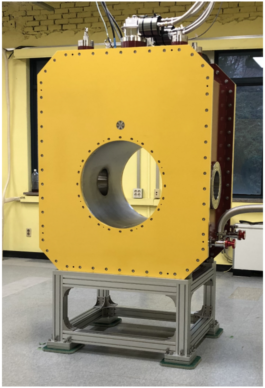
SUPER (SUbthreshold Pion Experiment at RAON)

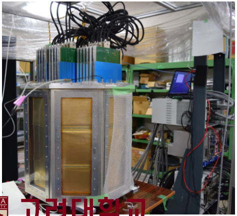
- We will optimize the detector configuration for efficient detection of π^0 and hard photons in *AA* collisions at KOBRA energies.

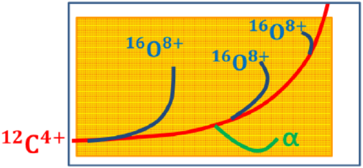


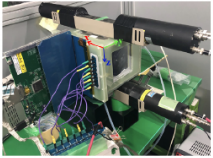


Superconducting Magnets and TPCs









Low-Energy Pion Production in NN Collisions

- Exclusive reactions for single pion production are:

$$pp \to pp\pi^0, \; pp \to pn\pi^+, \quad nn \to nn\pi^0, \; nn \to np\pi^-,$$

$$pn \to pn\pi^0, \; pn \to nn\pi^+, \; pn \to pp\pi^-$$

- Near the two-pion threshold, we need to consider the two pion production reactions:

$$pp \to pp\pi^0\pi^0, \; pp \to pp\pi^+\pi^-, \; pp \to pn\pi^+\pi^0, \; pp \to nn\pi^+\pi^+$$

$$nn \to nn\pi^0\pi^0, \; nn \to nn\pi^+\pi^-, \; nn \to pp\pi^-\pi^-, \quad nn \to np\pi^-\pi^0$$

$$pn \to pn\pi^0\pi^0, \; pn \to np\pi^+\pi^-, \; nn \to nn\pi^+\pi^0, \; pn \to pp\pi^-\pi^0$$

- The reactions involving distinguishable pions in the final state (in red) should be double-counted, so we expect in pp reactions [a]

$$\sigma_{pp\to\pi^+X} : \sigma_{pp\to\pi^-X} : \sigma_{pp\to\pi^0X} = 8:2:6 = 4:1:3$$

- The π^+/π^- ratios for pp reactions at low energy are

$$\frac{\sigma_{pp\to\pi^+X}}{\sigma_{pp\to\pi^-X}} = 4, \qquad \frac{\sigma_{nn\to\pi^+X}}{\sigma_{nn\to\pi^-X}} = \frac{1}{4}, \qquad \frac{\sigma_{pn\to\pi^+X}}{\sigma_{pn\to\pi^-X}} = 1.$$

[a] J.W. Norbury and L.W. Townsend, Nucl. Instru. Meth. B 254, 187 (2007).

Low-Energy Pion Production in AA Collisions

- For AA collisions, the probabilities of pp and nn reactions are denoted as

$$P(pp) = \frac{Z_P Z_T}{A_P A_T}, \qquad P(nn) = \frac{(A_P - Z_P)}{A_P}\frac{(A_T - Z_T)}{A_T}$$

- We therefore expect the π^+/π^- ratio to be

$$\frac{\sigma_{AA\to\pi^+X}}{\sigma_{AA\to\pi^-X}} = \frac{Z_P}{A_P}\frac{Z_T}{A_T}\frac{\sigma_{pp\to\pi^+X}}{\sigma_{pp\to\pi^-X}} + \frac{(A_P - Z_P)}{A_P}\frac{(A_T - Z_T)}{A_T}\frac{\sigma_{pp\to\pi^-X}}{\sigma_{pp\to\pi^+X}}$$

- The cross sections are[a]

$$\sigma_{AA\to\pi^+X} = (A_P A_T)^{2.2/3}\sigma_{pp\to\pi^+X}$$

$$\sigma_{AA\to\pi^-X} = \frac{(A_P A_T)^{2.2/3}\sigma_{pp\to\pi^+X}}{\frac{Z_P}{A_P}\frac{Z_T}{A_T}\frac{\sigma_{pp\to\pi^+X}}{\sigma_{pp\to\pi^-X}} + \frac{(A_P-Z_P)}{A_P}\frac{(A_T-Z_T)}{A_T}\frac{\sigma_{pp\to\pi^-X}}{\sigma_{pp\to\pi^+X}}}$$

$$\sigma_{AA\to\pi^0X} = (A_P A_T)^{2.4/3}\sigma_{pp\to\pi^0X}$$

[a] J.W. Norbury and L.W. Townsend, Nucl. Instru. Meth. B 254, 187 (2007).