NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
PROPOSAL FOR EXPERIMENT

Date Submitted: ______________________ Experiment # ______________________
(Assigned by NSCL)

TITLE: Two-particle correlation functions and isospin effects in nuclear reactions

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Is this a thesis experiment? Yes [✓ No] If yes, for whom? ______________________

OTHER EXPERIMENTERS: (please spell out first name)

Name	Organization	Check, if applicable Grad	Sr. Grad
Betty Tsang	NSCL		
Mike Famiano	NSCL		
Mark Wallace	NSCL		x
Andrew Rogers	NSCL	x	
Gary Westfall	NSCL		
Andrew VanderMolen	NSCL		
Lee Sobotka	WU		
Robert Charity	WU		
Romualdo de Souza	IU		
Silvie Hudan	IU		

REQUEST FOR PRIMARY BEAM SEQUENCE INCLUDING TUNING, TEST RUNS, AND IN-BEAM CALIBRATIONS (summary of the detailed beam delivery time calculation.)

	Isotope	Energy (MeV/nucleon)	Beam delivery time (Hours)	On-target time (Hours)
Primary beam 1	^{112}Sn	80	24	88
Primary beam 2	^{124}Sn	80	24	72
Primary beam 3	^{124}Sn	20	4	12

TOTAL REQUESTED HOURS: 224 (Calculated as per item 4. of the Notes for PAC27 in the Call for Proposals)

HOURS APPROVED: ______________________

HOURS RESERVED: ______________________

		SET UP TIME (before start of beam)	TAKE DOWN TIME
Access to:	Experimental Vault	14 days	_____7_____ days
	Electronics Set-up Area	14 days	_____7____ days
	Data Acquisition Computer	14 days	_____7____ days

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? _____11______ / ____1____ / ____04_____

DATES EXCLUDED: _Nov, 21-30, Dec. 18, 2004 -Jan. 4 2005_____________________________________

EXPERIMENTAL LOCATION:

___ Transfer Hall
___ N3 vault (92” chamber removed)
___ N4 vault (Sweeper line)
___ S2 vault (SuperBall line)
_x_ N2 vault
___ N4 vault User line
___ S1 vault (RPMS line)
___ S2 vault (RPMS line)
___ N3 vault (with 92” chamber)
___ N4 vault (Gas stopping line)
___ S1 vault (Irradiation line)
___ S3 Vault

EXPERIMENTAL EQUIPMENT:

___ A1900
_X_ 4pi Array
___ Neutron Walls
___ S800 Spectrograph
___ NaI Array
_X_ Other (give details): TeSCA array (Silicon Strips+CsI(Tl))
___ Beta Counting System
___ 92" Chamber
___ Modular Neutron Array
___ Segmented Ge Array
___ Neutron Emission Ratio Observer
___ Beta-NMR Apparatus
___ Sweeper Magnet
___ SuperBall Neutron Calorimeter
_X_ High Resolution Array

DETAIL ANY MODIFICATION TO THE STANDARD CONFIGURATION OF THE DEVICE USED, IF ANY:

TARGETS:
^{112}Sn and ^{124}Sn, 5mg/cm^{2}

PLEASE LIST ITEMS THAT REQUIRE NSCL DEVELOPMENT:

OTHER SPECIAL REQUIREMENTS: (Safety related items are listed separately on following pages.)

SUMMARY (no more than 200 words):

Isospin effects in two-particle correlation functions will be studied by means of the HiRA and TeSCA detector arrays. Event characterization will be performed with the MSU 4pi detector. Effects of the asymmetry term on two-proton correlation functions are predicted by IBUU simulations, reflecting a more pronounced pre-equilibrium emission and shorter emission times when a stiff density dependence is assumed. Relative emission times for t and ^{3}He fragments will also be studied by means of velocity gated correlation functions. These relative emission times are expected to be correlated with the neutron-proton relative emission times. Isospin dependent BUU simulations also indicate that these relative emission times are sensitive to details about the symmetry energy of asymmetric nuclear matter. Two-particle correlations for heavier isotopically resolved fragments will also be studied. in order to obtain a more comprehensive understanding of the relevant breakup densities and time scales for emission of the various light particles and heavier fragments.

(no more than 4 pages of text - 1 1/2 spaced, 12pt; no limit on figures or tables)

Please organize material under the following headings or their equivalent:

1. Physics justification, including background and references.
2. Goals of proposed experiment
3. Experimental details—apparatus (enclose sketch); what is to be measured; feasibility of measurement; count rate estimate (including assumptions); basis of time request (include time for calibration beams, test runs and beam particle or energy changes); technical assistance or apparatus construction required from the NSCL.
4. Status of previous work done at the CCF.

DESCRIPTION OF EXPERIMENT

Heavy-ion collisions have recently provided significant constraints on the equation of state (EOS) for symmetric nuclear matter [1]. Attention is now beginning to focus on the isospin-dependent asymmetry term of the nuclear EOS [1-4]. Indeed, the density dependence of this aymmetry term of the EOS governs many important properties of both exotic neutron-rich nuclei and neutron stars [2]. The asymmetry term i.e. symmetry energy, $E_{sym}(r)$, is proportional to the square of the isospin asymmetry, $b=(r_n-r_p)/(r_n+r_p)$. As a consequence, its effects are significantly more enhanced as matter becomes more asymmetric. The recent availability of beams of nuclei in a wide range of N/Z asymmetries therefore provides new and unique opportunities to study the asymmetry term and its density dependence.

The asymmetry energy has considerable effects on nuclear reaction dynamics. A number of observables have been suggested as sensitive probes of the symmetry energy. These include pre-equilibrium n/p energy spectra [3], neutron differential collective flow [3] and isoscaling phenomena in multifragmentation [4]. These experiment probes basically reflect the different sensitivities of pre-equilibrium proton and neutron emission rates to the density dependence of the symmetry energy [3]. Such sensitivities are predicted by simulations using isospin dependent transport models, such as the IBUU of ref. [3]. Fig. 1 shows IBUU predictions for central ^{52}Ca+^{48}Ca collisions at E/A=50 MeV of the average emission times for protons (filled symbols) and neutrons (open symbols) as a function of their momentum [5]. These simulations predict that a stiffer density dependence of the symmetry energy (γ=2) supplies a larger early pressure on the emitted nucleons leading to an earlier and more correlated emission of pre-equilibrium protons and neutrons, unlike the case of a soft symmetry energy (γ=0.5) where the proton and neutron emission times differ greatly.

Goals of proposed experiment

We plan to study this phenomenon with two-particle correlation functions. Two-proton correlations at small relative momenta display a final interaction peak at 20 MeV/c relative momentum that has a strong sensitivity to the space-time distributions of particle emitted during a nuclear reaction. This peak is primarily sensitive to the spatial separation *r* between the two protons at the time the second proton is emitted; the distribution of spatial separations is described by the two-proton emitting source function, *S(r)*. IBUU simulations have been used to predict the influence of the density dependence of the symmetry energy on *S(r)* for central ^{52}Ca+^{48}Ca collisions at E/A=80 MeV [5]; the results are shown for different symmetry energies in Fig. 2. The short-range pre-equilibrium portion of the emitting source at relative distances *r<10 fm* is more pronounced if a stiff symmetry energy is used. Conversely, the source corresponding to the stiff density dependence is less extended in space, reflecting less pronounced emission at later times after the system has expanded. In addition to dynamical contributions to *S(r)* calculated by IBUU and shown in Fig. 2, there are additional contributions from the secondary decay of excited nuclear fragments and residues that contribute at larger values of *r* and cannot be modeled by IBUU. The fraction of measured protons that are of dynamical origin and predictable by IBUU is therefore not a prediction of IBUU, but must be determined by imaging analyses [6] as discussed below.

Using the Koonin-Pratt equation, one can relate the source function to the correlation function. Fig. 3 shows two-proton correlation functions *C(q)= 1+R(q)* predicted by IBUU simulations for central ^{52}Ca+^{48}Ca collisions at E/A=80 MeV as a function of the two proton relative momentum *q* [5]. The correlation function is calculated from proton pairs with total momenta in the center of mass systems (CMS) larger than 500 MeV/c. This total momentum gate selects mainly protons emitted in the early pre-equilibrium stage of the reaction that dominates the shape of the source function *S(r)* at *r*<25 fm. The prominent peak at relative momentum 20 MeV/c is due to the nuclear final state interaction between the protons. Its height depends strongly on the shape of the source function at r< 10 fm. It is seen that a stiff density dependence of the symmetry energy produces a larger height of the peak at 20 MeV/c, indicating a more enhanced proton pre-equilibrium emission, as it is expected because of the larger pressure induced by a stiffer symmetry energy [5]. Unfortunately, the height also depends on the relative contributions from fast pre-equilibrium proton pairs and slow pairs emitted from evaporation phenomena and secondary decays [6,7]. Thus, we will rely not on the height of the peak in the correlation function, but rather on its shape for which the most important feature is the width from which source information can be obtained without ambiguity [6,7].

Fig. 4 shows the comparison between the correlation functions *R(q)* for a soft and a stiff symmetry energy. Here, we have normalized the maximum value of *R(q)* so that the shapes of the predicted correlations can be easily compared. This normalization show that a strong effect of the symmetry energy is expected to be observed if accurate measurements can be achieved at small relative momenta *q*<15 MeV/c. Such measurements require detector arrays with a high granularity. Fortunately, the HiRA (High Resolution Array) and the TeSCA (Texas Silicon-CsI Array) have the necessary high granularity to resolve relative angles as small as 0.1^{o}. Using these devices, two-proton emitting sources calculated with Isospin-dependent BUU simulation will be compared to the source functions extracted from the measured two-proton correlation functions, following the techniques described in [6].

Another important goal of the experiment will be to extend the measurements to include complex particle correlation functions and unlike particle correlations to investigate on the freeze-out densities and the chronology of emission for several fragment species. Current cluster production models employed in transport theoretical calculations predict that the timescale of emission of light clusters such ^{3}H and ^{3}He will be largely governed by the timescale for emission of their constituent neutrons and protons [8]. Fig. 1 shows that the density dependence of the symmetry energy affects also the relative emission times of neutrons and protons. With a soft symmetry term (squares), proton emission is systematically delayed with respect to neutron emission and one expects ^{3}He emission to be delayed with respect to ^{3}H emission. This difference in emission times reduces substantially when a stiff EOS is used (triangles). Non-resonant or Coulomb dominated correlation functions between non-identical particles can be used to determine the chronology of their emission and quantitative information of the relative emission times can be obtained from such measurements [9,10]. In particular, if one analyzes non-resonant or Coulomb dominated correlation functions for non-identical particle pairs (label for simplicity by *a* and *b*), one finds that the comparison between velocity-gated correlation functions with $v_a>v_b$ and $v_b>v_a$ provide means to determine which particle has been emitted first [9,10].

Recently, we have also solved problems with the quantitative interpretation of resonant d-α correlations stemming from the influence of collective motion [11], and we anticipate that quantitative analyses can be extended to much heavier mass pairs. Through such analyses, we have been able to determine freeze-out densities by methods that are for the first time independent of secondary decay [12]. We propose to apply these methods in the proposed measurement in order to obtain a comprehensive understanding of the breakup dynamics of these collisions. Since pre-equilibrium n and p emission depends on the symmetry term of the EOS, also the N/Z ratio of the left residue and its subsequent break-up into complex fragments depends on the asymmetry term. We anticipate being able to obtain separately the density profiles of the emitting sources of proton rich and neutron rich fragments.

As correlation functions in general and heavy fragment correlation functions in particular are strongly sensitive to collective motion, the MSU 4pi detector will be instrumental for determining the reaction plane, the collective motion and the impact parameter of collisions being investigated.

Experimental Details: detectors and count rates

The HiRA and TeSCA arrays will be mounted on a rail inside the chamber of the 4pi detector. Fig. 5 show this rail system when it was successfully used for the experiment performed in 1996 with the Catania Hodoscope. The array will be centered at 90^o in the center of mass of the reaction and cover a wide angular range so as to allow measurements at $\theta_{cm}=90°$ where the effects of the symmetry energy are expected to be observed for a wide range of energies in the CMS.

The effects of the symmetry energy are expected to disappear when more symmetric nuclear matter is considered. So, we plan to study both ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn reactions, providing a very large range of N/Z asymmetry to help isolate the isotopic dependence at the focus of the experiment.

The experiment will be performed in the N2 experimental vault. Using the small emittance tune developed for Exps. 1002 and 1032, we propose to degrade the primary ^{112}Sn and ^{124}Sn beams and transmit them through the 4pi array. The list of beams that are expected at NSCL next year include ^{124}Sn for example at E/A=120 MeV and an intensity of 1.5pnA. This beam can be degraded to E/A=80 MeV, with a loss intensity that will not be a problem for our experiment. The 4pi array is capable of taking central collision data with a rate of about 2.5×10^3 events/sec. With an intensity of 0.05pnA and target thicknesses of 5mg/cm^2, a rate of about 2.5×10^3 central collisions ($b/b_{max}<0.3$) is expected to occur. This corresponds to about 2×10^8 central collisions per day. Our past experience on correlation function analysis suggests that very high statistics is required in order to perform high-resolution measurements at small relative momenta, especially when gates on the velocities and directions of the emitted particles are applied. For this reasons, we ask for 3 days beam time for each of the two systems ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn. We also ask for 2 shifts of beam time in order to tune our electronics before data taking and one day for each of the primary beams.

Calibration is a very important issue for good correlation function measurements. If the commissioning experiment for HiRA is approved, we can limit the calibration to a measurement of proton recoils, using a ^{124}Sn beam degraded to E/A=20 MeV. We request 2 shifts for this difficult calibration, including degrading, which is intended to verify that the calibration is properly transferred from the commissioning experiment. After more experience with this procedure, it may be possible to reduce or eliminate the need for extra calibration beams, but for the moment, it is essential. Altogether, the beam time request is for 28 shifts or 224 hours of accelerator time.

Status of previous work at the CCF

This is a new collaboration.

Bibliography

1. Pawel Danielewicz, Roy Lacey and William G. Lynch, Science 298, 1592 (2002)
2. J.M. Lattimer and M. Prakash, Ap. J., **550**, (2001) 426 and refs. therein.
3. Bao-An Li, Phys. Rev. Lett. 88, 192701 (2002) and refs. therein.
4. M.B. Tsang et al., Phys. Rev. Lett. 86, 5023 (2001).
5. L.-W. Chen, V. Greco, C.M. Ko, and B.-A. Li, Phys. Rev. Lett. 90, 162701-2 (2003).
6. G. Verde et al., Phys. Rev. C 67, 034606 (2003).
7. G. Verde et al., Phys. Rev. C 65, 054609 (2002).
8. P. Danielewicz and P. Schuck, Phys. Lett. B 274, 268 (1992).
9. C.J. Gelderloos, J.M. Alexander, NIM 349, 618 (1995).
10. R. Ghetti et al., Phys. Rev. Lett. 91, 092701 (2003).
11. G. Verde et al., in preparation.
12. W. Tan et al., in preparation.

Safety Information

It is an important goal of the NSCL that users perform their experiments safely, as emphasized in the Director’s Safety Statement. Your proposal will be reviewed for safety issues by committees at the NSCL and MSU who will provide reviews to the PAC and to you. If your experiment is approved, a more detailed review will be required prior to scheduling and a Safety Representative needs to be designated.

SAFETY CONTACT FOR THIS EXPERIMENT: ____

HAZARD ASSESSMENTS (CHECK ALL ITEMS THAT MAY APPLY TO YOUR EXPERIMENT):

______x___ Radioactive sources required for checks or calibrations.
__________ Transport or send radioactive materials to or from the NSCL.
__________ Transport or send— to or from the NSCL—chemicals or materials that may be considered hazardous or toxic.
__________ Generate or dispose of chemicals or materials that may be considered hazardous or toxic.
__________ Mixed Waste (RCRA) will be generated and/or will need disposal.
__________ Flammable compressed gases needed.
__________ High-Voltage equipment (Non-standard equipment with > 30 Volts).
__________ User-supplied pressure or vacuum vessels, gas detectors.
__________ Non-ionizing radiation sources (microwave, class III or IV lasers, etc.).
__________ Biohazardous materials.

PLEASE PROVIDE BRIEF DETAIL ABOUT EACH CHECKED ITEM.

We will need to calibrate the silicon detectors with source made using the thorium source maker in the hot lab.

DETAILED BEAM REQUIREMENTS

The information supplied in this section will serve as the basis for the total beam time requested from the PAC. In addition to Beam-on-target time[1] entered below, an estimate of the beam delivery time[2] calculated according to the guidelines under the section entitled “Beam Delivery Time Calculation” in the PAC 27 Call for Proposals will also be presented to the PAC.

For each primary beam requested, please fill in the table below. Not all items will apply to all experiments. Please add additional primary and secondary beams as needed. Please list the total time requested for each primary beam on the first page of this proposal.

Primary Beam 1 (from beam list, to be included in **Beam Delivery Time**) Primary beam tune ___ hrs
Isotope ^{112}Sn
Energy[3] 80 MeV/nucleon
Minimum intensity 0.1 (particle nA)

Modification of A1900 standard configuration Addt’l time per Tom Ginter ____ hrs

Development of special optics Addt’l time per Tom Ginter ____ hrs

Secondary beam A from primary beam 1 Delivery time per table ____ hrs
Isotope ____
Energy ____ MeV/nucleon
Rate[4] ____ (particle nA•sec)$^{-1}$
A1900 Momentum acceptance ± ____ %
Acceptable purity ____ %
Additional requirements[5] ____ Event-by-event momentum correction from position
in A1900 Image 2 measured with ___ PPAC ___ Scintillator
____ Timing start signal from A1900 extended focal plane

Secondary beam B from primary beam 1 Delivery time per table ____ hrs
Isotope ____
Energy ____ MeV/nucleon
Rate ____ (particle nA•sec)$^{-1}$
A1900 Momentum acceptance ± ____ %
Acceptable purity ____ %
Additional requirements ____ Event-by-event momentum correction from position
in A1900 Image 2 measured with ___ PPAC ___ Scintillator
____ Timing start signal from A1900 extended focal plane

If experiment is not in A1900 Tune to vault (4 hrs) ____ hrs

Beam-on-target time for primary beam 1 **____ hrs**
On-target time for primary beam 1 ____ hrs
On-target time for secondary beam A ____ hrs
On-target time for secondary beam B ____ hrs

Beam delivery time for primary beam 1 **____ hrs**

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[1] Beam-on-target time is the time that the beam is needed for the purpose of the experiment, including activities such as testing, debugging the experimental setup, and calibrations.

[2] Beam delivery time is the time required by the NSCL for beam development and beam delivery; this time is not part of the time available for performing the experiment.

[3] A primary beam can be delivered with reduced energy by passing it through a degrader of appropriate thickness; this process necessarily impacts the beam properties.

[4] The rate for secondary fragment should be reported in units of particles per second per particle-nanoampere of primary beam.

[5] These capabilities are described in detail in the A1900 standard configuration.

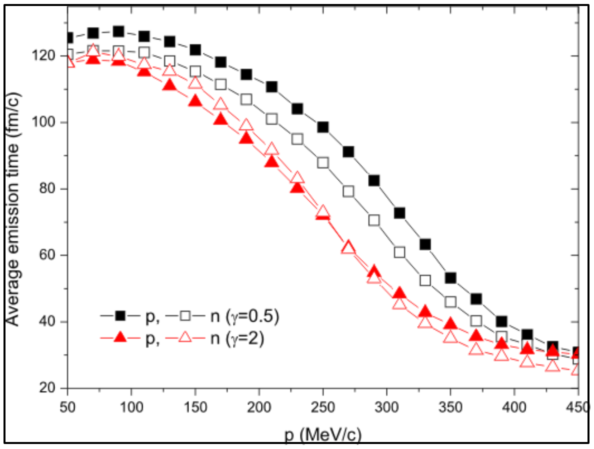

Fig. 1: Average emission for protons (solid) and neutrons (open) as a function of momentum for soft (black) and stiff (red) asym. terms.

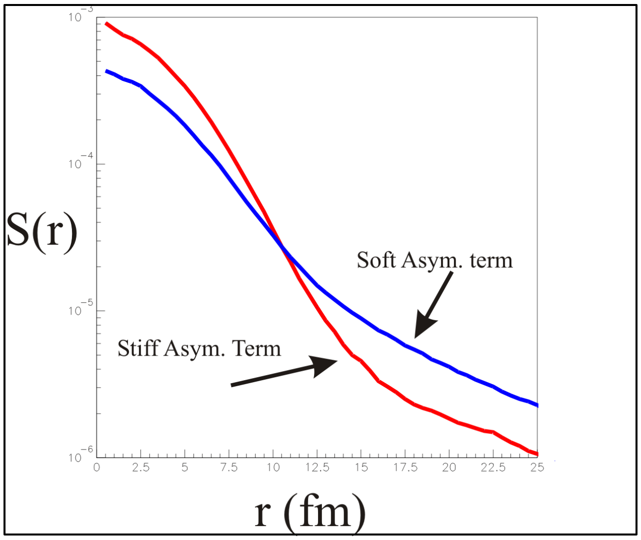

Fig. 2: Two particle source S(r) for soft (black) and stiff (red) asym. terms.

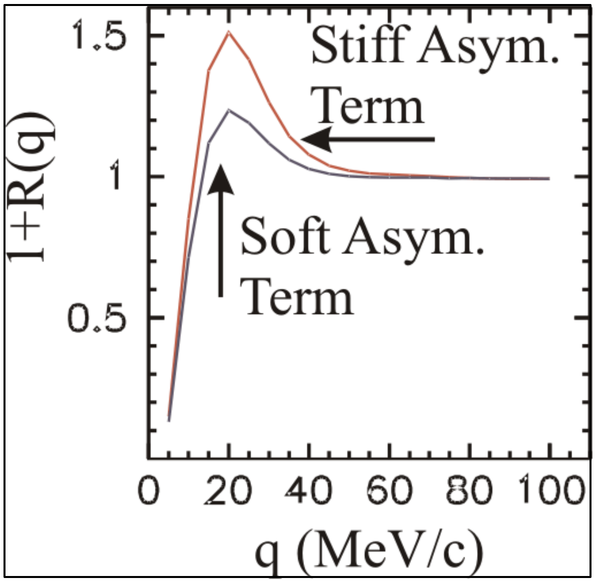

Fig. 3 Two proton correlation functions for energetic, P_{tot}>500 MeV protons and a stiff (red curve) or a soft (blue curve) asym. term.

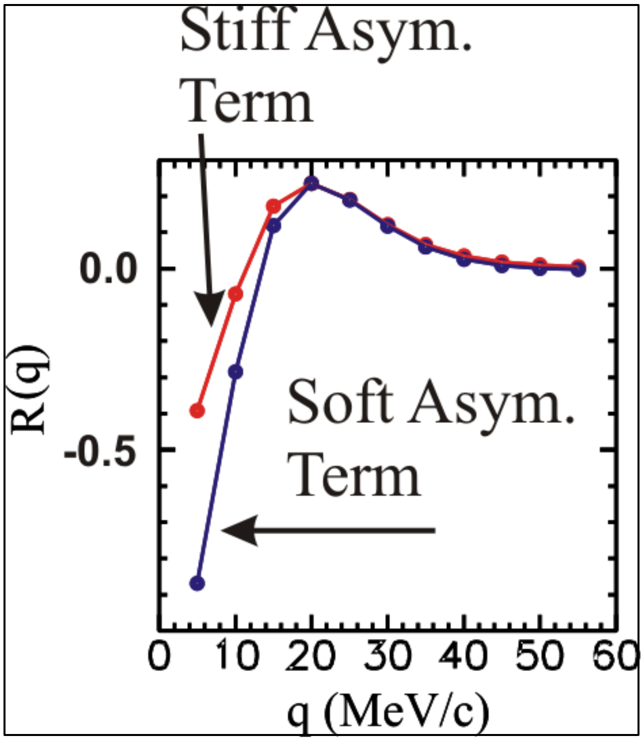

Fig. 4 Two proton correlation function for stiff (red) and soft (blue) asymmetry terms after renormalizing them to the same peak value to enable easy comparison.

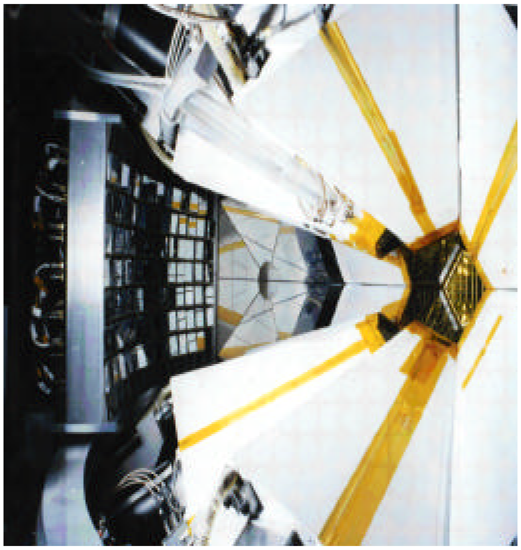

Fig. 5: Picture of the Catania array situated on the movable rail in the interior of the MSU 4pi detector. The HiRA, etc. will occupy the space of the Catania array in the new experiment.