FRENA - Proposed Areas of Research

(Facility for Research in Experimental Nuclear Astrophysics)

A National Facility

Proposed by

Nuclear & Atomic Physics Group

Saha Institute of Nuclear Physics

P. Banerjee

The main goal of SLENA 2008 is to outline a road map of nuclear astrophysics research in India for the next 10 years by :

- identify the key-problems in nuclear astrophysics at present;
- collect the inputs necessary for the experimental facility;
- identify research interests and expertise of different research institutions and universities;
- strengthen ties between the existing nuclear physics laboratories, theoretical nuclear physics groups, and nuclear astrophysics modellers in India as well as abroad.

Scheme

- **Measurements in Nuclear Astrophysics**
- **Some key problems**
- **FRENA** – A brief description
- The scope of research using FRENA in the initial stages
- Relevance

Nuclear Astrophysics involves the study of

- Synthesis of Elements (Nucleosynthesis)
- Evolution of Cosmic sites (Early Universe, Interstellar medium, red giants, supernova, etc.)

Our understanding of Nucleosysthesis and energy generation mechanism depends on our knowledge of the
RATES OF REACTIONS
OF ASTROPHYSICAL INTEREST

Therefore, we need to measure these rates

The reaction rate per particle-pair is

$$< \sigma v >= \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$

The probability of tunnelling through the Coulomb Barrier can be approximated by

$$P = \exp(-2\pi\eta) = \exp\left[-\left(\frac{E_G}{E}\right)^{\frac{1}{2}}\right]$$

where η is the Sommerfeld parameter and $2\pi\eta = 31.29 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{\frac{1}{2}}$

The cross-section can be written as

$$\sigma(E) \quad \alpha \quad \exp\left(-2\pi\eta\right)$$

The geometrical part of the cross-section depends on the De Broglie wavelength, i.e.,

$$\sigma(E) \quad \alpha \quad \pi\lambda_{db}^2 \quad \alpha \quad \frac{1}{E}$$

By combining these two expressions, the cross-section for charged-particle reactions can be written as

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$$

By substituting this *σ(E)* into the general expression for the reaction rate per particle-pair, we get

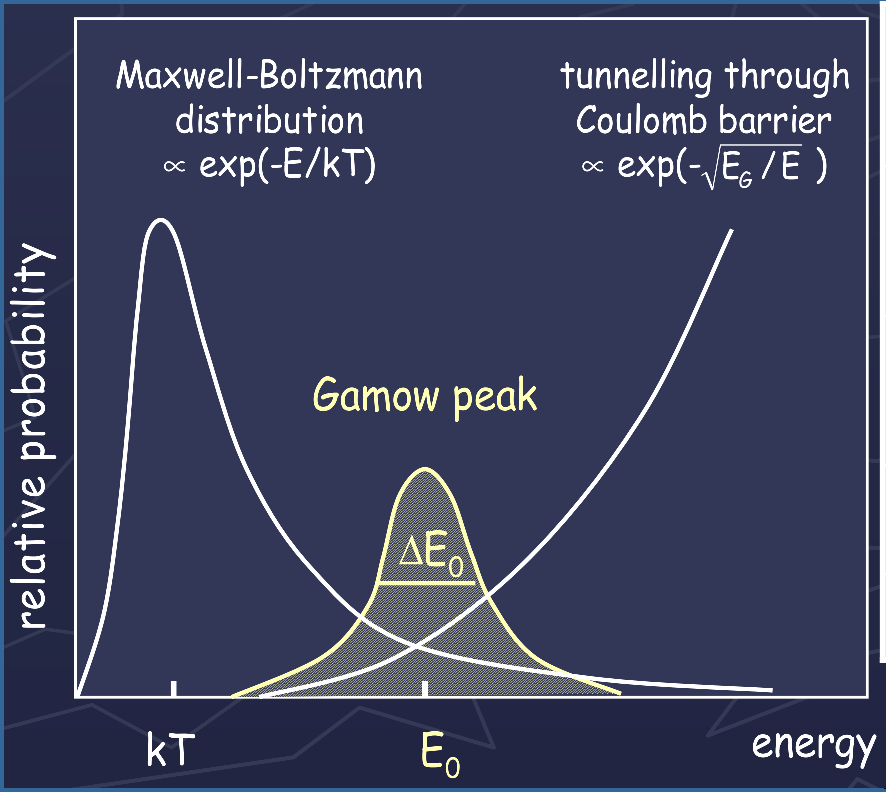
$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \left(\frac{E_G}{E}\right)^{\frac{1}{2}}\right] dE$$

Now, ***exp(-E/kT)*** is small at large energies, while ***exp[-(*** $E_G/E)^{0.5}$ ***]*** is small at low energies. The product of these two terms gives a value of the integral which peaks at an energy E_0 given by

$$E_0 = \left(\frac{bkT}{2}\right)^{\frac{2}{3}} = 1.22(Z_1^2 Z_2^2 \mu T^2)^{\frac{1}{3}} \ \ \mathrm{keV}$$

E_0 is known as the effective burning energy

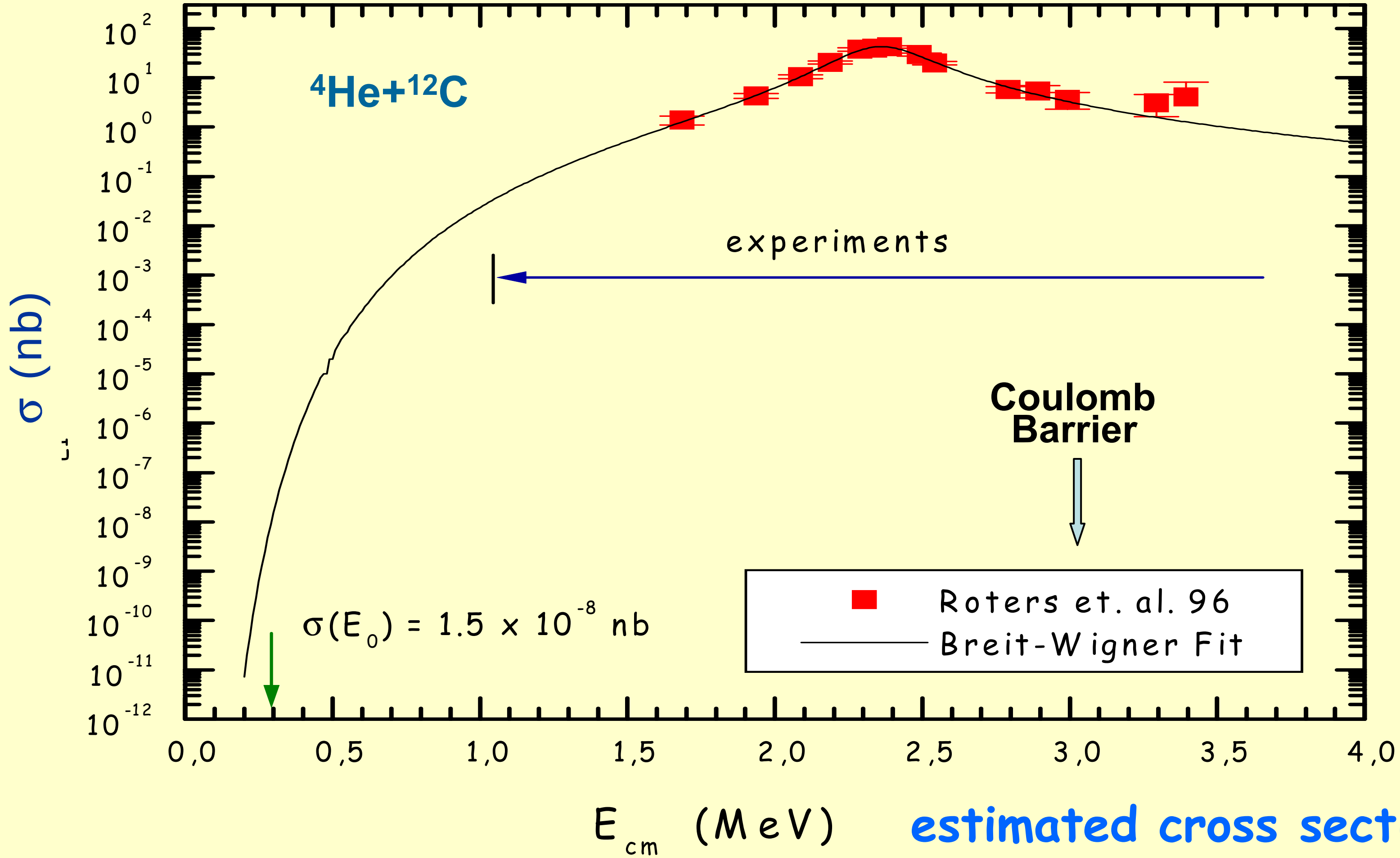
Stellar reactions occur at *$E_0 \pm \Delta E_0/2$*.
This *E_0* is far below the Coulomb barrier



Reaction	E_{CB} (keV)	$E_0 \pm \Delta E_0/2$ (keV)
$^3He(^4He,\gamma)^7Be$	1118	22.4±6.2§
$^{15}N(p,\gamma)^{16}O$	1711	26.6±7.2§
$^{12}C+^{12}C \rightarrow ^{24}Mg^*$	6660	1523±296 ‡
$^{70}Ge+\alpha$	9910	4500±965 †

§ → T_6=15 (Sun) † → T_9=1.8
‡ → T_6=100 (AGB stars)

- Non-resonant reaction cross-sections decrease exponentially by orders of magnitudes at sub-Coulomb energies.



Gamow peak at E ~ 300 keV

estimated cross section
$\sigma \sim 10^{-17}$ barn !

The low reaction cross-section near E_0 prevents a direct measurement in the Laboratory

Measurements are made at higher energies and extrapolated to E_0

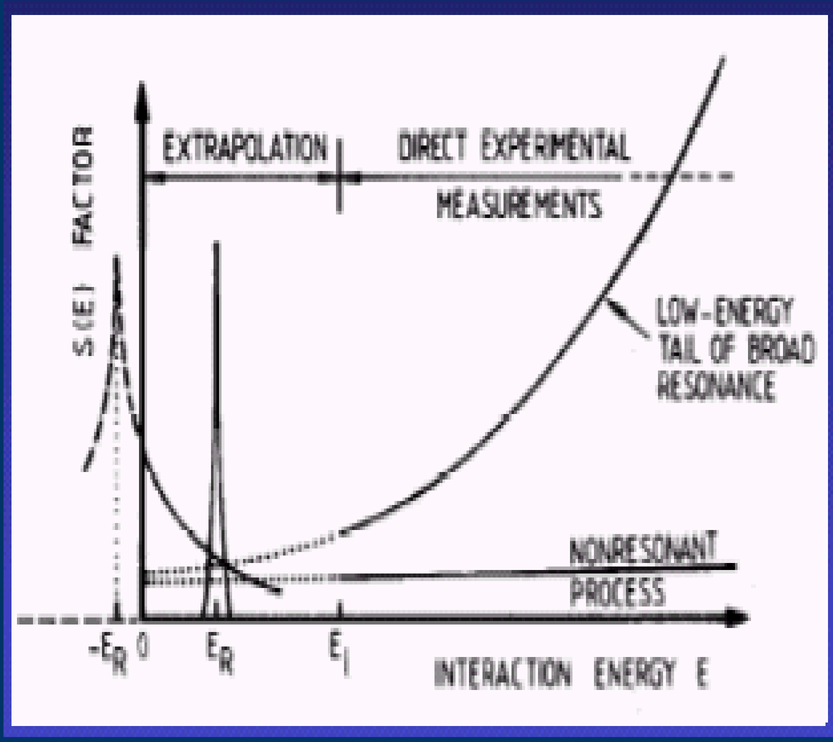
The cross-section can be expressed as

$$\sigma(E) = S(E)\ E^{-1} \exp(-2\pi\eta)$$

nuclear origin	non-nuclear origin
Weak Energy Dependence	**Strong Energy Dependence**

***S(E)*, the Astrophysical S-factor is extrapolated to lower energies**

However, such extrapolations are often hazardous as seen from



Difficulties :

a) the energy dependence of S(E) is different for different systems

b) Presence of resonances and resonance-tails at low-energy lead to large errors

There is a need to account for all reaction contributions to extrapolate reliably:

- direct component,
- resonance components
- electron screening

Therefore, the primary goal of Experimental Nuclear Astrophysics

⇓

Measurement of $\sigma(E)$ at energies at or near the Gamow peak

Requirements for an Experimental facility

- intense beams of different species in the keV-MeV range to cover various stellar astrophysical conditions.
- detectors with high efficiency & resolution and good solid angle coverage
- Proper targets → Ultra High purity, Gas targets
- low background environment → active and passive shielding

FRENA (a unique facility in India)

A 3 MV, high current Tandem accelerator

A 500 kV single-ended accelerator with a high-current ECR ion-source

State-of-the-art detector systems including Clover Ge detectors, large volume NaI(Tl), BGO, Plastic scintillators, large area Si detectors, etc.

Sophisticated target laboratory

FRENA (Phase II) will have facilities for

- Neutron-induced studies
- Heavy-ion bunching
- Magnetic spectrometer

The 3 MV Tandetron

- Terminal Voltage - 0.2 to 3.0 MV
- Typical Beam Currents at 3 MV after quadrupole triplet lens:
  - H^+ - 500 μA
  - He^{2+} - 200 μA
  - Heavier Ions – 20 – 50 μA
- Pulsed beam of H^+, $^2H^+$ and He^{2+}
- Standard Terminal voltage Resolution – 3×10^{-5} ($\Delta E/E$) (100 V at 3 MV, i.e. Energy steps of less than a keV)
- Terminal Voltage stability - ±300 V (GVM stabilization)
  ±80 V (slit stabilization)
- Terminal Voltage ripple – 30 Vpp

Some key Problems in Nuclear Astrophysics

1 Study of the reaction $^{3}He(\alpha,\gamma)^{7}Be$

This reaction is one of the major uncertainties in the determination of the high energy solar neutrino flux that results from $^{7}Be(p,\gamma)^{8}B$

The reaction is also important for understanding the primordial ^{7}Li abundance

Discrepancy persists between prompt and γ-ray activity data

2 The $^{14}N/^{15}N$ abundances are not well understood

These abundances are affected by a large number of reactions - $^{14}N(n,p)^{14}C$, $^{14}N(n,\gamma)^{15}N$, $^{14}C(n,\gamma)^{15}C$, $^{15}N(n,\gamma)^{16}N$, $^{14}C(p,\gamma)^{15}N$, $^{18}O(p,\alpha)^{15}N$, $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,\alpha)^{12}C$, $^{14}C(a,\gamma)^{18}O$, $^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$

Most of these reactions are important for ^{19}F abundance also

3 **The $^{14}N(p,\gamma)^{15}O$ reaction – the slowest CNO cycle reaction**

Recent results are a factor of 2 less than the NACRE values
At present, the ^{14}N abundance in AGB stars is incompatible with AGB model predictions

4 **Helium Burning Phase**

The $^{12}C(\alpha,\gamma)^{16}O$ is of central importance to stellar evolution.

This reaction helps to determine the mass of the core following He-burning, and the C/O ratio which greatly influences the future evolution of the star.

After years of concerted effort, **experimental rates do not agree with stellar model predictions** and
the rate for this reaction is still not known with
the required accuracy of about 20%.

5

Heavy-ion burning

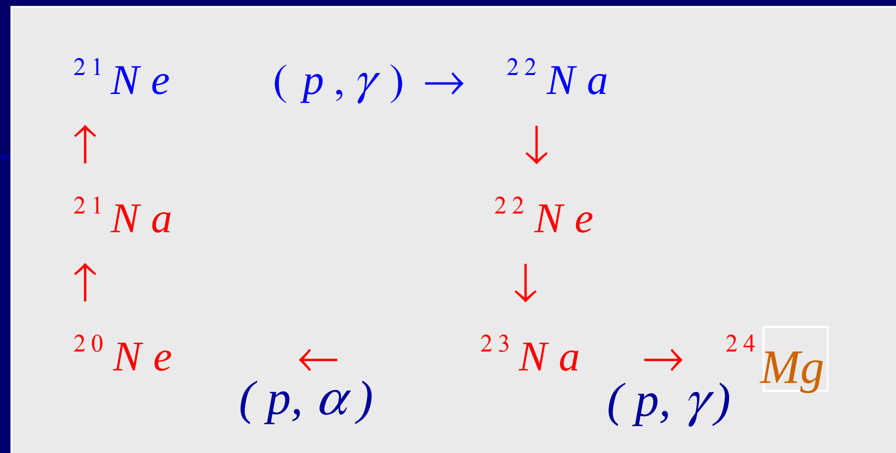
The subsequent heavy-ion burning phases depend on the nucleosynthesis of ^{12}C and ^{16}O during the He-burning phase.

The $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$ and capture of protons and alpha particles by the fusion products are important.

Neither the fusion processes, nor the subsequent proton and α capture reactions are sufficiently well known for reliable modeling of the later phases of stellar evolution.

6

The Ne-Na cycle



A recent measurement of the ^{23}Na (p, γ)^{24}Mg reaction rate shows an increase of the rate by a factor of 10 below T=0.1 GK

The competition from (p, γ) reduces the efficiency of the (p, α) channel and the Ne-Na set of reactions becomes a chain, not a cycle.

If Ne-Na cycle feeds the Mg-Al cycle more than expected, Mg-Al cycle nucleosynthesis becomes more efficient

^{25}Mg(p, γ)^{26}Al is important to measure

7 **$^{22}Ne(\alpha, n)^{25}Mg$ - dominant source of neutrons for the s-process near T = 0.2 –0.3 GK in massive stars**

Although the **$^{22}Ne(\alpha,n)^{25}Mg$** reaction has been widely studied, the different data sets show large uncertainties, especially at energies below 1 MeV. Thus, new investigations of **$^{22}Ne(\alpha,n)^{25}Mg$** are desirable.

The other neutron producing reaction is $^{13}C(\alpha,n)^{16}O$

8 **Nova nucleosynthesis studies** (reactions initiated by protons)

Nuclear physics input to nova model calculations consists mainly of cross sections for p-induced reactions involving stable and unstable target nuclei, and β^+-decay half-lives.

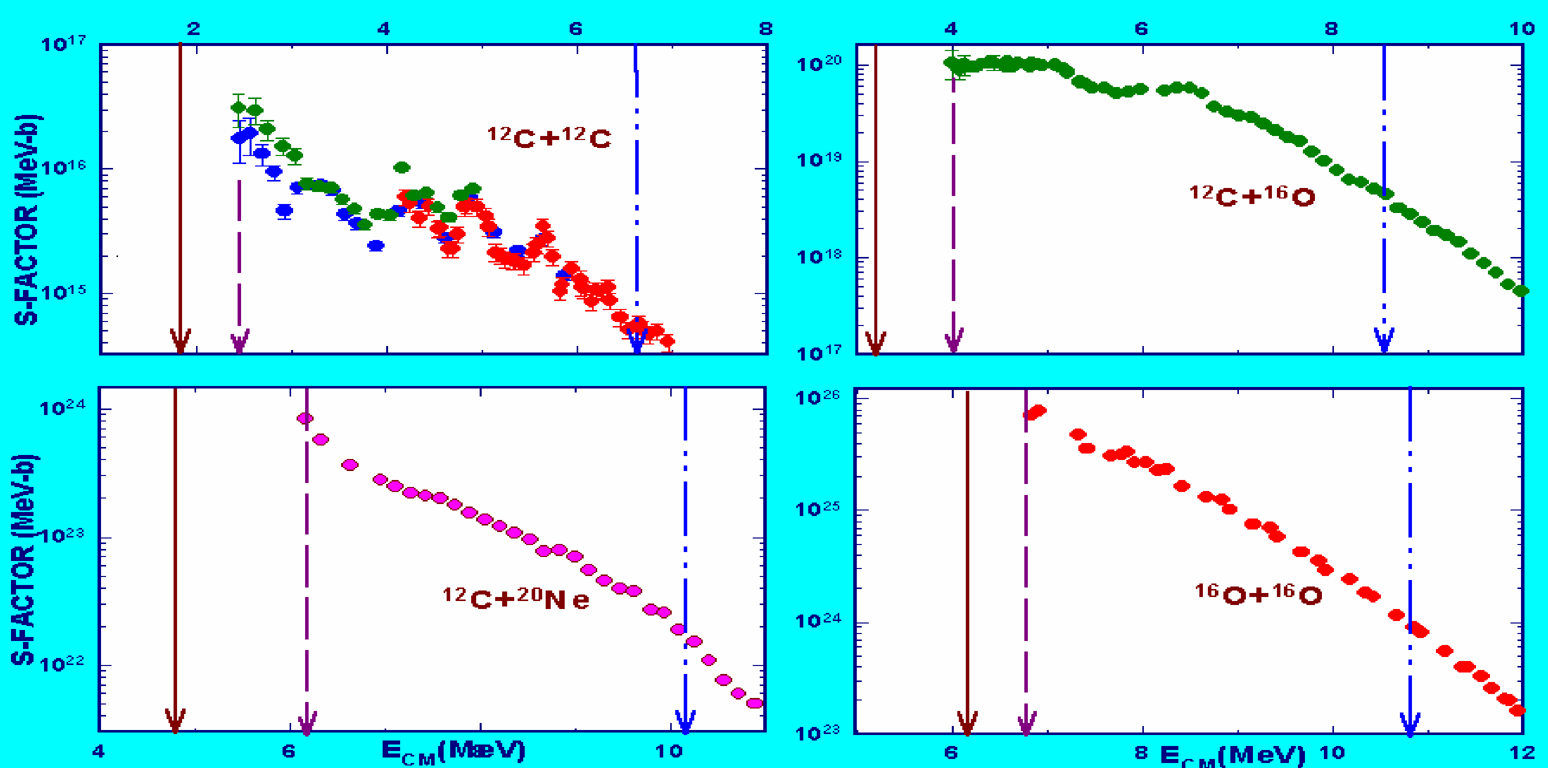
Main uncertainties affecting nova nucleosynthesis studies are localized in **$^{18}F(p,\alpha)^{15}O$, $^{25}Al(p,\gamma)^{26}Si$, $^{26}Al^g(p,\gamma)^{27}Si$, and $^{30}P(p,\gamma)^{31}S$**.

Possible Research areas with FRENA

Reaction	Coulomb barrier (MeV)	Q-value (MeV)	Temperature T_9 (^oK)	Gamow peak E_o (MeV)	Gamow window ΔE_o (MeV)
$^{12}C+^{12}C$	6.66	13.93	0.6 2.0	1.73 3.84	0.88 1.23
$^{16}O+^{16}O$	10.76	16.54	1.0 2.4	3.90 7.00	1.62 3.35
$^{4}He+^{12}C$	3.10	7.16	0.2 0.6	0.31 0.66	0.17 0.42
$^{15}N+p$	1.71	4.96	0.2 3.0	0.15 0.91	0.12 1.12
$^{3}He^{+4}He$	1.12	1.59	0.2 3.0	0.13 0.77	0.11 1.03

Study of Heavy-ion reactions

- $^{12}C + ^{12}C$; E_{CB} = 6.65 MeV Q = 13.93 MeV
- $^{12}C + ^{16}O$; E_{CB} = 8.45 MeV; Q = 16.76 MeV
- $^{12}C + ^{20}Ne$; E_{CB} = 10.16 MeV; Q = 18.97 MeV
- $^{16}O + ^{16}O$; E_{CB} = 10.76 MeV; Q = 16.54 MeV



$^{12}C + ^{12}C \Rightarrow$

$^{23}Mg + n$, Q= -2.60 MeV
$^{23}Na + p$, Q= 2.24 MeV
$^{20}Ne + \alpha$, Q= 4.62 MeV

Region of Astrophysical interest – 1 to 3 MeV

Occurs

- in massive stars in the late stages of stellar evolution
- in accreting neutron stars and
- in exploding white dwarfs producing type I supernovae

Why is $^{12}C + ^{12}C$ Cross-section important?

- Nucleosynthesis of ^{20}Ne and ^{23}Na and subsequent evolution
- Times scale for stellar C burning
- Ignition conditions for type I SN

Study of Heavy-ion Reactions

$$^{12}C + {}^{12}C \rightarrow {}^{20}Ne + \alpha$$
$$\rightarrow {}^{23}Na + p$$
$$\rightarrow {}^{23}Mg + n$$

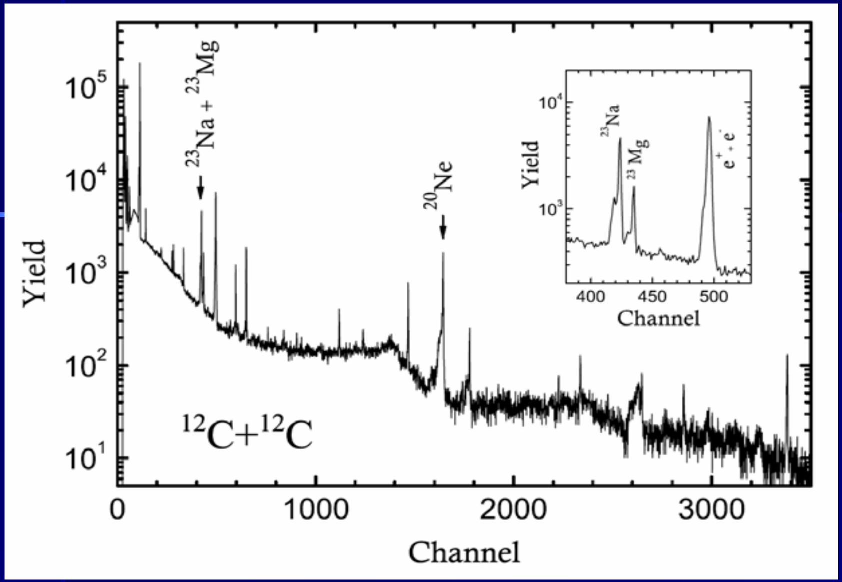
A. Detection of Light particles - n, p, α

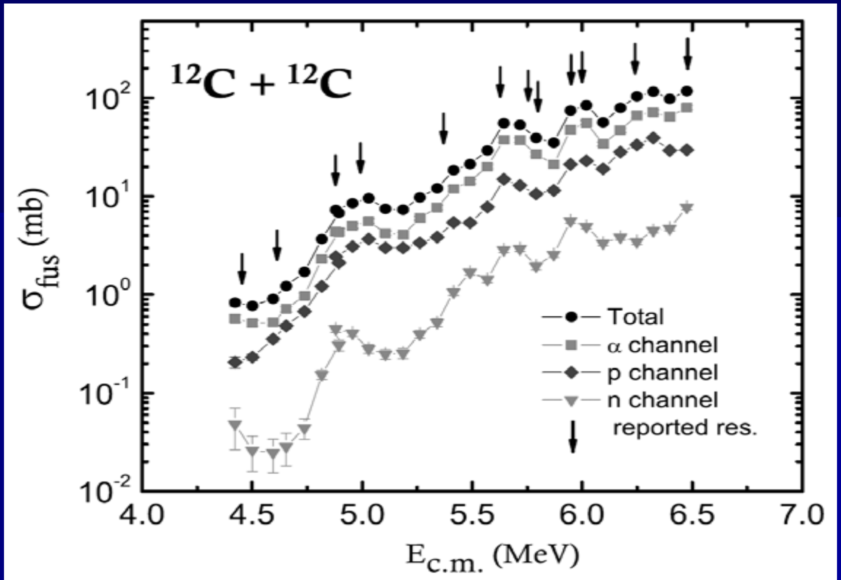
B. Detection of heavy residues - ^{20}Ne, ^{23}Na, ^{23}Mg

C. Detection of the prompt γ-rays following de-excitation of residues in excited states. (residues formed directly in their ground state are not accessible)

D. Residual activity method - Detection of γ-rays following the decay of the residues in the g.s.

Recent results on $^{12}C + {}^{12}C$ (E. F. Aguilera et al., PHYSICAL REVIEW C **73**, 064601 (2006))





$E_{c.m.}$ (MeV)	σ_α (mb)	Error (mb)	σ_p (mb)	Error (mb)	σ_n (mb)	Error (mb)	σ_{tot} (mb)	Error (mb)
4.5	0.60	0.04	0.26	0.02	0.03	0.01	0.89	0.04
5.1	4.53	0.24	3.38	0.17	0.24	0.03	8.15	0.30
5.49	15.30	0.83	6.14	0.33	1.61	0.11	23.05	0.90
6.1	37.35	1.88	21.77	1.08	3.20	0.20	62.31	2.17

A simple calculation of cross-section at a lower energy

$\sigma = 5.1x10^{-9}$ b at E = 2.46 MeV

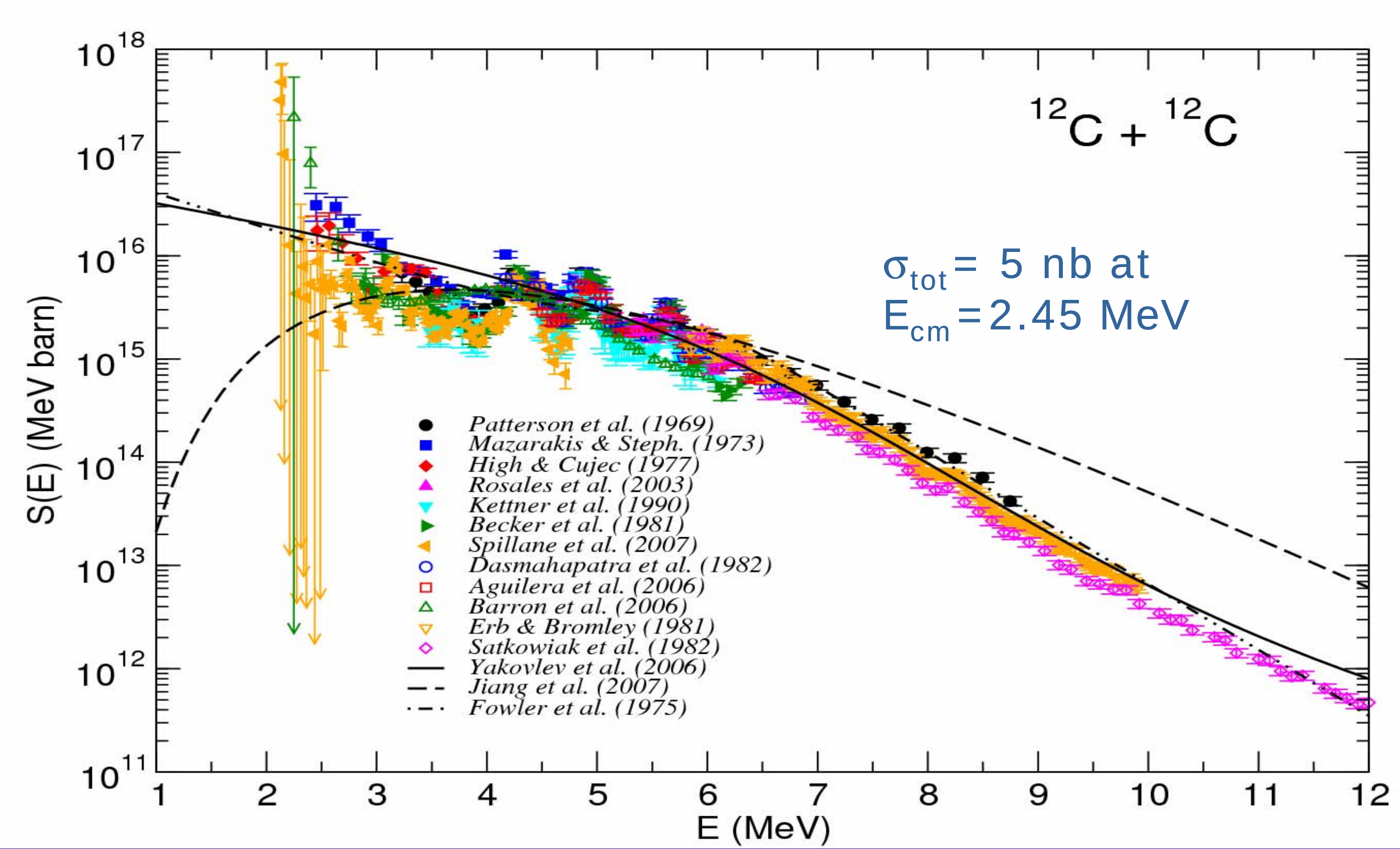
Therefore, $S = \sigma E e^{87.21/\sqrt{E}} = 17.5x10^{15}$ MeV-b

Let us calculate σ ατ E= 2.0 MeV

Assume S (2.0 MeV) = S (2.46 MeV)

It turns out that
$\sigma(2.0) = (17.5x10^{15}/2.0)e^{-87.21/\sqrt{2.0}} = 1.46x10^{-11}$ b

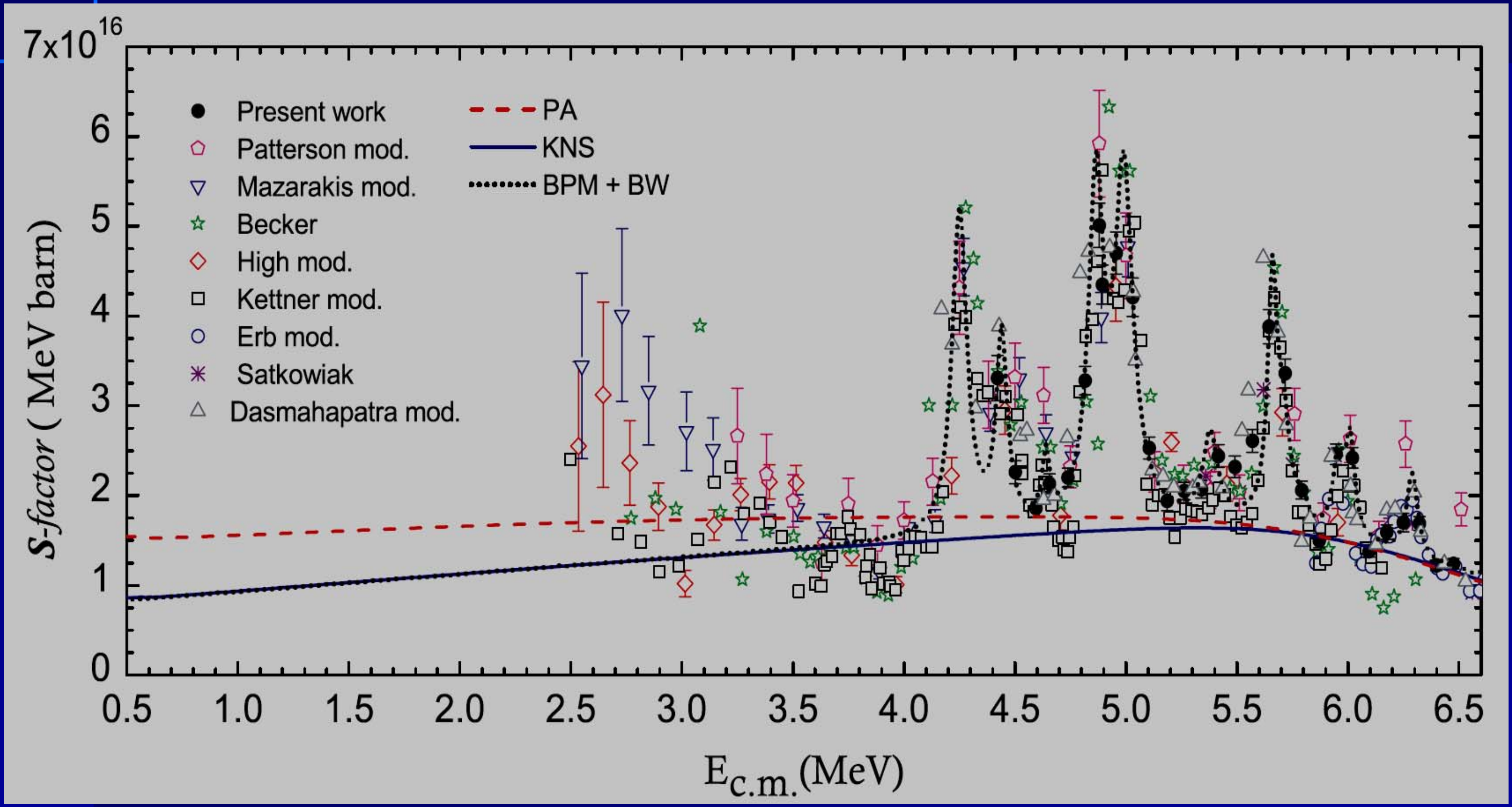
σ falls by more than 2 orders of magnitude



Further measurements in order to

- ❑ Extend data to lower energies
- ❑ Large discrepancies in available data
- ❑ Large uncertainties at Low energies

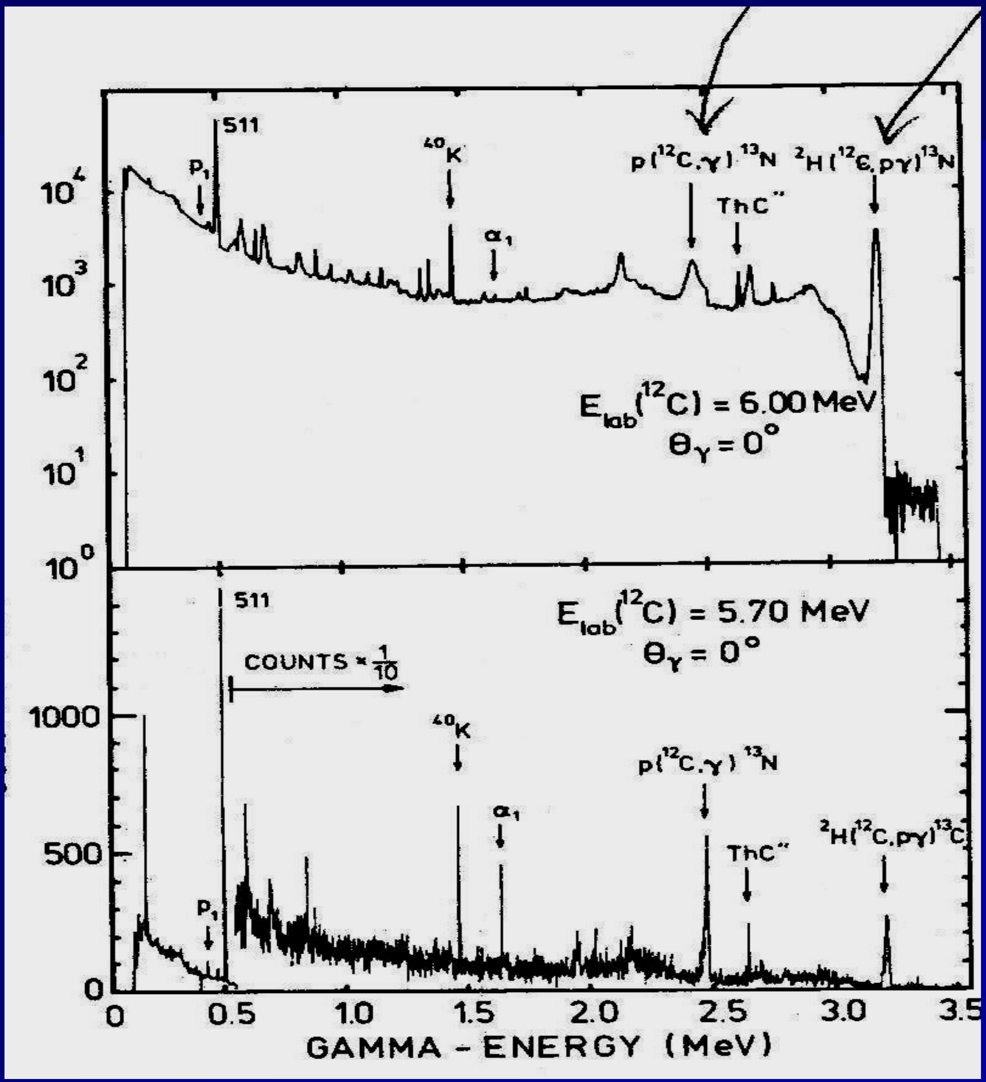
Resonances in $^{12}C + ^{12}C$ reaction



E. F. Aguilera et al., PHYSICAL REVIEW C **73**, 064601 (2006)

Principal sources of uncertainty at low Energies

- ^1H and ^2H impurity in target
- Beam-induced and cosmic-ray background
- Carbon build-up



We propose to reduce target contamination by

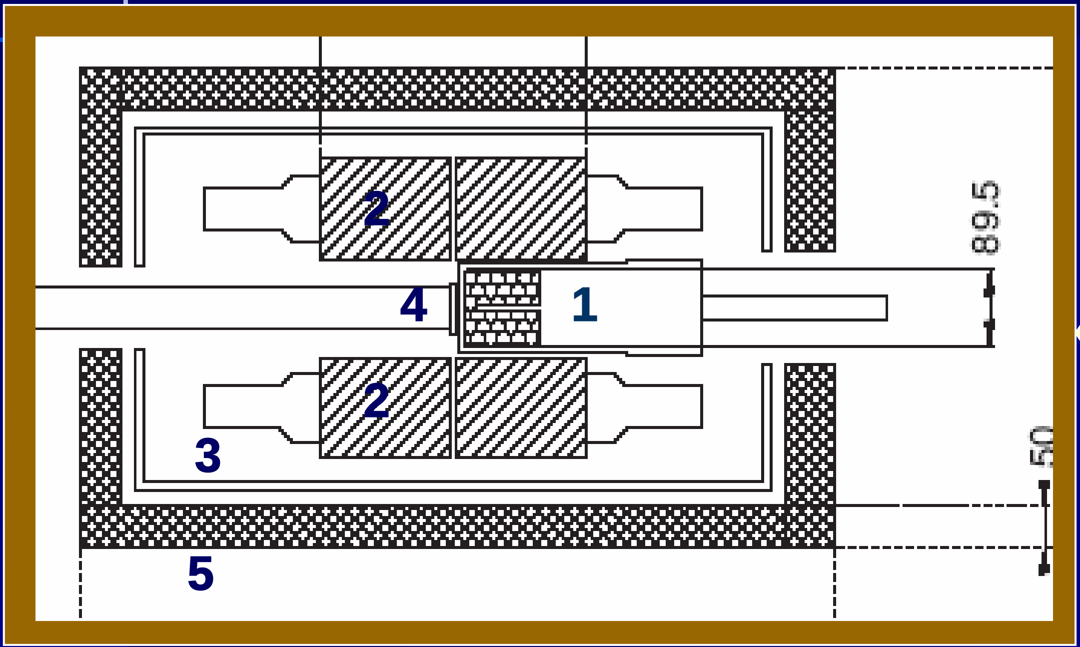
- Use of ^{12}C deposited on baked Ta as target
- Use of gas target (like CO)

The background
a critical problem for low energy cross-section measurements

- Cosmic ray muons
- Muon-induced neutrons & radioactivity
- Radon & A=210 Pb-Bi-Po daughters
- Gamma and neutron emission from materials
- Radon emanation from materials
- Beam induced reactions

Background minimisation

- Passive or Active Shielding around Detectors
- Compton suppression
- Use of Pulsed Beam
- Use of Ancillary Detectors



Detector set up at LENA

1. HPGe (582 cm^3)
2. NaI(Tl) (16 optically isolated crystals each with its own PMT in an annulus)
3. Lead shield (passive shielding)
4. Target (1.1 cm from detector face)
5. Plastic Scintillator (Five 50 mm thick plates arranged in a box; vetoes cosmic muon induced background; useful in sea-level, low yield experiments)

Relevance of FRENA

The stable beam facility (for exploring stellar quiescent burning) will complement the upcoming RIB facilities in the country (useful for studying explosive stellar burning)

There is a large group of experimentalists at SINP and in other laboratories in India working on nuclear structures and reactions.
FRENA will utilize this enormous experience and expertise.

Theoretical Nuclear Astrophysicists in the country and at SINP will contribute to and benefit from FRENA.

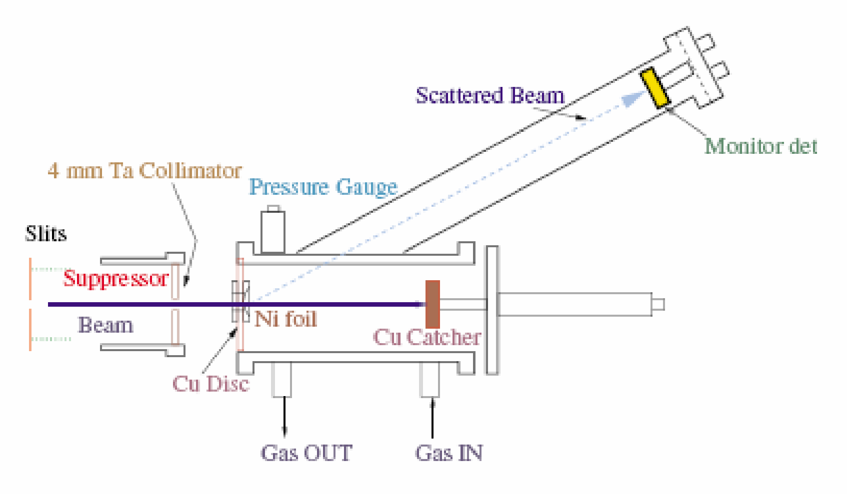
Open up international Collaboration

Thank You

Proposed Research Activities (using 500kV Accelerator)

- $^{3}He(^{4}He, \gamma)^{7}Be$ (E_0 = 130-750 keV)

- The $^{3}He(^{4}He,g)^{7}Be$ reaction is one of the remaining major sources of uncertainty in determining the high energy solar neutrino flux that results from $^{7}Be(p,\gamma)^{8}B$



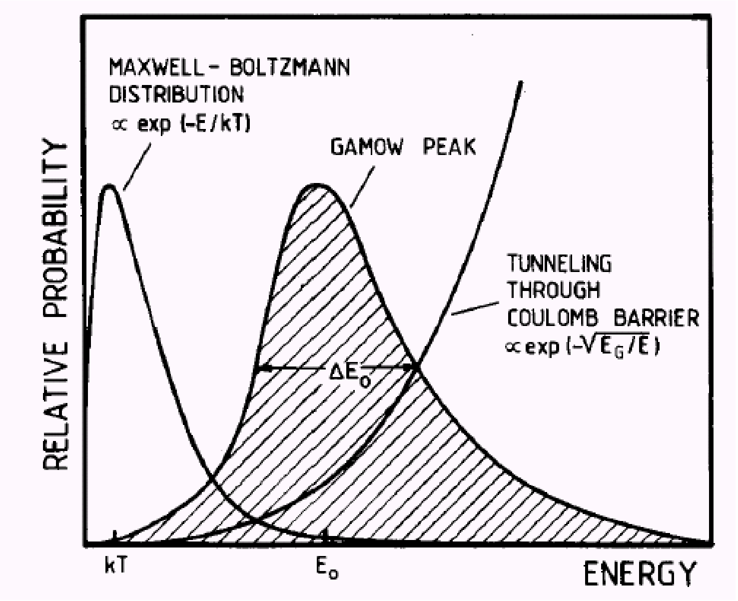
UNDERGROUND MEASUREMENTS

- The ratio of the *S(0)* factor for $^{15}N(p,\alpha)^{12}C$ and $^{15}N(p,\gamma)^{16}O$ determines the relative contributions of the first and the second cycle to the total rate of energy production.

- The second cycle (reached by $^{15}N(p,\gamma)^{16}O$ capture process) is important for the nucleosynthesis of ^{16}O and ^{17}O

LUNA: future with the 400 kV facility and even more...

Reaction	Q-value (MeV)	Burning energy (keV)	Lowest meas. energy (keV)	LUNA limit (keV, estimate)
$^{15}N(p,\gamma)^{16}O$	12.13	10-300	130	50
$^{17}O(p,\gamma)^{18}F$	5.6	35-260	300	65
$^{18}O(p,\gamma)^{19}F$	8.0	50-200	143	89
$^{22}Ne(p,\gamma)^{23}Na$	8.8	50-300	250	68
$^{23}Na(p,\gamma)^{24}Mg$	11.7	100-200	240	138
$^{2}H(\alpha,\gamma)^{6}Li$	1.47	50-300	700 (direct) 50 (indirect)	50
$^{12}C(\alpha,\gamma)^{16}O$	7.16	300	950	500
$^{15}N(\alpha,\gamma)^{19}F$	4.01	364	536	364
$^{13}C(\alpha,n)^{16}O$	2.21	170-250	270	200
$^{22}Ne(\alpha,n)^{25}Mg$	-0.47	470-700	850	630



NACRE - Nuclear Astrophysics Compilation of REaction Rates

Existing Facilities worldwide for Nuclear Astrophysics

1. **LENA at TUNL (Triangle Universities Nuclear Laboratories) at North Carolina, USA:**
   a) 200 kV high current accelerator (up to 5 mA)
   b) 1 MV Van de Graaff (up to 100 μA)

2. **LUNA at Gran Sasso, Italy**
   LUNA I – 50 kV (1992-2001)
   LUNA II – 400 kV (2000-2006)

3. **ERNA (European Recoil Separator for Nuclear Astrophysics) at Bochum, Germany**
   4 MV Dynamitron Tandem Accelerator

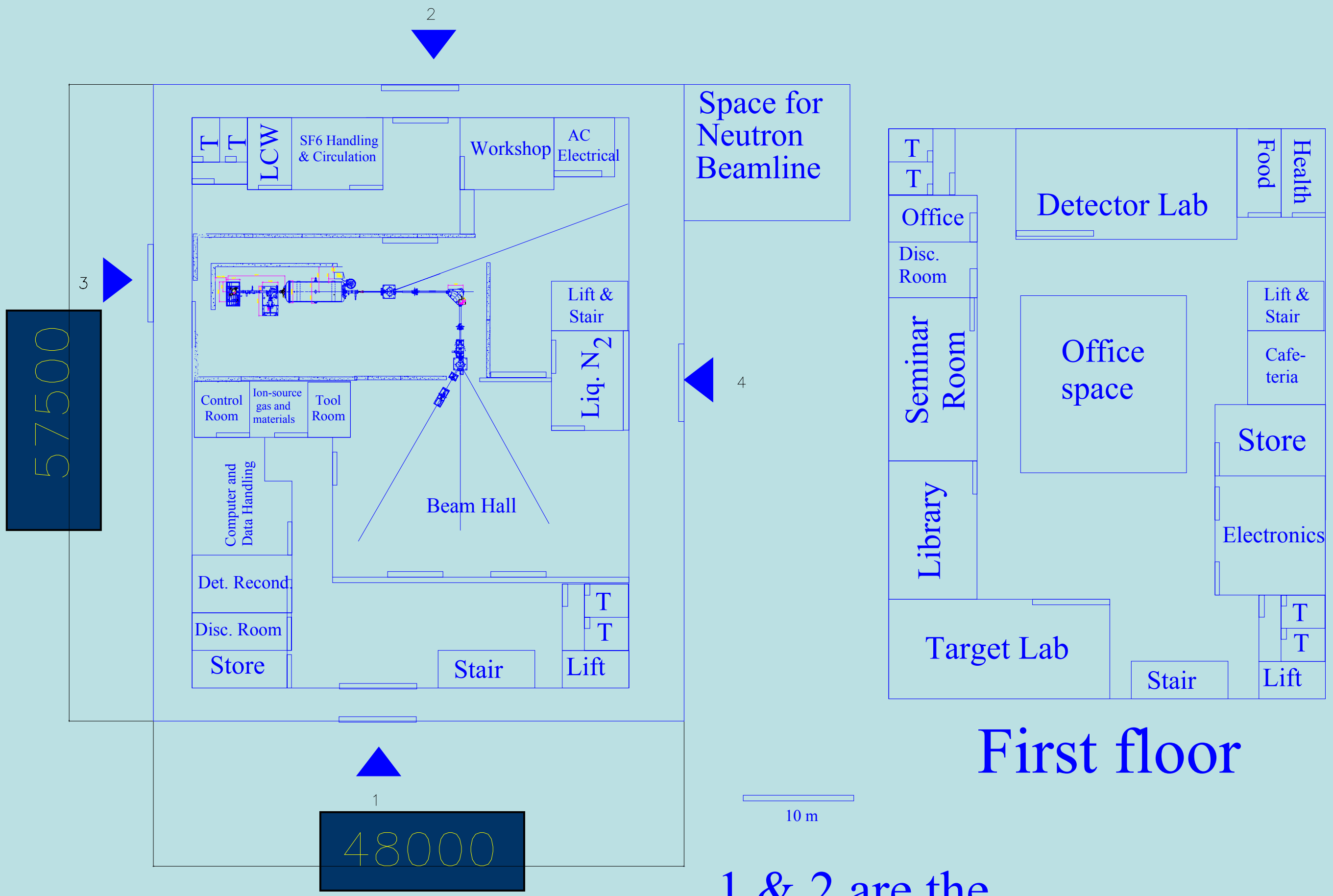
4. **JINA at Notre Dame**
   Have several accelerators; currently (since 1993) a 3.5 MV Van de Graaff is in use for studies in Nuclear Astrophysics

Backgrounds can be measured and subtracted

- In narrow resonances, background can be measured by running at energies just above or below the resonant energy

- Otherwise, substitute the target by a chemically similar target (especially for gas targets)

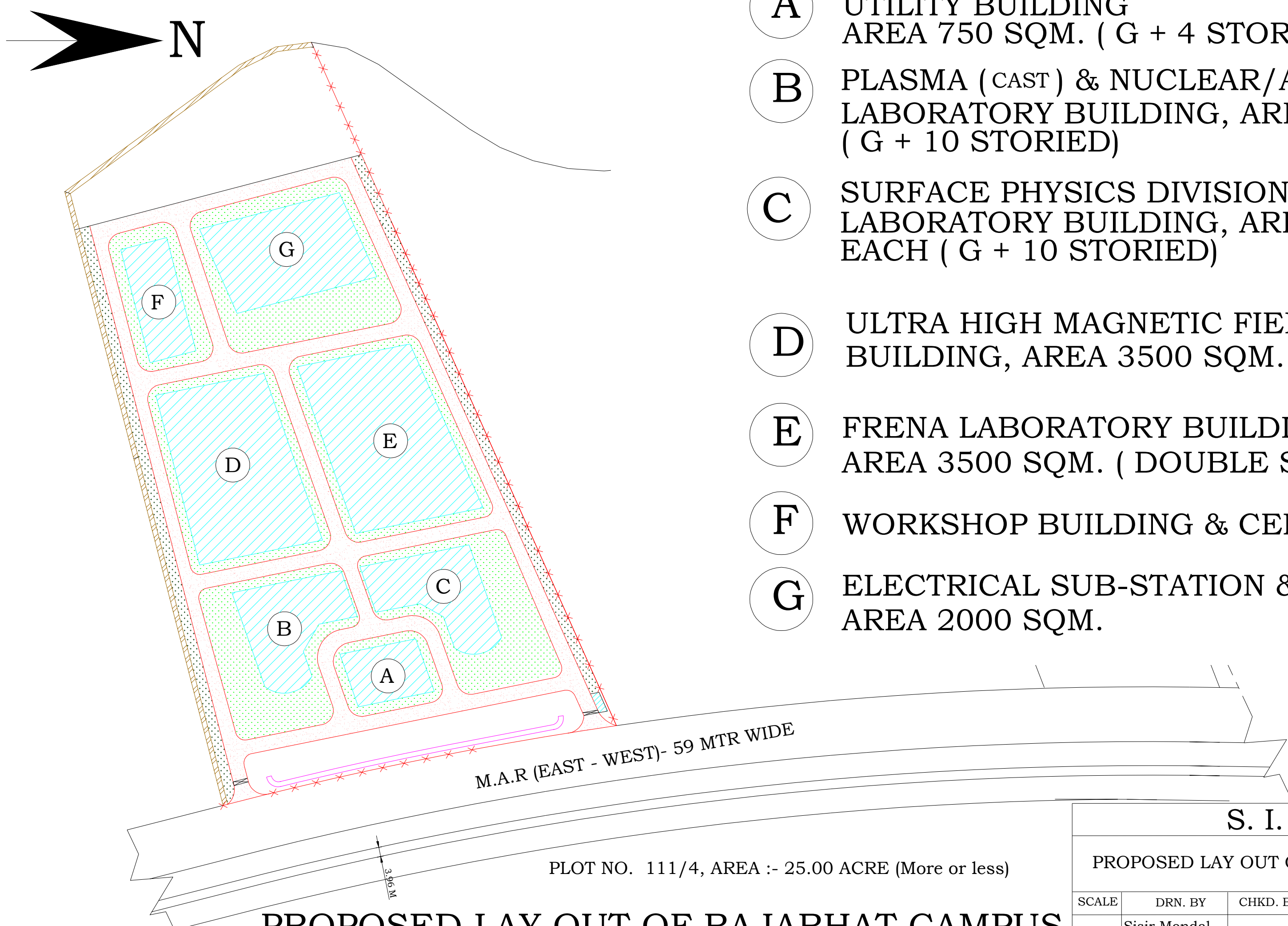
FRENA- Floor Layout



Ground floor

First floor

1 & 2 are the Main Entrances; 3 & 4 are for heavy-eqipments



A — UTILITY BUILDING
AREA 750 SQM. (G + 4 STORIED)

B — PLASMA (CAST) & NUCLEAR/ATOMIC PHYSICS
LABORATORY BUILDING, AREA 1750 SQM.
(G + 10 STORIED)

C — SURFACE PHYSICS DIVISION (CENSUP) & OTH
LABORATORY BUILDING, AREA 1750. SQM.
EACH (G + 10 STORIED)

D — ULTRA HIGH MAGNETIC FIELD LABORATORY
BUILDING, AREA 3500 SQM. (SINGLE STORIE

E — FRENA LABORATORY BUILDING,
AREA 3500 SQM. (DOUBLE STORIED)

F — WORKSHOP BUILDING & CENTRAL STORE, A

G — ELECTRICAL SUB-STATION & SERVICE BUILI
AREA 2000 SQM.

PROPOSED LAY OUT OF RAJARHAT CAMPUS

S. I. N. P.

PROPOSED LAY OUT OF RAJARHAT CAMPUS

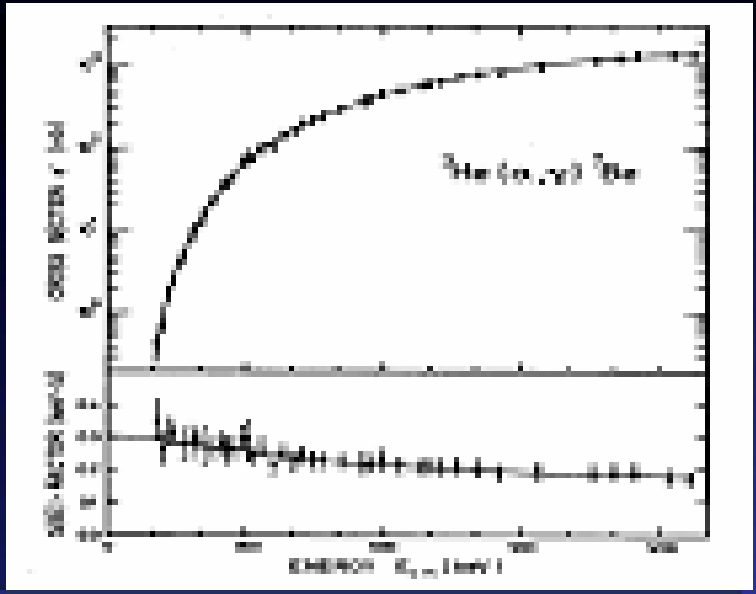
SCALE	DRN. BY	CHKD. BY	DATE	SKETCH NO.	REV.
NTS	Sisir Mondal & Nilkanta Sinha	R.Sengupta	01.06.07	SINP-RJHC.No.01	B1

Schedule of Machinery & Equipment

Sr. No.	Item Description	Estimated Cost (lakhs)	Probable date of Purchase Order (mm/yy)	Likely date of delivery (mm/yy)	Phasing of Expenditure					
					1st Year *	2nd Year*	3rd Year	4th Year	5th Year	XII Plan
1.	3 MV Tandetron with	3000	April, 2008	October, 2009	500	1500	800	200	-	3000
2.	Liquid Nitrogen plant	50	April, 2009	June, 2009	-	-	40	5	5	50
3.	Chilled Low-Conductivity water system	50	April, 2009	June, 2009	-	-	40	5	5	50
4.	Computers and networking	50	April, 2009	December 2009	-	-	30	10	-	40
5.	Detectors, Electronics, Data Acquisition systems	250	September, 2009	March, 2010	-		100	40	-	140
6.	500 kV Accelerator	200	October, 2010	September, 2011	-	-	-	100	60	160

Stellar burning rates

$$\langle\sigma v\rangle = \int \sigma(E)\cdot E\cdot \exp(-E/kT)\, dE$$



ASTROPHYSICAL S(E)-FACTOR

$$\sigma(E) = E^{-1}\exp(-2\pi\eta)\, S(E)$$

non-nuclear origin
STRONG energy dependence

nuclear origin
WEAK energy dependence

$$2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{1/2}$$

Gamow factor

μ in amu and E_{cm} in keV

Maximum reaction rate at E_0

$$E_0 = \left(\frac{bkT}{2}\right)^{2/3} = 0.122\left(Z_1^2 Z_2^2 A\right)^{1/3} T_9^{2/3} \quad \text{MeV}$$

$$\Delta E = \frac{4}{\sqrt{3}}\sqrt{E_0 kT} = 0.237\left(Z_1^2 Z_2^2 A\right)^{1/6} T_9^{5/6} \quad \text{MeV}$$

Energy available from thermal motion

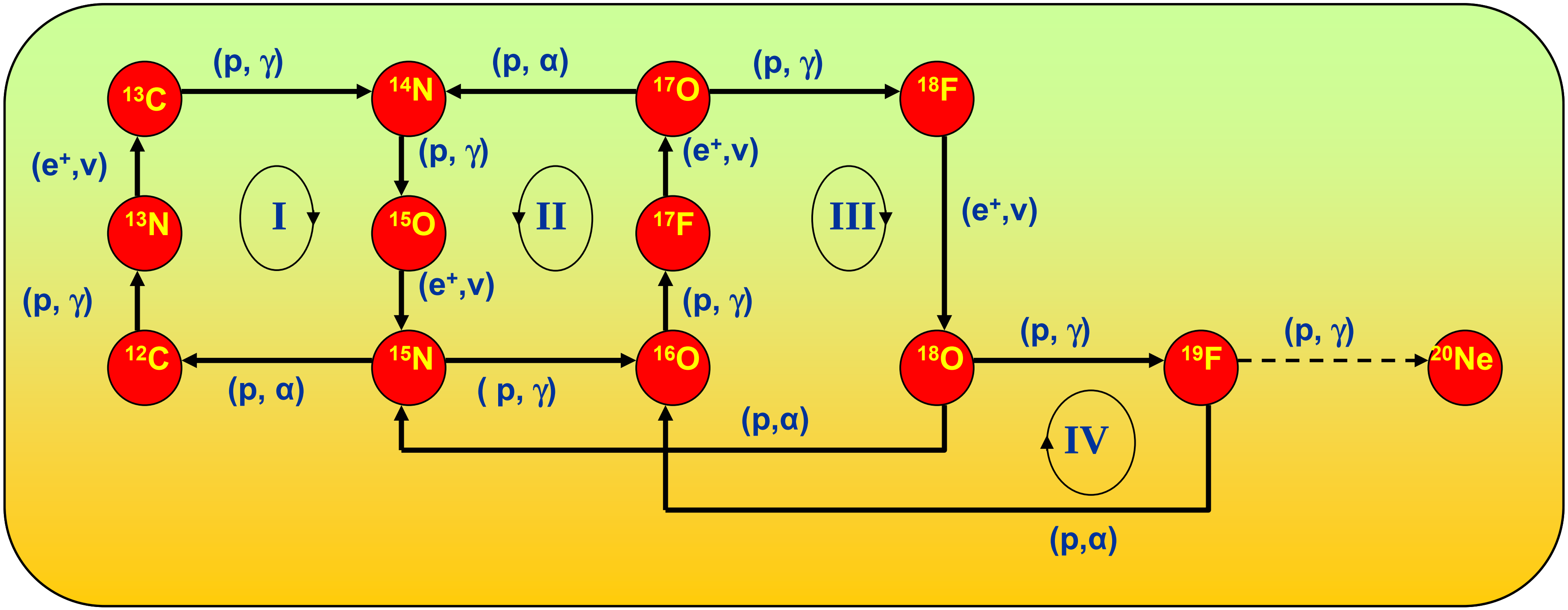
$$kT \sim 8.6 \times 10^{-8}\, T[K] \quad \text{keV}$$

$T \sim 15\times10^6$ K (e.g. our Sun) $\Rightarrow$ kT ~ 1 keV

$T \sim 10^{10}$ K (Big Bang) $\Rightarrow$ kT ~ 2 MeV

Data EXTRAPOLATION down to astrophysical energies is NEEDED !

CNO Cycles



(p, γ)
(p, α)
(p, γ)
13C
14N
17O
18F
(e+,v)
(p, γ)
(e+,v)
13N
I
15O
II
17F
III
(e+,v)
(p, γ)
(e+,v)
(p, γ)
(p, γ)
(p, γ)
12C
15N
16O
18O
19F
20Ne
(p, α)
(p, γ)
(p,α)
IV
(p,α)

Switching magnet type “A” (first one directly after the accelerator)

- **Deflection angles** : 5 exit ports at $+20^{o}$, 0^{o}, -15^{o} and -30^{o}

- **Mass energy product** : at +/- 30^{o}: 32 MeV.AMU
  : at +/- 20^{o}: 72 MeV.AMU
  : at +/- 15^{o}: 125 MeV.AMU
  : at +/- 10^{o}: 284 MeV.AMU

- **Gap** : 32 mm

- **Stability**
  . over 1 hour : 10^{-4}
  . over 8 hours : 2×10^{-4}

$p_1 \Rightarrow$ 0.440 MeV γ-ray of ^{23}Na in the ^{23}Na+p channel.
$\alpha_1 \Rightarrow$ 1.634 MeV γ-ray of ^{20}Ne in the ^{20}Ne+α channel

Beam transport at 200 kV about 25% of injected beam
Switching magnet ports 1) 20, 0, -15 and -30 degrees
2) 30, 15, 0 and -20 degrees

ME/q^2 = 32 MeV.AMU at 30 deg.
= 72 MeV.AMU at 20 deg.
= 125 MeV.AMU at 15 deg.

Energy resolution of a 50-100 μA, 3 MeV H beam = 250 eV (10^{-4})
mainly due to energy straggling in the stripper

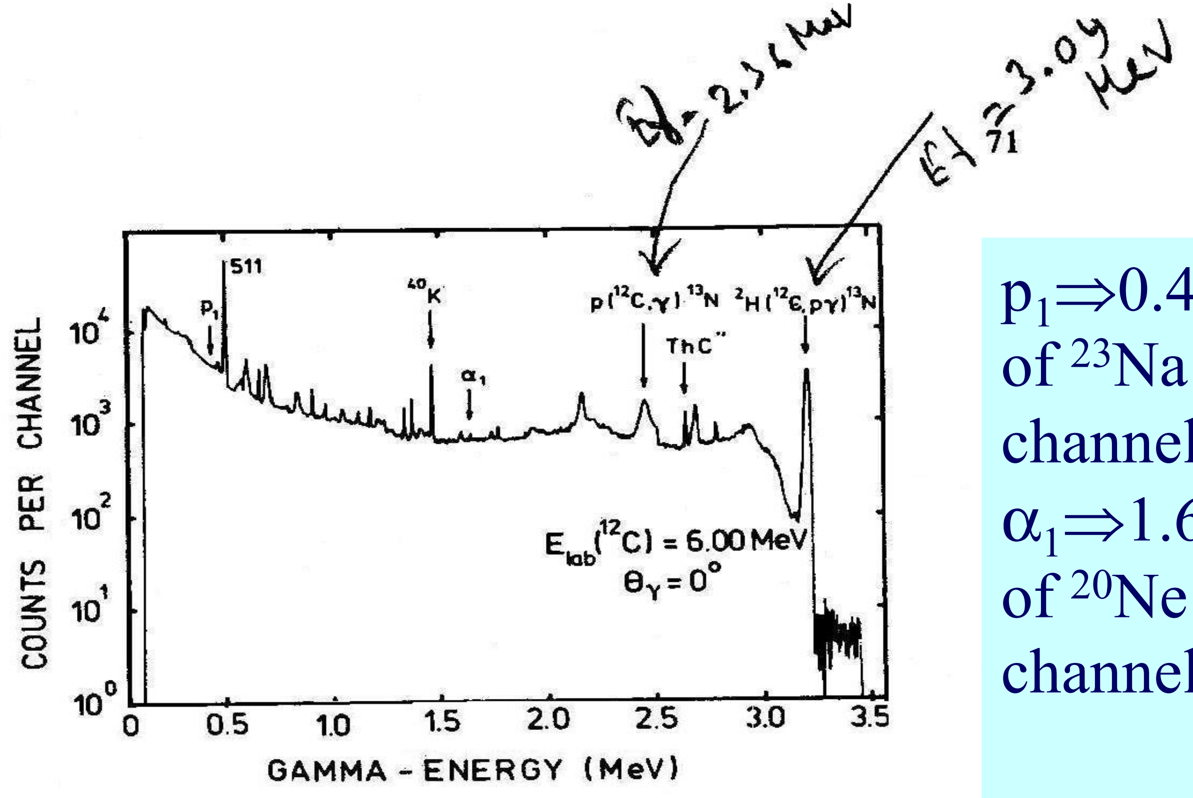
No foil stripper to avoid worse energy resolution

Beam position stability within 50 μm

Beam purity is more important in $^{12}C(^{4}He,\gamma)^{16}O$ where a small impurity of ^{16}O in the beam would lead to large errors (since a small number of ^{16}O product nuclei are to be detected)

Charge-particle (p) detection in $^{12}C+^{12}C$ would also be difficult if there is H contaminant in the target; contaminant H, elastically scattered would have to be identified from p in the $^{23}Na+p$ channel

$^{12}C+p$ capture has a resonance at E_{cm} = 2.25 MeV
$E\gamma$ = 2.37 MeV



$p_1 \Rightarrow 0.440$ MeV γ-ray of ^{23}Na in the ^{23}Na+p channel.

$\alpha_1 \Rightarrow 1.634$ MeV γ-ray of ^{20}Ne in the ^{20}Ne+α channel

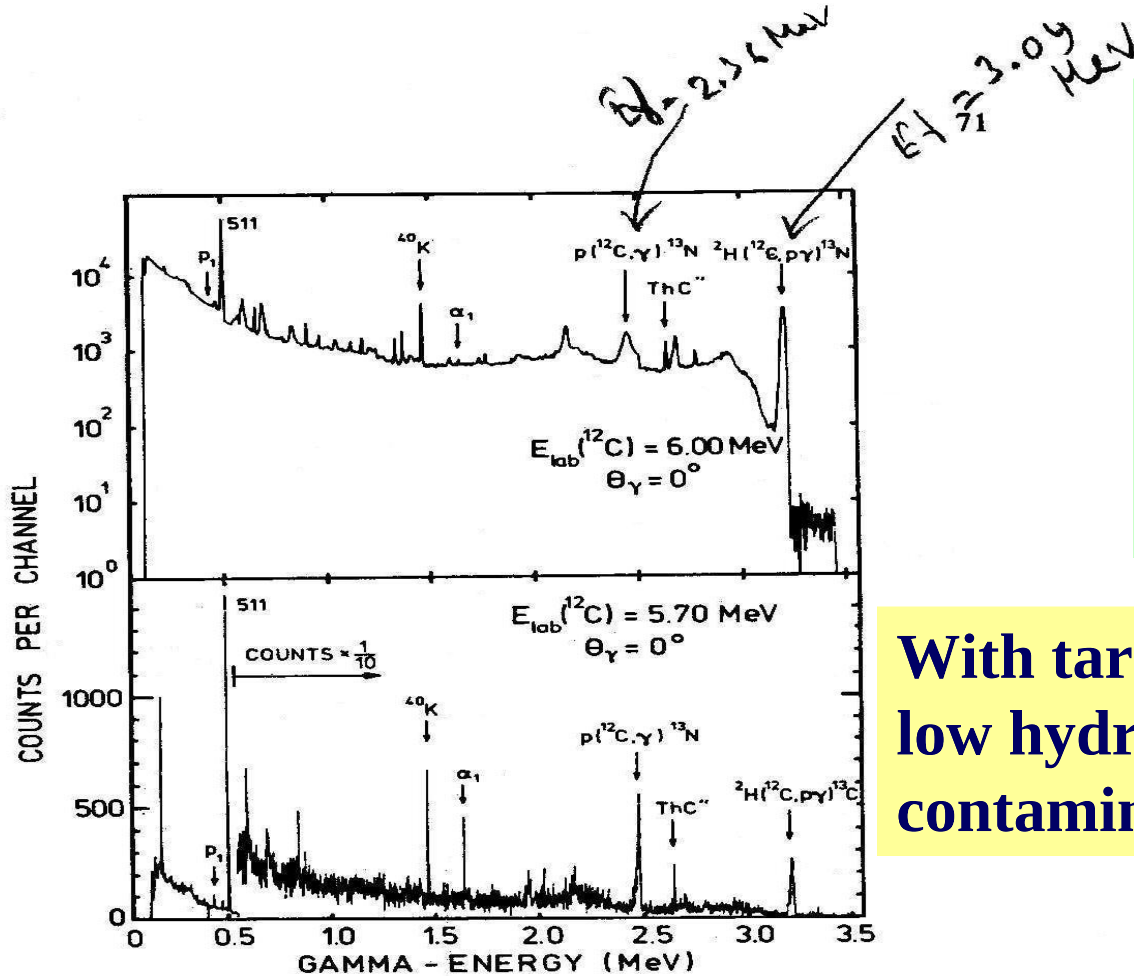
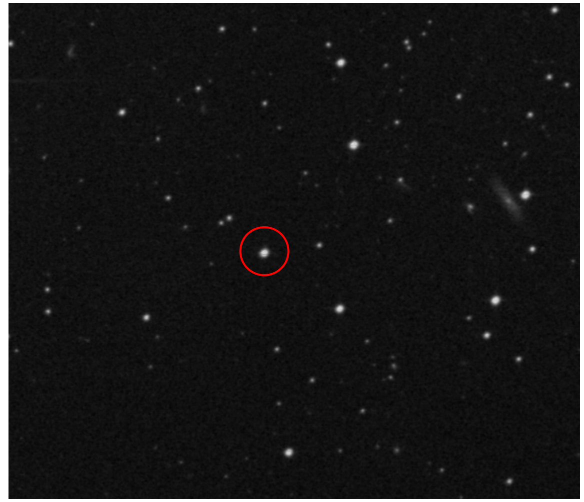


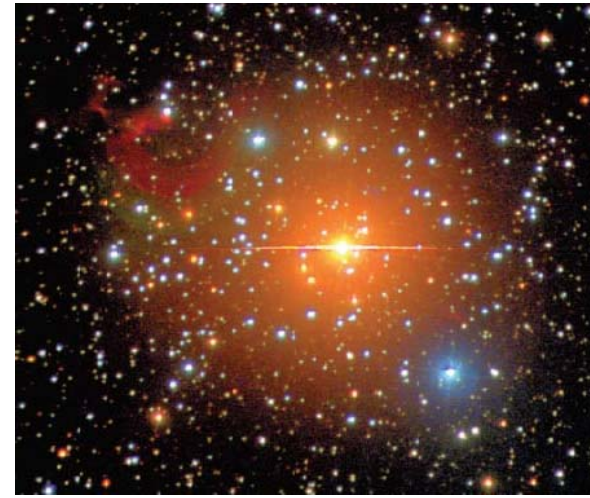
Fig. 6. (a) Sample γ-ray spectrum obtained with a standard carbon target at $E_{lab}(^{12}C) = 6.00$ MeV. The spectra obtained in this beam energy range are dominated by background radiation created by the interaction of the ^{12}C beam with the ^{1}H and ^{2}H contaminations (few atom %) in the target. **(b)** Sample γ-ray spectrum at $E_{lab}(^{12}C) = 5.70$ MeV obtained with a 13 μg/cm^2 thick carbon target of low hydrogen contamination (0.02 atom %). The well-known $E_p = 457$ keV resonance ($\Gamma = 39$ keV) in $^{12}C(p,\gamma)^{13}N$ corresponds in the inverse reaction $^{1}H(^{12}C,\gamma)^{13}N$ to an energy of $E_{cm}(^{12}C + {}^{12}C) = 2.74$ MeV

$p_1 \Rightarrow 0.440$ MeV γ-ray of ^{23}Na in the ^{23}Na+p channel.

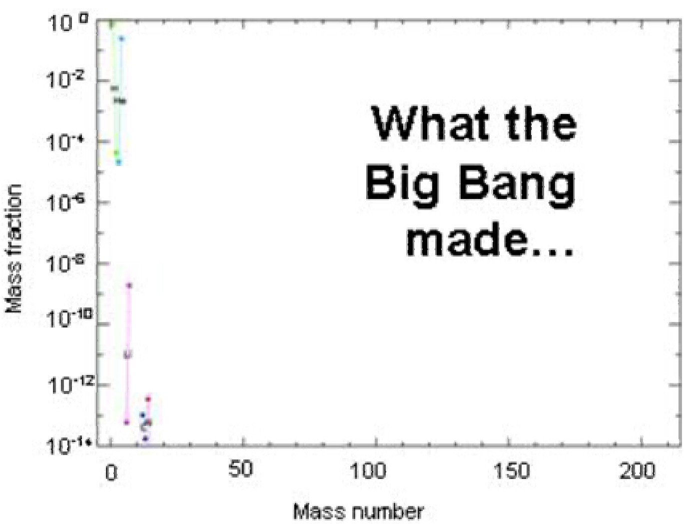
$\alpha_1 \Rightarrow 1.634$ MeV γ-ray of ^{20}Ne in the ^{20}Ne+α channel

With target of low hydrogen contaminant

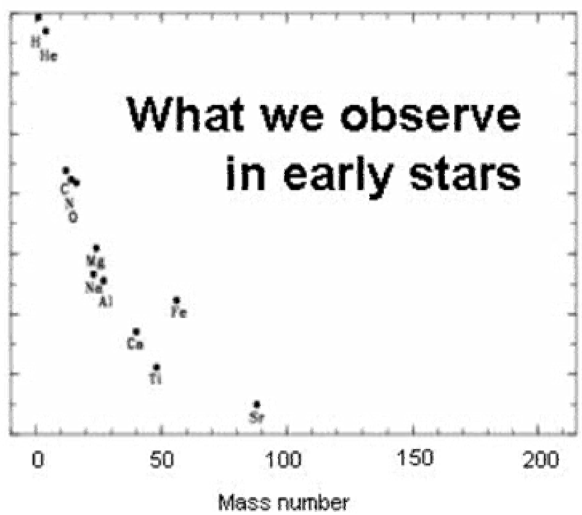




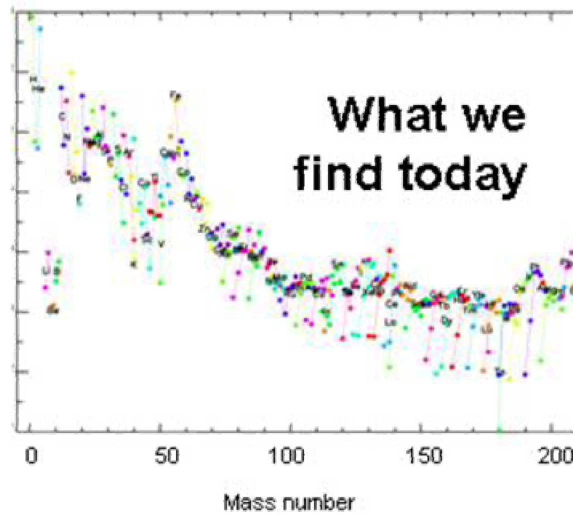
Nucleosynthesis History



(The primordial abundance pattern)
Brian Fields (2002)



(The abundance pattern in the oldest observed stars He1017 & HH1327)
Anna Frebel (2006)

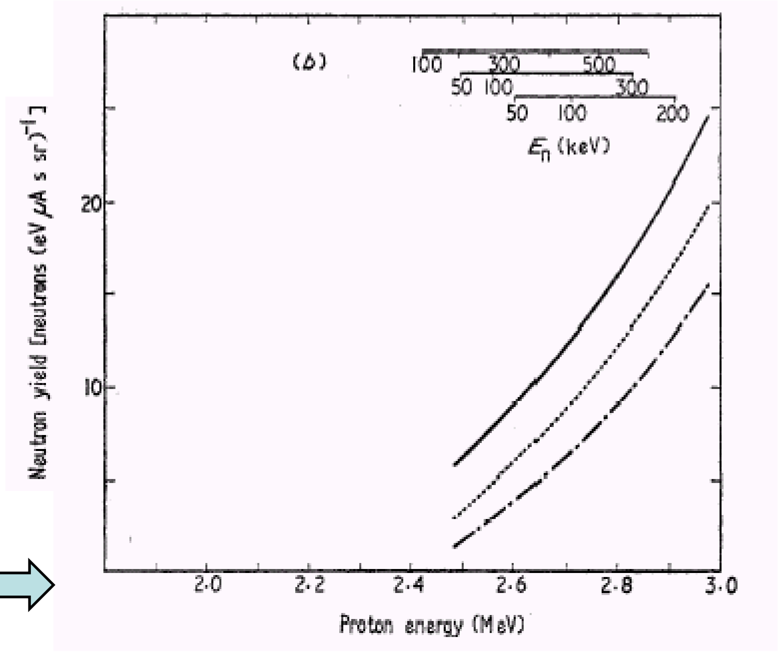


(The solar abundance pattern)
Grevesse & Noels (1995)

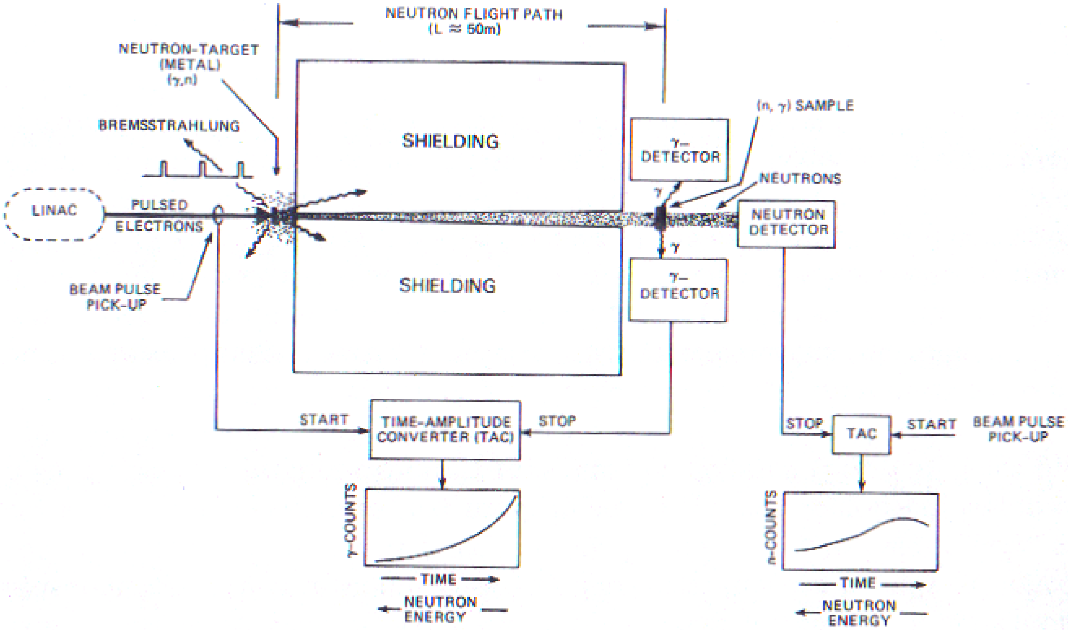
Experiment

Neutron can be generated from $^{7}Li(p,n)^{7}Be$ [E_{th}(Lab.)=1.878 MeV] Using high current pulsed proton beam

Differential neutron yield from a thick target at 30º 90º and 120º.



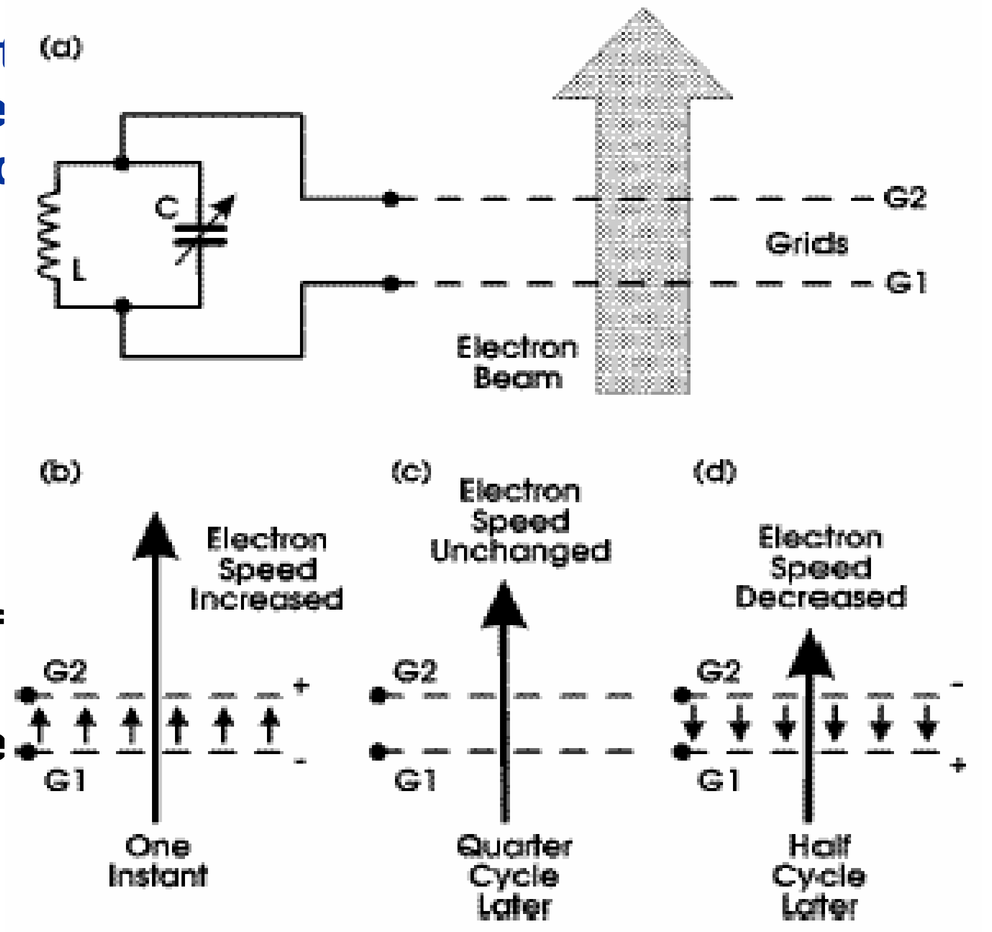
Schematic layout of TOF measurement;



Beam Pulsing - Klystron Buncher

VELOCITY MODULATION

• An electron beam moves at
a constant speed towards t
grids, G1 and G2, connecte
to opposite ends of a tuned
circuit.
• A RF electric field is
produced between G1 and
• At certain instants of tim
electrons arriving at G1 wi
be accelerated if they are
moving in the same directi
as the field, one quarter of
cycle later they will be
unaffected and a half cycle
later they will be slowed
down because they are
moving in the
opposite direction to the field.



ANNEXURE-D

Schedule of proposed major activities of the project

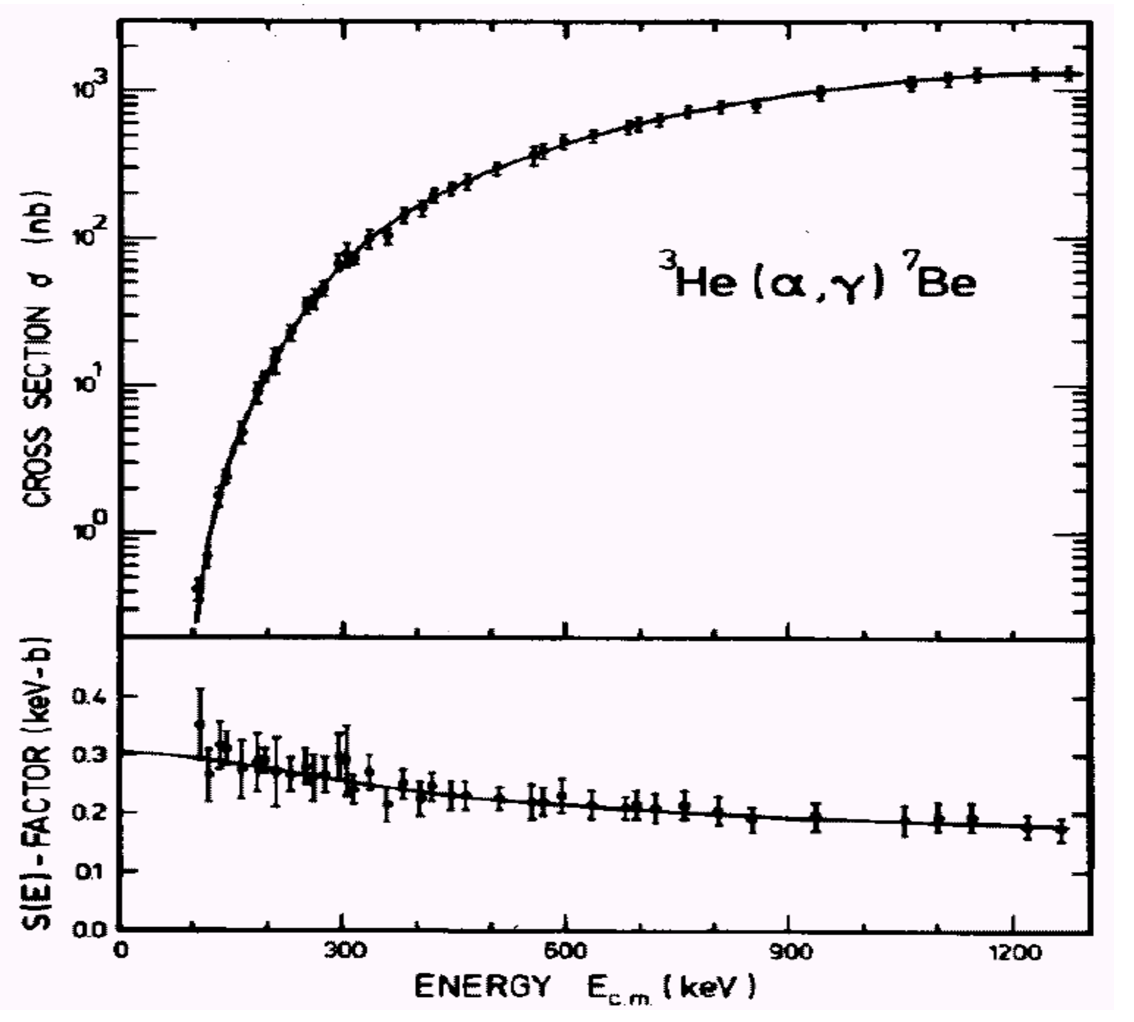
Sl No	Major activity	Cost (lakhs)	% weightage	Start Date (mm/yy)	Completion date (mm/yy)
1	Installation of 3 MV Tandetron along with one beam line	3000	85.8	To be delivered in October, 2009	To be assembled by April, 2010
2	Installation of LCW and Liquid Nitrogen Plant	100	2.8	June, 2009	September, 2009
3	Computers and Networking	40	1.1	August, 2009	November, 2009
4	Setting up of Detectors, Electronics, Data Acquisition systems	140	4.0	October, 2009	February, 2010
5	First Experiment using FRENA			June, 2010	
6	Development of 500 kV Accelerator	160	4.6	October, 2010	September, 2011
7	Preliminary measurements of the beam characteristics of 500 kV machine			January 2112	

FRENA is a National Facility, being developed by SINP

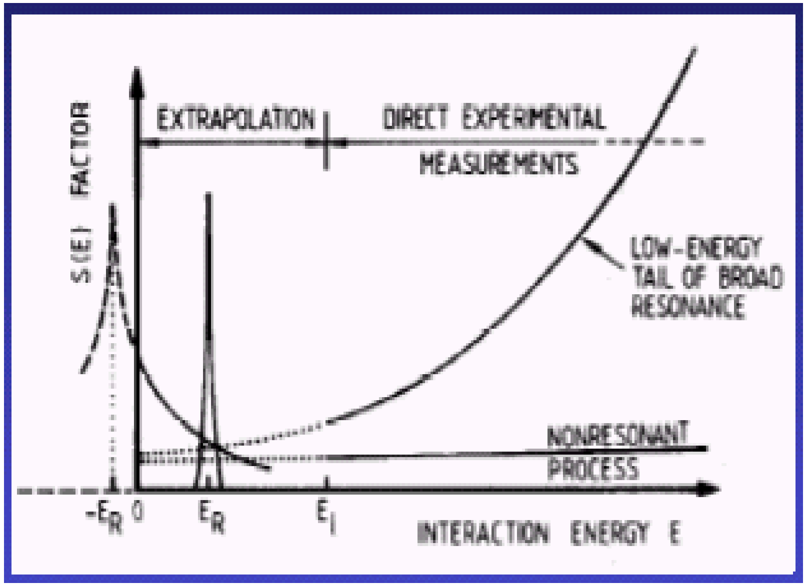
We have discussed the Proposal at various meetings attended by Scientists from India and abroad

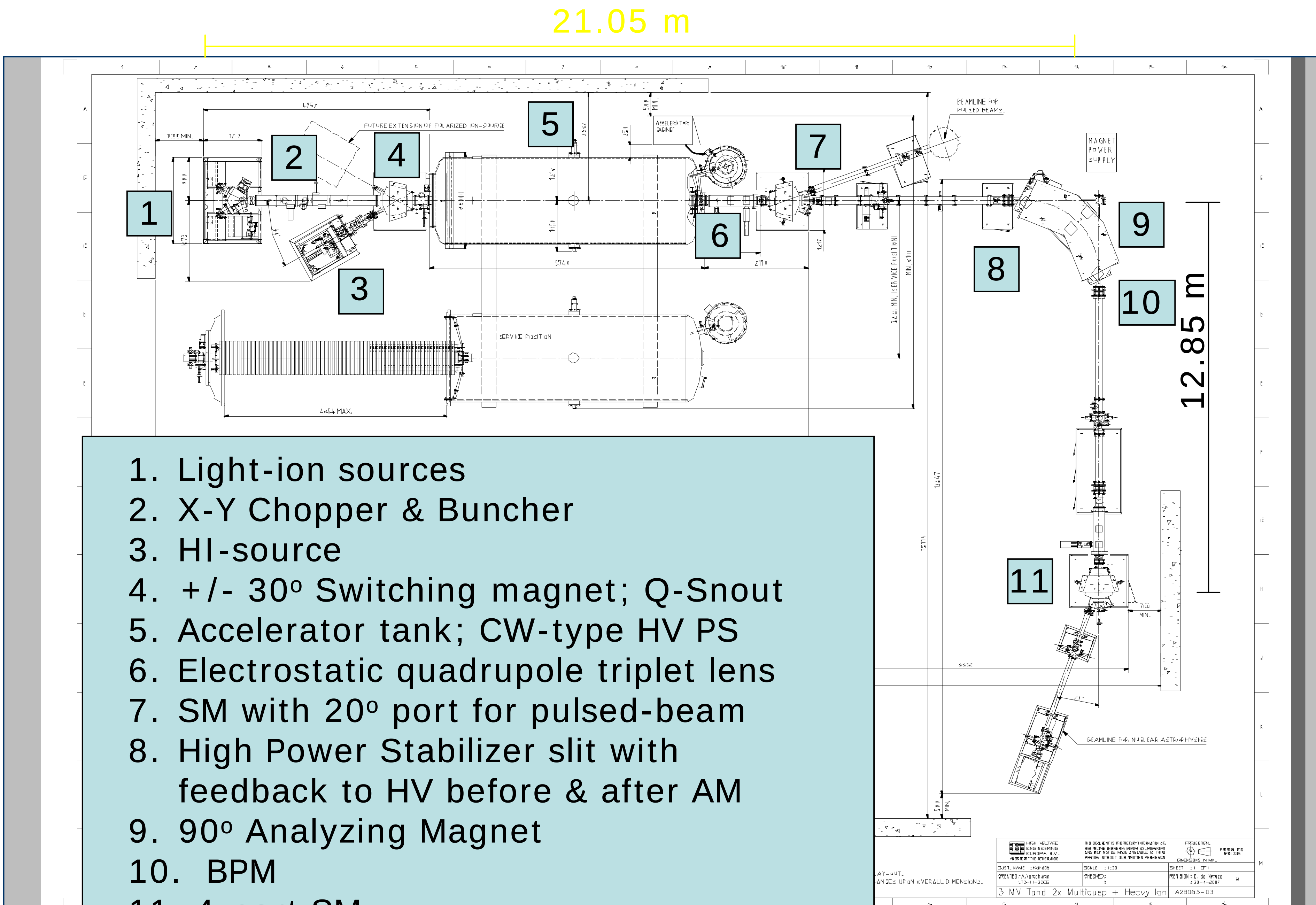
If necessary, we will enter into a national level collaboration subsequently

1. Machine stability
2. HVEE machine at other places
3. How can we improve upon the existing data



CROSS SECTION σ (nb)
10^3
10^2
10^1
10^0
$^3He(\alpha,\gamma)^7Be$
S(E) - FACTOR (keV-b)
0.4
0.3
0.2
0.1
0.0
0
300
600
900
1200
ENERGY $E_{c.m.}$ (keV)


S(E) FACTOR
EXTRAPOLATION
DIRECT EXPERIMENTAL
MEASUREMENTS
LOW-ENERGY
TAIL OF BROAD
RESONANCE
NONRESONANT
PROCESS
-E_R
0
E_R
E_I
INTERACTION ENERGY E



1. Light-ion sources
2. X-Y Chopper & Buncher
3. HI-source
4. +/- 30º Switching magnet; Q-Snout
5. Accelerator tank; CW-type HV PS
6. Electrostatic quadrupole triplet lens
7. SM with 20º port for pulsed-beam
8. High Power Stabilizer slit with feedback to HV before & after AM
9. 90º Analyzing Magnet
10. BPM
11. 4-port SM

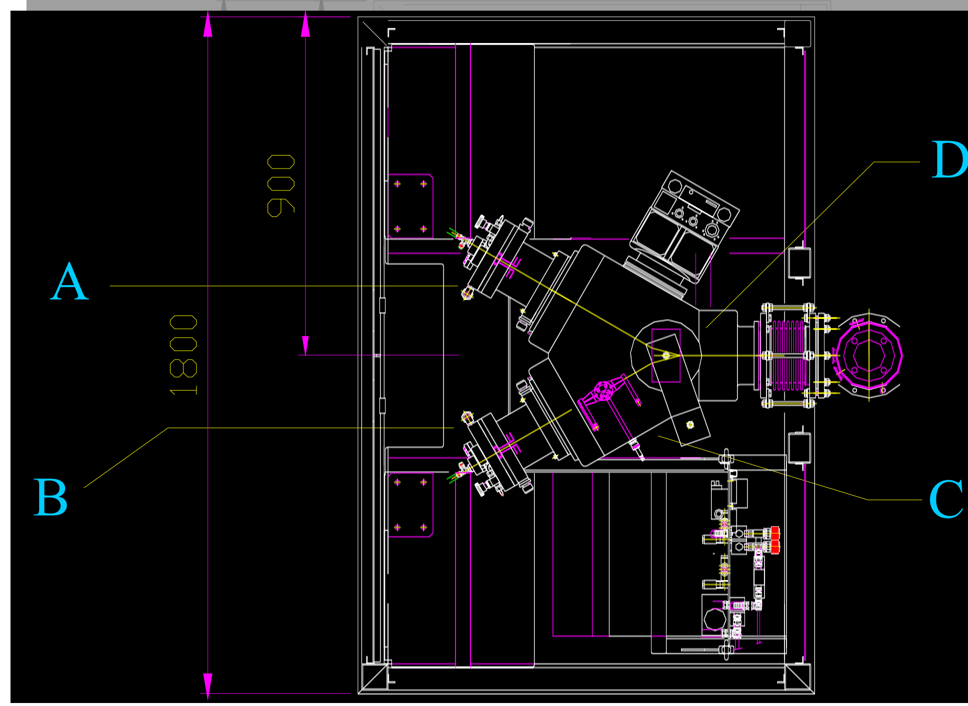
Dual Source Injector for H & He

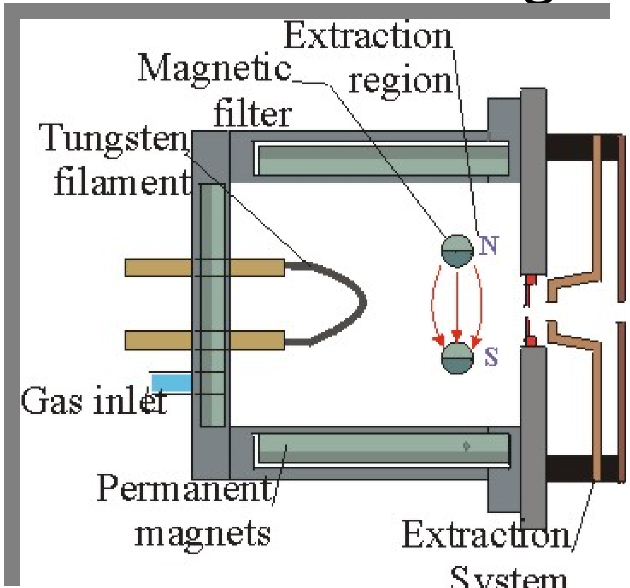
A – Multi-cusp ion source for H;

B - Multi-cusp ion source for He;

C - Li Charge exchange column;

D - +/- 30° switching magnet

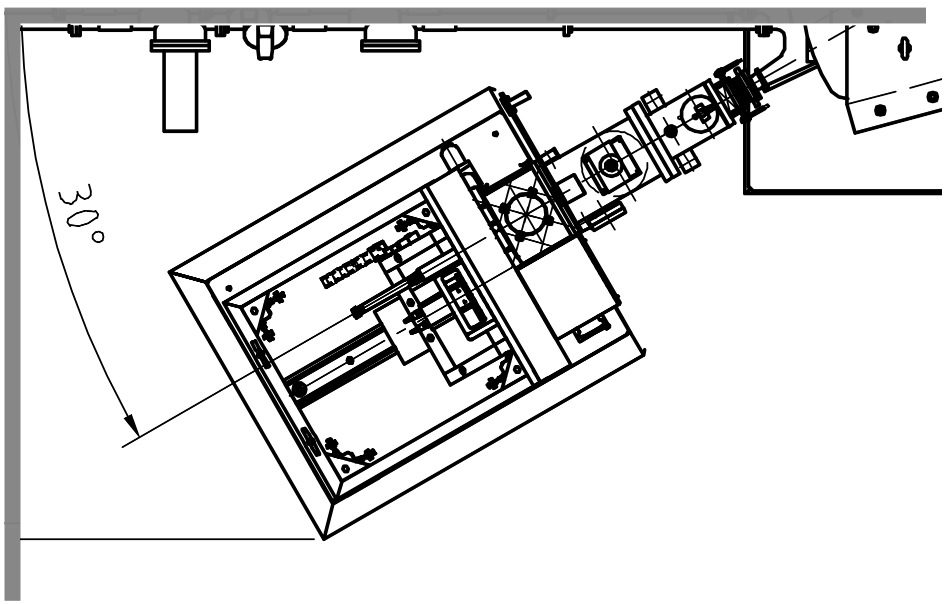




A Filament discharge Multi-cusp Ion source

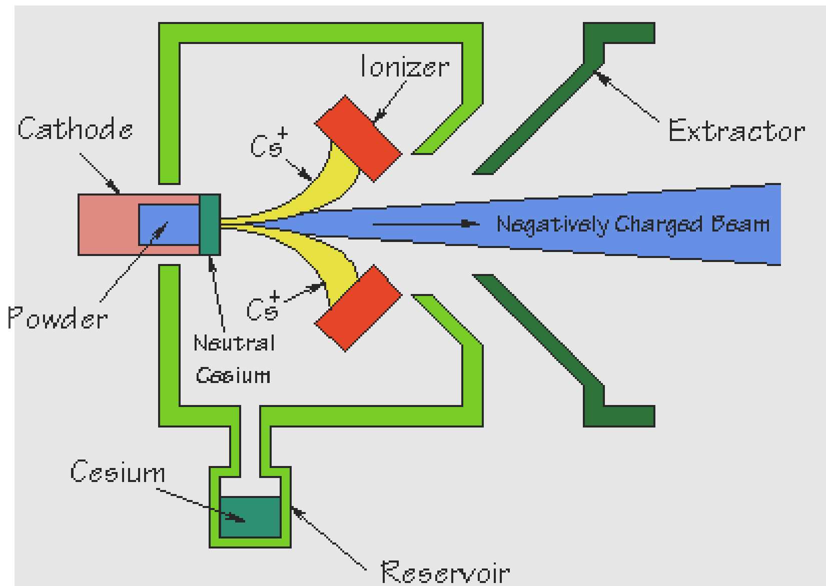
The magnetic field generated by the Sm-Co permanent magnets efficiently confine the primary ionizing electrons.

Heavy-ion source (SNICS type)



	3.0 MV	200 kV
$^{7}Li^{+}$		0.5 eμA
$^{11}B^{3+}$	10 eμA	
$^{12}C^{+}$		12 eμA
$^{12}C^{3+}$	40 eμA	
$^{16}O^{+}$		15 eμA
$^{16}O^{3+}$	50 eμA	

- Multi target (up to 50 targets) sputter ion source with automatic changing of sputter targets for prolonged beam times
- Computer-controlled insertion of target at pre-set time intervals



SNICS II Schematic Diagram

Specifications of the Analyzing Magnet

ME/q^2	48 AMU-MeV
Bending radius	1500 mm
Maximum magnetic field	0.67 Tesla
Stability (over 1 hour)	10^{-5}
(over 8 hours)	3×10^{-5}

Pulsed beam operation (2 & 4 MHz)

- Pulse-Intensity: (for pulse-width of 2 ns FWHM)

		Pulse intensity (charge) in epC	
Species	Energy	Guaranteed	Expected
H^+	4 MeV	7.5	12.5
D^+	4 MeV	5.0	10.0
He^{2+}	6 MeV	1.25	2.5

The 500 kV Electrostatic accelerator

Will consist of

- ❑ A Cockroft-Walton type high voltage supply
- ❑ High-current ECRIS ion-source
- ❑ Necessary analyzing and steering magnets

This low energy accelerator will be developed using the available expertise in the country.

To be used for studying the reactions of the H and He-burning Phases, using H and He beams.

The facility, when developed and tested, would be housed underground once laboratory becomes available.

Budgetary Figures

Item	Cost (Rs. lacs)	Progressive total
3 MV Tandetron	3000	3000
Detectors + Electronics	140	3140
Computers and networking	40	3180
LCW + Liquid N_2 Plant	100	3280
500 KV Accelerator	160	3440
Salary + Travel + Cont.	60	3500

Space requirement	3,500 sq. m.
Power requirement	100 kW

Additional Manpower Requirement:

(1) Technical : Engineers – 2 (Civil – 1, Electrical – 1);
Scientific Officers - 3

(2) Auxiliary : 1

Total 6

Scientific Officers – installation, operation and maintenance of 3 MV Tandetron

Existing Man-power – Experimental Nuclear Physics Group at SINP

The Group is working in active collaboration with scientists from IUAC, New Delhi and VECC, Kolkata

Milestones

Sl. No.	Major activity	Cost (lacs)	Start Date (mm/yy)	Completion date (mm/yy)
1	Infrastructure Development (Building, Laboratories, etc.)	800	April, 2007	September, 2009
2	Laying and distribution of Electrical Power lines, UPS, Air Conditioning,	200	April, 2009	September, 2009
3	LCW + Liquid Nitrogen Plant	100	June 2009	September ‘09
4	Installation of 3 MV Tandetron along with one beam line	3000	Delivery in October, 2009	To be assembled by April, 2010
5	Computers and Networking	40	August ‘09	November ‘09
6	Setting up of Detectors, Electronics, Data Acquisition systems	140	October, 2009	February, 2010
7	First Experiment using FRENA		June, 2010	
8	Development of 500 kV Accelerator	160	October, 2010	September, 2011
9	Preliminary measurements of the beam characteristics of 500 kV machine		January 2012	

Measurement of reaction cross-sections

Methods of measurement depend on the detection of the products. Example:

$$^{12}C + ^{12}C \longrightarrow \begin{cases} ^{20}Ne + \alpha \\ ^{23}Na + p \\ ^{23}Mg + n \end{cases}$$

i) Light particle method $\Rightarrow$ Detection of n, p, α

ii) Heavy residue method $\Rightarrow$ " of ^{20}Ne, ^{23}Na, ^{23}Mg

Difficult at low energies. a) low K.E. of the residues

b) large elastic events.

iii) γ-ray method $\Rightarrow$ Detection of the γ-rays following de-excitation of residues in excited states.

iv) Residual activity method $\Rightarrow$ Detection of the γ-rays following the decay of the residues in the g.s.