Probing the Heavens from Deep Underground: A Proposal

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for a collaboration between UGC-DAE CSR &

University of Delhi, Banaras Hindu University, Aligarh Muslim University, Mangalore University, Calicut University, Panjab University, Central University of Kerala, Central University of Haryana, University of Calcutta, Visva Bharati, IIT Ropar, IIT Roorkee ………

Meeting@TIFR, 6-7 August, 2022

Connecting the Earth & the Heavens

There is NO accelerator up there !

Energies for the NUCLEAR reactions provided by the THERMAL motion of the nuclei: THERMONUCLEAR reactions.

Maxima of the Maxwell-Boltzmann distribution in

(i) Sun (15 MK): 1.3 keV (ii) classical nova (300 MK): 26 keV (iii) supernova (5 GK): 430 keV

Stars are "cold"

Gamow (1928), Condon & Gurney (1929): tunneling through the Coulomb barrier

Probability for tunneling (at E << Ec),

$$P = \exp(-2\pi\eta)$$

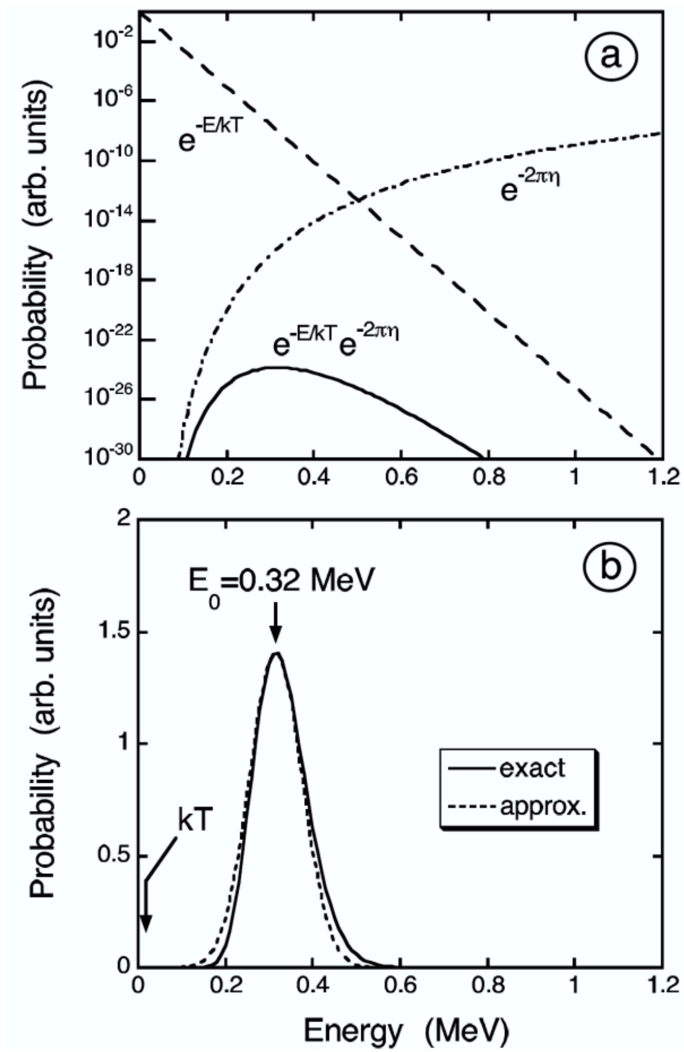
$$\{2\pi\eta = 0.98951013 * Z_0 * Z_1 * [m_{01} * (1/E)]^{1/2}\}$$

Window for Stellar Reactions

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} S_0 \int_0^\infty e^{-2\pi\eta}\, e^{-E/kT}\, dE$$

tends to 0 for small energies

tends to 0 for large energies



Maximized at the Gamow Peak with,

$$E_0 = 0.1220\left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0+M_1} T_9^2\right)^{1/3} \quad \text{(MeV)}$$

and,

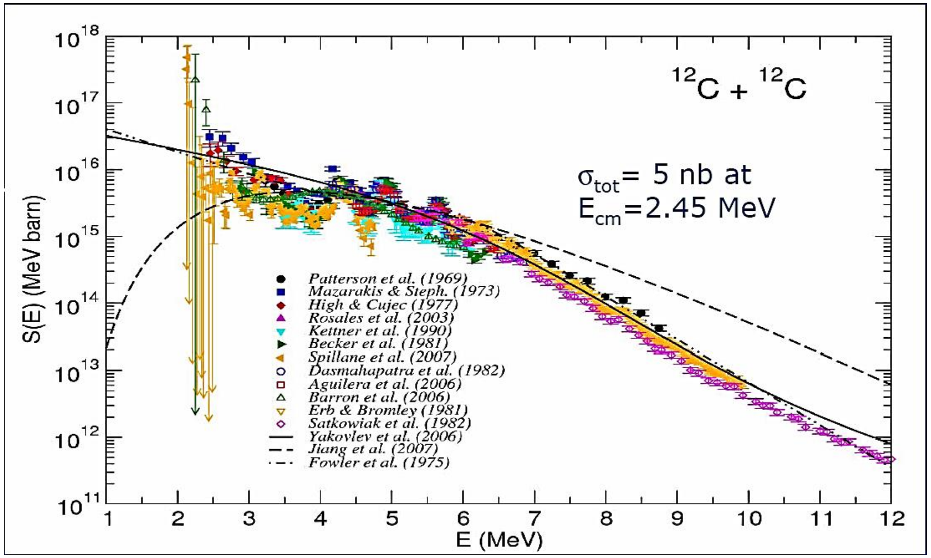
$$\Delta = \frac{4}{\sqrt{3}}\sqrt{E_0 kT} = 0.2368\left(Z_0^2 Z_1^2 \frac{M_0 M_1}{M_0+M_1} T_9^5\right)^{1/6}$$

$^{12}C(\alpha,\gamma)^{16}O$ reaction illustrated here

Heart of the Problem

Measurement of cross-sections at the Gamow peak or nearest to it

Repeated measurements for a single reaction, trying to improve on the uncertainties & to reach as close to the Gamow window as possible.



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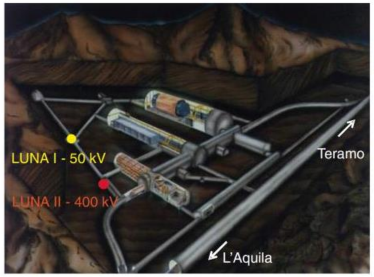
LUNA: a laboratory for underground nuclear astrophysics

H Costantini[1], A Formicola[2], G Imbriani[3,4], M Junker[2], C Rolfs[5] and F Strieder[5]



5. The future of underground laboratories

Although LUNA is yet unique in the world and will continue for several more years, it is hoped that similar facilities will be created in time worldwide. Each fusion reaction takes a couple of years for its complete study. Since there are many reactions to be reinvestigated, there is a clear need for additional underground facilities. We discuss in the following sections

What do you Ask for in a Nuclear Astrophysics Research Facility ?

Accelerator Characteristics

Energy, Stability, Resolution, Current, Provision for Beam Diagnostics etc.

Setup Characteristics

Target chamber (current measurement, target monitoring, detector positions, target cooling)

Detection setups (efficiency, resolution)

Background Characteristics

Passive shielding & active shielding

Analysis techniques (Coincidence gating) for background reduction.

Background & Its Reduction

Beam Induced (target contaminants etc.)

Sources

Natural (Cosmic, room.....)

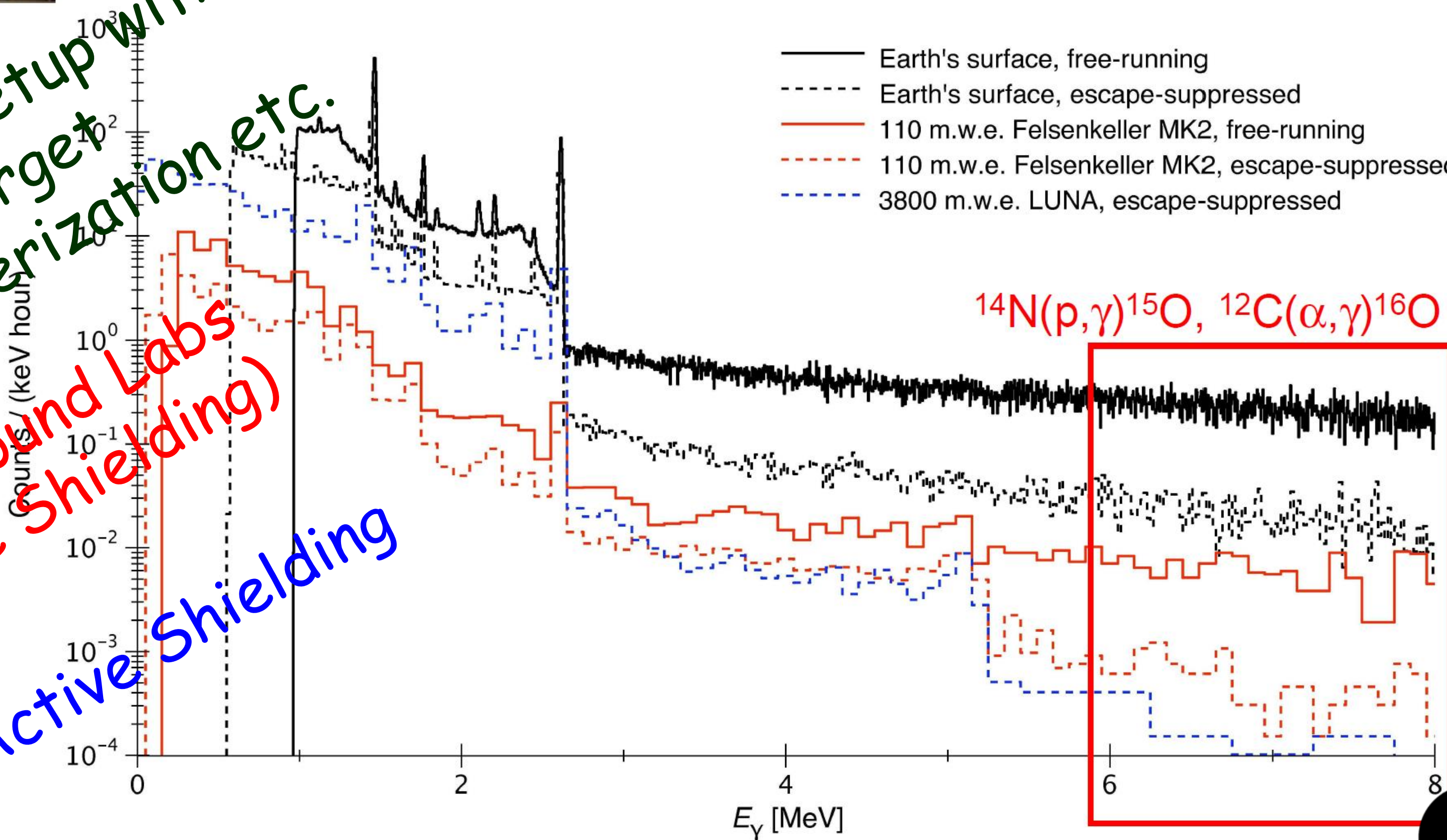
Compton / pair-production interactions

Way Outs

Careful setup with target characterization etc.

Underground Labs (Passive Shielding)

Active Shielding



Nuclear Astrophysics Underground
LUNA @ LNGS

Rock overburden of 1400 m (3800 m.w.e)

- Reduction in muon component (by 10^6), neutron component (by 10^3) and γ component (by 10)
- γ background above 3 MeV in a HPGe detector reduced by a factor of 2500.
- Enhancing the effect of passive shielding

Two accelerators

- 50 kV (home-made) & 400 kV (commercial)
- Intense beam currents, long-term stability (max. reaction rate), precise energy determination (exp. energy dependence of the x-section)

Measurements at the Underground Facility LUNA @ LNGS

Study of p-p chain reactions at Gamow peak energies

^{3}He(^{3}He, 2p)^{4}He & d(p,γ)^{3}He (with 50 kV machine)

Reactions studied at the 400 kV machine

^{14}N(p,γ)^{15}O (impact on the CNO neutrino production & on the age of globular clusters)

^{3}He(^{4}He,γ)^{7}Be impacting ^{7}Li production in BBN

^{15}N(p,γ)^{16}O (CNO) and ^{25}Mg(p,γ)^{26}Al (MgAl)

^{17}O(p,γ)^{18}F (CNO) (classical novae)

^{2}H(α,γ)^{6}Li (^{6}Li production in BBN)

^{17}O(p,α)^{14}N & ^{22}Ne(p,γ)^{23}Na (NeNa)

Nuclear Astrophysics Underground
JUNA @ CJPL

Rock (marble) overburden of 2400 m; radioactively quiet

Cosmic background TWO orders of magnitude less than in Gran Sasso

Accelerator

400 kV high current accelerator for nuclear astrophysics.

Reactions

$^{12}C(\alpha,\gamma)^{16}O$, $^{13}C(\alpha,n)^{16}O$, $^{19}F(p, \alpha)^{16}O$: at or near Gamow window; x-sections ~ pbarn & lower

$^{25}Mg(p, \gamma)^{26}Al$: precise measurement of 92 keV resonance

https://doi.org/10.1051/epjconf/202226008001

Higher & Heavier

Beyond H-burning – reactions at higher temperatures (energies)

Need for higher voltage MV accelerators.

Prospective pursuits

$^{12}C(\alpha,\gamma)^{16}O$ (Gamow energy ~ 300 keV): decides He-burning time scale. C,O abundance at the end of He-burning. Ne, Na, Mg, Al ejected during Type II SN scales with C abundance. Stellar models sensitive to the x-section. Precision ~ 10% or better, required to constrain stellar evolution.

$^{13}C(\alpha,n)^{16}O$ (Q = 2.216 MeV) & $^{22}Ne(\alpha,n)^{25}Mg$ (Q = -0.478 MeV) n-sources for s-process. Operate under different conditions. Important for understanding heavy element production.

Reactions of Interest (Ref.: LUNA MV Proposal) in the Contemporary Nuclear Astrophysics Efforts

Reaction	Gamow Energy, in MeV (T9)	Lowest Energy reached in Measurement, in MeV	Last Measurement	Remarks
$^{12}C(\alpha,\gamma)^{16}O$	0.2-0.3 (0.1-0.2)	$E_{cm} = 0.89$	Plag *et al.* Phys. Rev. C86, 015805(2012)	Lowest energy measurement reported by Hammer *et al.* (Nucl. Phy. A758, 363c(2005)). Energy reached in the last measurement is E_{cm} = 1.002 MeV. Measurement down to E_{cm} = 0.95 reported by Kunz *et al.* (Phys. Rev. Lett. 86, 3244(2001))
$^{13}C(\alpha,n)^{16}O$	0.2 (0.09)	$E_{cm} < 0.3$	Heil *et al.* Phys. Rev. C78, 025803(2012)	Heil *et al.* measurement upto E_{cm} = 318 keV. Lowest energy by Drotleff et al., (Ap. Jour. 414, 735(1993)) with high uncertainty.
$^{22}Ne(\alpha,n)^{25}Mg$	0.6 (0.3)	$E_{cm} = 0.482$	Jaeger *et al.* Phys. Rev. Lett. 87, 202501(2001)	Jaeger *et al.* measurement upto E_{cm} = 482 keV. Lowest energy by Drotleff *et al.*, (Ap. Jour. 414, 735(1993)) with result as upper limit. Very deviant from Jaeger *et al.*
$^{14}N(\alpha,\gamma)^{18}F$	0.3 (0.15)	Resonance at E_α (lab) = 0.573 MeV	Gorres *et al.* Phys. Rev. C62, 055801(2000)	
$^{18}O(\alpha,\gamma)^{22}Ne$	0.6 (0.35)	Resonance at E_α (lab) = 0.470 MeV	Dababneh *et al.* Phys. Rev. C68, 025801(2003)	
$^{15}N(\alpha,\gamma)^{19}F$	0.35-0.5 (0.2-0.3)	Resonance at E_α (lab) = 0.679 MeV	Wilmes *et al.* Phys. Rev. C66, 065802(2002)	
$^{16}O(\alpha,\gamma)^{20}Ne$	0.3	Resonance at E_α (lab) = 1.1 MeV	Constantini *et al.* Phys. Rev. C82, 035802(2010)	
$^{12}C(^{12}C,p)^{23}Na$	1.5 (0.5)	$E_{lab} = 2.1$ MeV	Spillane *et al.* Phys. Rev. Lett. 98, 122501(2007)	Also considered in a feasibility study by Caciolli *et al.* (Eur. Phys. Jour. A39, 179(2009)).
$^{12}C(^{12}C,\alpha)^{20}Ne$	1.5 (0.5)	$E_{lab} = 2.1$ MeV	Spillane *et al.* Phys. Rev. Lett. 98, 122501(2007)	

How low you can reach ?

MV & Underground

LUNA-MV: 3.5 MV single ended accelerator to produce H, He, ^{12}C beams; two beam lines for solid & gas target experiments.

CASPAR: 1 MV tandem accelerator from University of Notre Dame installed at the Sanford Underground Research Facility (SURF), USA. Depth of 4850 ft. (4300 m.w.e.) H, He beams

Felsenkeller: "shallow underground accelerator laboratory" 45 m of (hornblende monzonite) rock coverage located in Dresden (Germany) & housing 5 MV Pelletron

MV accelerator in the country ?

Proposal

Low energy (~ 3-4 MV) high current accelerator at an underground site (INO ?)

Superior energy resolution

Stability over long period of operation. Easy operation (possibly unmanned for underground machine)

Experimental facilities

Detectors (gamma, charged particle, neutrons) & associated instrumentation (pulse processing electronics – analog & digital, data acquisition system)

Target Preparation

Workshop

Neutron beam facility in an ISOLATED, SHIELDED site ?

Development of the Proposal

20th July, 2022: online meeting of the nuclear physics research community based at Universities & Institutes.

17-18 May, 2017: Workshop for finalizing the proposal, hosted by the Kolkata Centre and attended by interested researchers (~50) from across the country.

11th April, 2017: meeting of the Scientific Management Board of the INO Collaboration @ TIFR.

18-19 March, 2017: Collaboration Meeting of INO @ BHU.

27th August, 2015: meeting with local (Kolkata) participants (from VECC, SINP etc.) at the Kolkata Centre.

24-25 June, 2015: session on the proposal during a workshop at the Mangalore University. Attended by researchers from Universities & Institutes.

Underground Accelerator Wish List

3.5 MV in-line Singletron positive Ion Accelerator

I	Ion source & associated beam extraction components	Gas based ECR Ion source Single gas system	Spieces : $1H^{+}$ (500 eμA, 1200 μA) , $4He^{+}$(300 eμA – 700 μA), $12C^{+}$, $12C^{2+}$(100 eμA – 200 μA), +16O2+ (150 eμA – 250 eμA)
II	Accelerating system	In-line parallel fed Cockroft Walton type terminal voltage Voltage grading resistors	Terminal Voltage : 0.2 – 3.5 MV Terminal voltage stability ± 350 V With upgraded system ± 100 – 175 V Terminal ripple 150 V_{RMS} Terminal ripple 20 V_{RMS} with low ripple add-on kit
		Beam energy spread < 50 eV (estimated) for all terminal voltages and currents Beam current stability is typically 2% for 1 hour.	
III	Beamlines	Two beamlines at ± 35° with all vacuum components as well as beam diagnostics components (BPM, focusing elements)	3 m long at +35° 2.5 m long at -35°
		Vacuum system comprising of pumps, measuring devices valves are included. There is a provision for 0° beam-dump at the analyzing magnet.	
IV	SF_6 system	Recovery & pressure evacuation system	Mobile pressure handling vessel Storage tanks Vacuum systems etc.

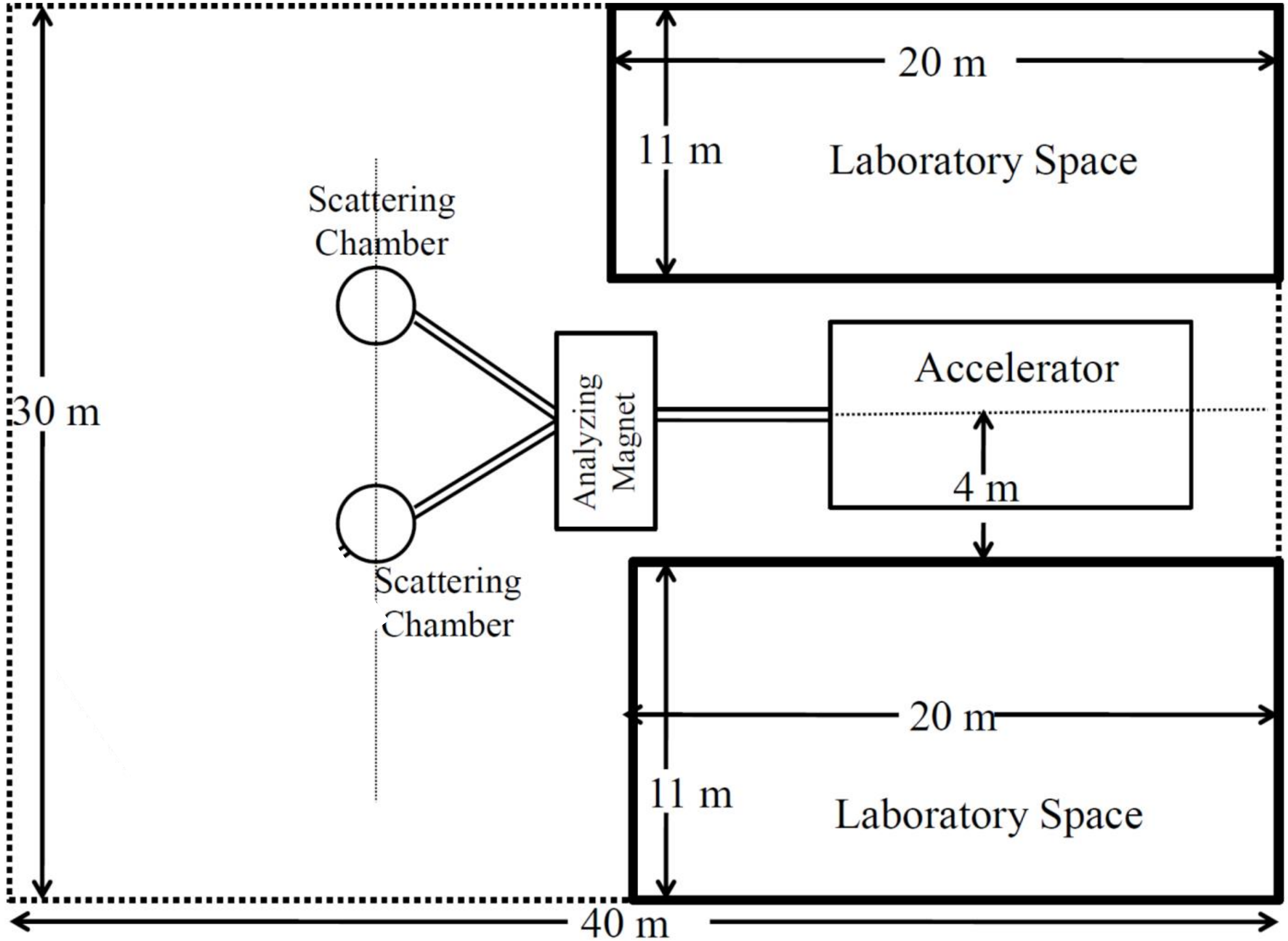
High current

Energy definition & stability

Experimental Area

Tentative Layout

Accelerator + Control + Associated Facilities (Target Laboratory, Detector Laboratory, Electronics Laboratory, Mechanical Workshop, User Office etc.)



Accelerator Price Estimate: INR 30 Cr. (2016)

Measurements @ Underground Accelerator Facility
Reaction Yield

Reaction: Projectile + Target

Yield = Amount of Target * Amount of Beam * Probability of Reaction

Target: mass thickness (mg/cm^2) indicating number of target nuclei per unit area

Beam: current indicating number of beam particles per unit time

Probability of reaction: cross section

Magic Formula: $(3.76/A_{target})$ * Target thickness ($\mu g/cm^2$)

* Beam Current (pnA) = Yield / s

Quantifying the Target
Target Thickness

Target Mass thickness of interest

Straight Forward: Measure the mass (precision weighing for mg / μg), Measure the area (graph paper) and.........(valid only for reasonably thick target)

Indirect Procedures for thin targets: α-absorption, Rutherford Back Scattering (RBS)
[No target degradation during the experiment]

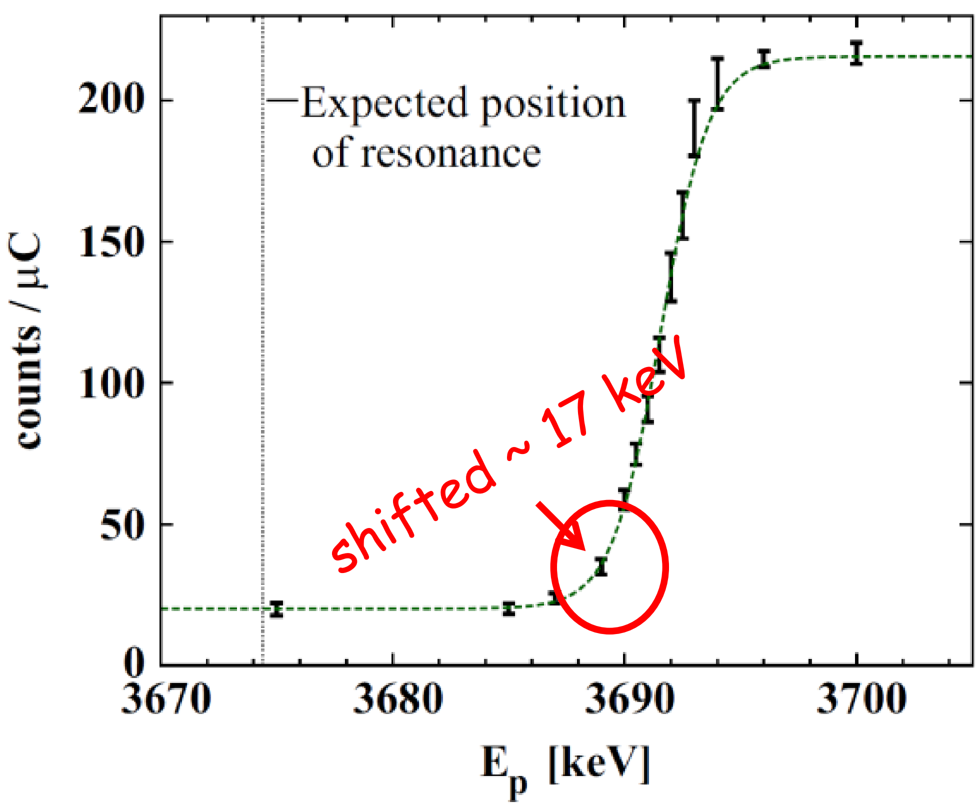
Cross section measurements plagued by interfering reactions of the beam with the contaminants present, even though in traces, in the target / backing. Possibilities of dominant cross-sections.

Contaminant	Reaction	E_γ (keV)
^{19}F	^{19}F(p,$\alpha\gamma$)^{16}O	6130
^{11}B	^{11}B(p,γ)^{12}C	4439
	^{11}B(p,α)2α	
^{15}N	^{15}N(p,$\alpha\gamma$)^{12}C	4439
^{12}C	^{12}C(p,γ)^{13}N	
^{13}C	^{13}C(p,γ)^{14}N	2313
	^{13}C(α,n)^{16}O	
^{16}O	^{16}O(p,γ)^{17}F	495
^{23}Na	^{23}Na(p,γ)^{24}Mg	1369
	^{23}Na(p,$\alpha\gamma$)^{20}Ne	1634
^{27}Al	^{27}Al(p,γ)^{28}Si	17[illegible]

Beam Energy Calibration
Use of Resonances

Sensitivity of calibration of analyzing magnet to beam line geometry & uncertainties from finite opening angle of beam entrance slits to analyzing magnet.

Constant offset to be incorporated in data analysis.



$^{27}Al(p,\gamma)^{28}Si$ reaction

Resonance at Ep = 3674.4 keV used to calibrate the beam energy.

[HORUS facility, Netterdon et al., NIMA 754, 94(2014)]

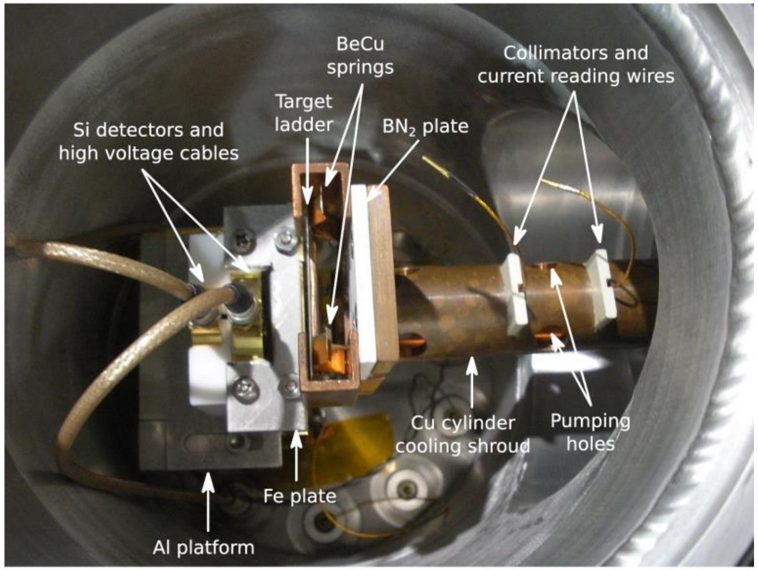
Quantifying the Beam

Beam Current

Measurement of Beam Current: Where ? How ?

Current Meters: reading out current at different positions (preceding the target, at the target & beam dump (Faraday Cup). Facilitate diagnostics

Our interest: Number of beam particles bombarding the target, to be extracted from beam current.



Measurement of beam current preferably at multiple positions (in the proximity of the target).

Galinski et al. [@ ISAC-II TRIUMF]

Measurement # 1

Total Cross-section from Angular Distribution

$$N_{comp} = \sigma . N_{projectile} . N_{target}$$

For every γ-ray transition, $W^{i}(\theta) = A^{i}_{0}[1 + \Sigma_{k=2,4} a_k P_k(\cos\theta)]$

Measured intensities at each angle corrected for the number of projectiles, efficiency & dead-time.

$$\sigma = \Sigma_{i=1}^{N} A^{i}_{0} / N_{target}$$

Nuclear Instruments and Methods in Physics Research A 754 (2014) 94–100

Contents lists available at ScienceDirect

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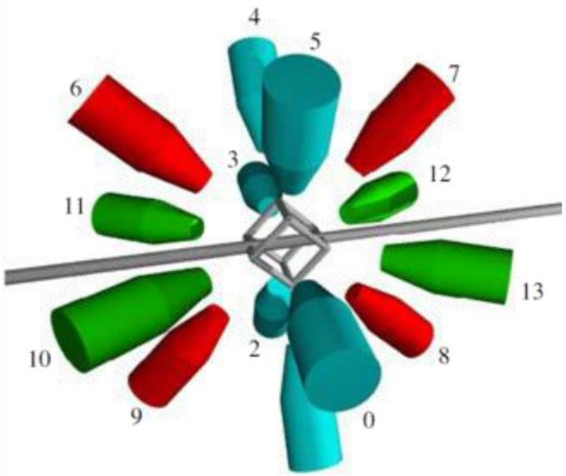
journal homepage: www.elsevier.com/locate/nima

ELSEVIER

The γ-ray spectrometer HORUS and its applications for nuclear astrophysics

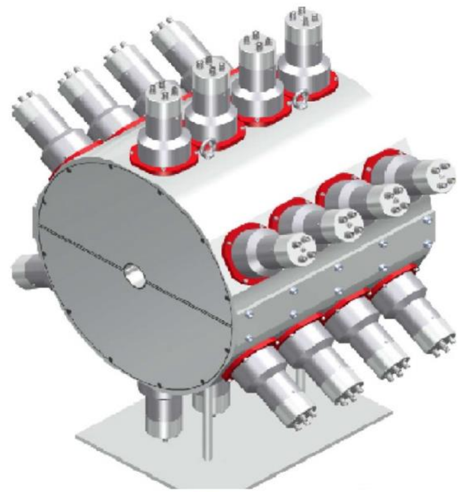
L. Netterdon*, V. Derya, J. Endres, C. Fransen, A. Hennig, J. Mayer, C. Müller-Gatermann, A. Sauerwein [1], P. Scholz, M. Spieker, A. Zilges

Institute for Nuclear Physics, University of Cologne, Zülpicher Straße 77, D-50937 Cologne, Germany



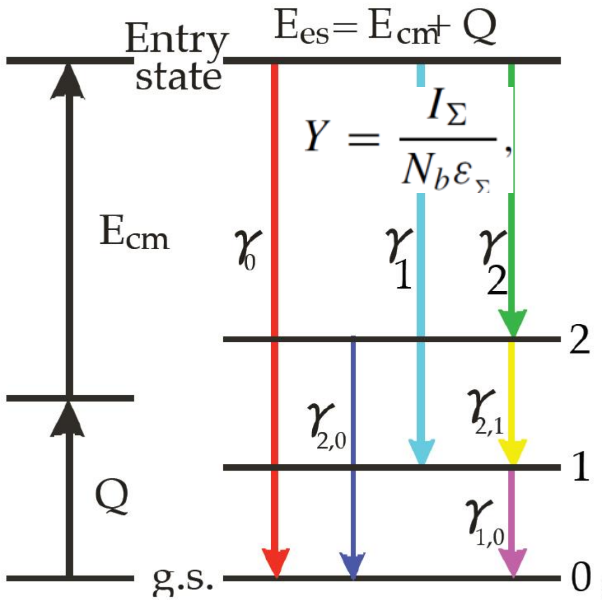
14 detector positions (HPGe, Clover / Cluster) with 6 of them Compton suppressed.

Measurement # 2
Total x-section from γ-ray Summing



SuN @ MSU
(Spyrou et al.)

2 x 4 segmented, each read by 3 PMTs



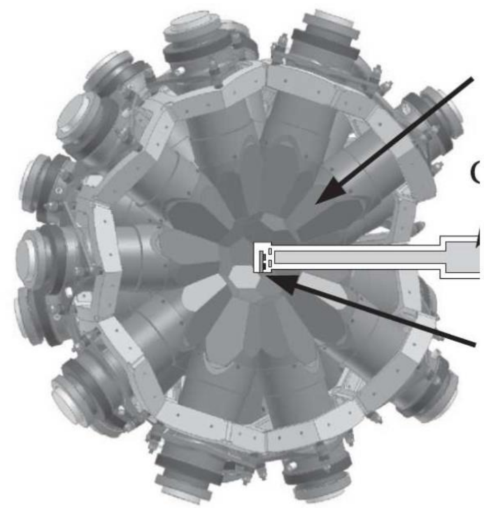
PHYSICAL REVIEW C **86**, 015805 (2012)

$^{12}C(\alpha, \gamma)^{16}O$ studied with the Karlsruhe 4π BaF_2 detector

R. Plag* and R. Reifarth
Universität Frankfurt am Main, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main,

M. Heil
GSI Darmstadt, Planckstrasse 1, 64291 Darmstadt, Germany

F. Käppeler, G. Rupp, F. Voss, and K. Wisshak
of Technology, Campus North, Institute of Nuclear Physics, P.O. Box 3640, 76021 K



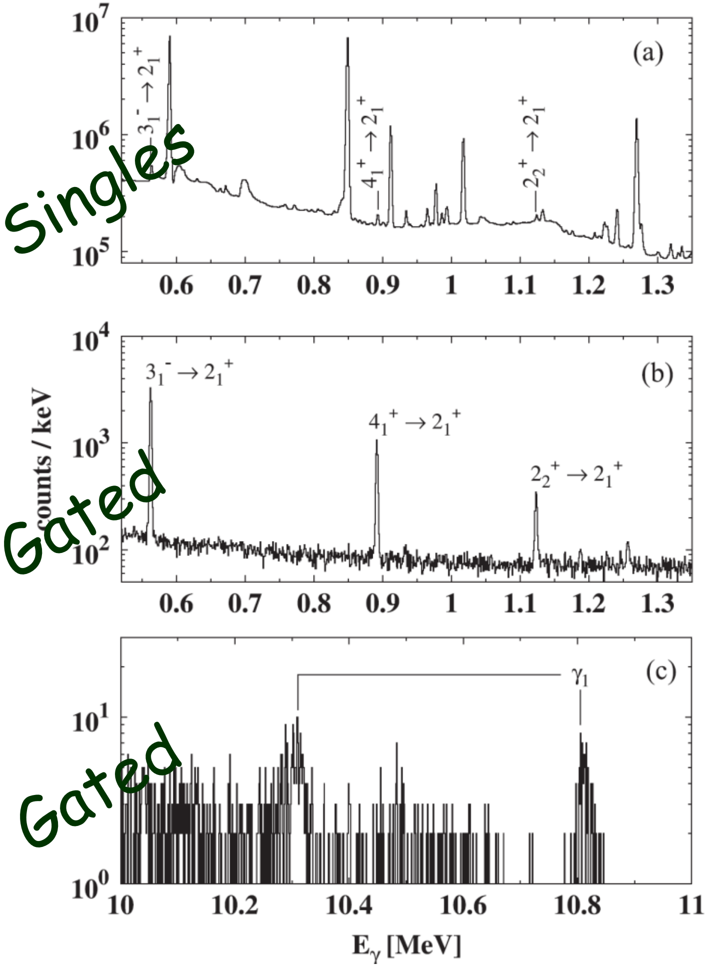
4π BaF_2 @ Karlsruhe
(Kaeppler et al.)

42 modules (hexagonal & pentagonal), 10 mm id &15cm thick

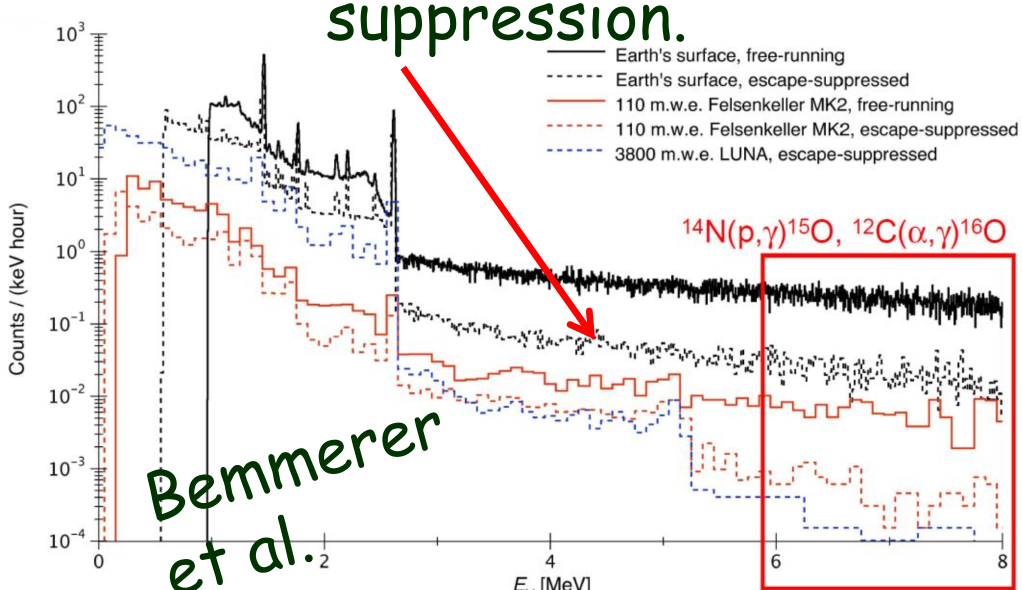
Coincidence Measurements & Background Suppression

$^{89}Y(p,\gamma)^{90}Zr$ @ E_p = 4.7 MeV
[Netterdon et al. (NIMA, 2014)]

Gate on 2_1^+ -> 0^+ transition (facilitate observation of cn -> 2_1^+ along with its SE peak)



Improved background with escape suppression.



Bemmerer et al.

Routine procedures in our trade

Over Ground Accelerator Facility @ University

Man power training.

Target characterization (RBS etc.) for the underground experiments.

Feasibility studies.

Will ensure maximum effective usage of the underground facility.

3.0 MV "T" shaped Tandetron Accelerator System

I	Ion source & associated beam extraction components	Duoplasmatron Ion source	For direct H- (25 – 35 eμA) & He+ (5 eμA) Other species also supported. With an upgrade higher beam currents are also available.
		Single source heavy-ion sputter source	Can be configured for multi target with add-on All species except inert gases
		Option for higher beam currents also available.	
II	Accelerating system	Medium current plus parallel Cockroft Walton type terminal voltage power supply.	Terminal Voltage : 0.2 – 3.0 MV Terminal voltage stability ± 300 V Terminal ripple 300 V_{RMS} Terminal ripple 30 V_{RMS} with low ripple add-on kit
		Options for beam bunching Ports at ±30° at the analyzer. Option for multiport also available.	
III	Beamlines	Three beamlines at ± 30° and at 100, with all vacuum components as well as beam diagnostics components (BPM, focusing elements)	3 m long beamlines
		Vacuum system comprising of pumps, measuring devices valves are included.	
IV	SF_6 system	Recovery & pressure evacuation system	Mobile pressure handling vessel Storage tanks Vacuum systems etc.

Summary & Outlook

Will be one of the few such facilities in the world & will attract international collaborations.

Will warrant the contribution of the Indian community in the global endeavours being pursued in the domain of nuclear astrophysics research.

Will provide a training ground in the field of precision measurements.

Will lead to collateral developments in instrumentation and computational infrastructure.

Collaborations Invited !