Nuclear Physics Institute ASCR, p.r.i.

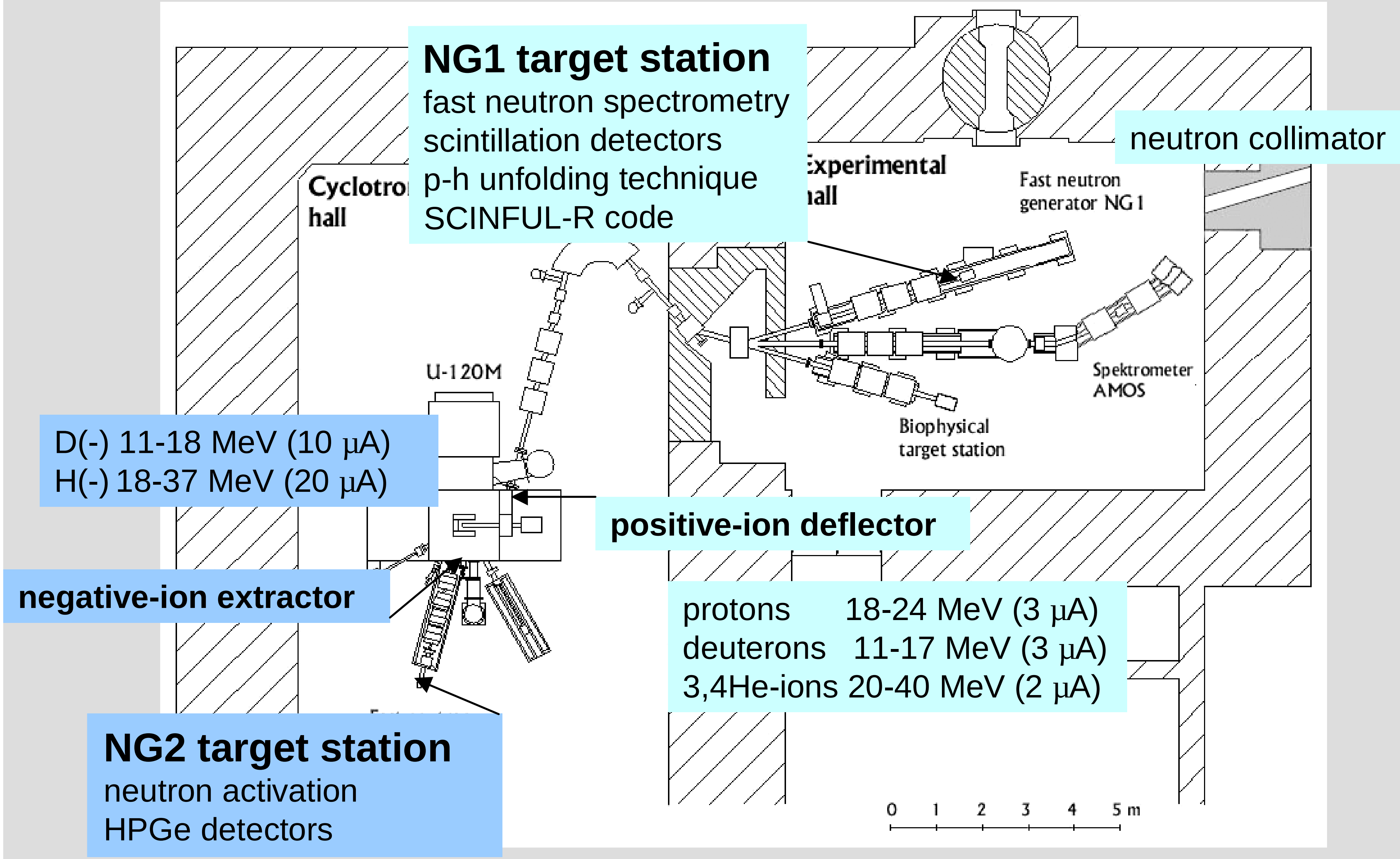
V.Kroha

Nuclear Reactions Dept.

-Nuclear Astrophysics

-Neutron Physics

NPI variable-energy cyclotron U-120M



Facilities of Nuclear reactions department of NPI Řež

Cyclotron :	protons	12 – 24 MeV
	deuterons	12 – 17 MeV
	^{3}He – ions	20 – 52 MeV
	^{4}He – ions	20 – 40 MeV
	posibility of axial injection	

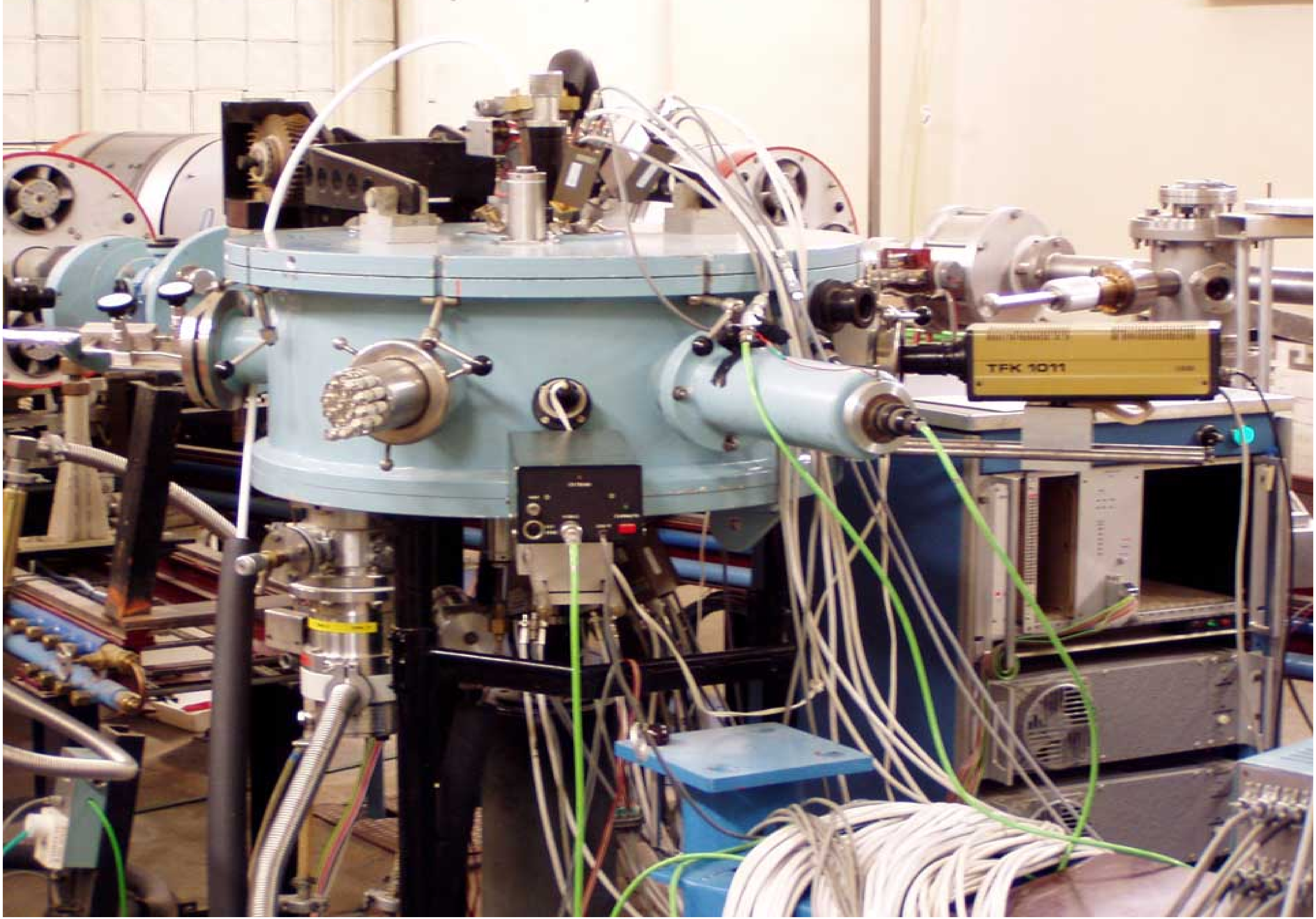
Tandem : 4 MV, ECR source, heavy ions available

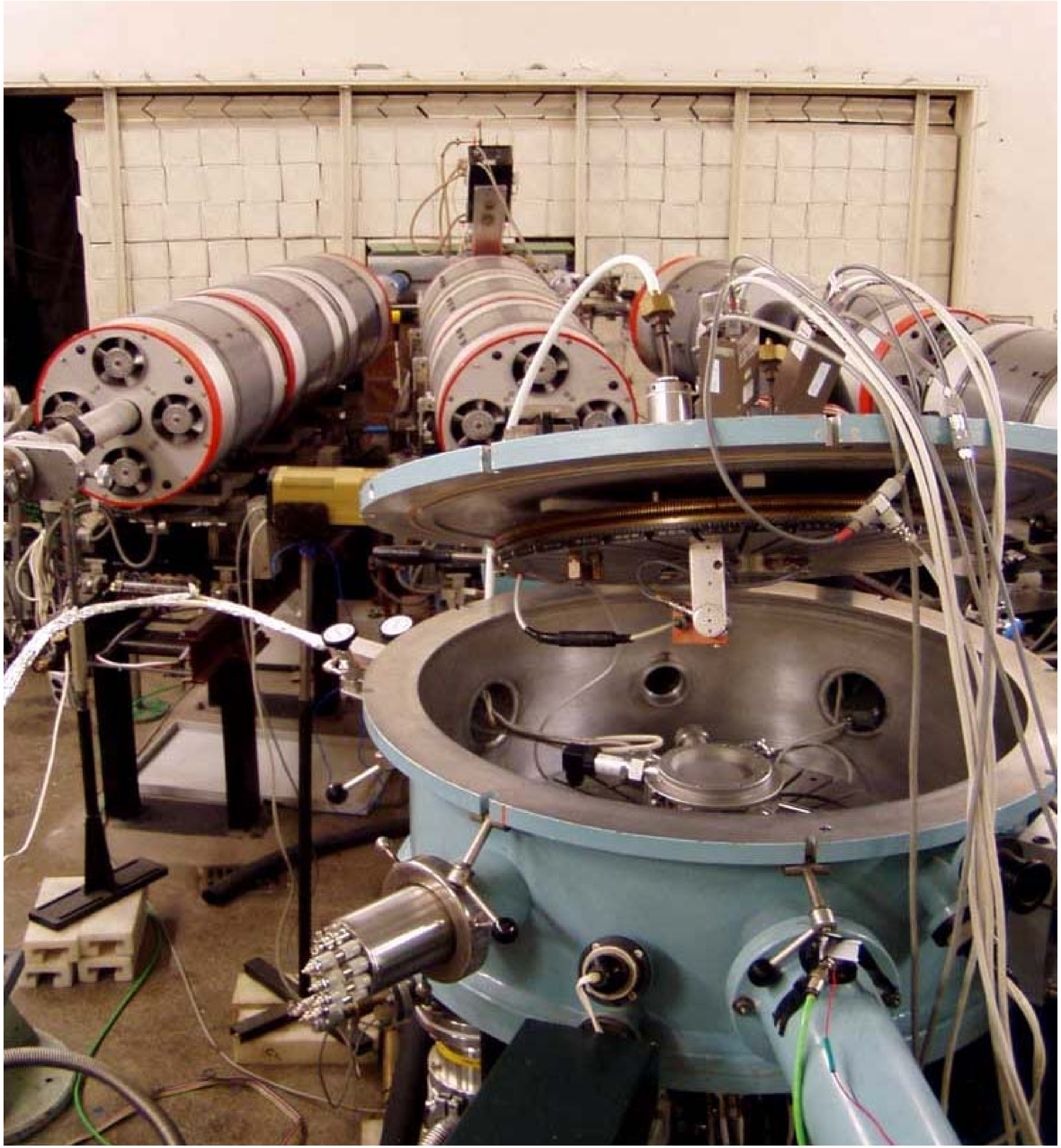
exploatation during next two years for

nuclear physics research

Aparatus :

- achromatic magnetooptical system AMOS for „zero-angle measurements (up to 20 deg)
- target chamber for angular cross sections measurements
- gas target chamber
- $\Delta E - E$ telescopes with semiconductor detectors
- spectroscopical electronic for multiparameter registration
- fast on-line CAMAC system for multiparameter easurements
- neutron generators NG 1 and NG 2 for activation xperiments and application research
- neutron spectrometers


TFK 1011

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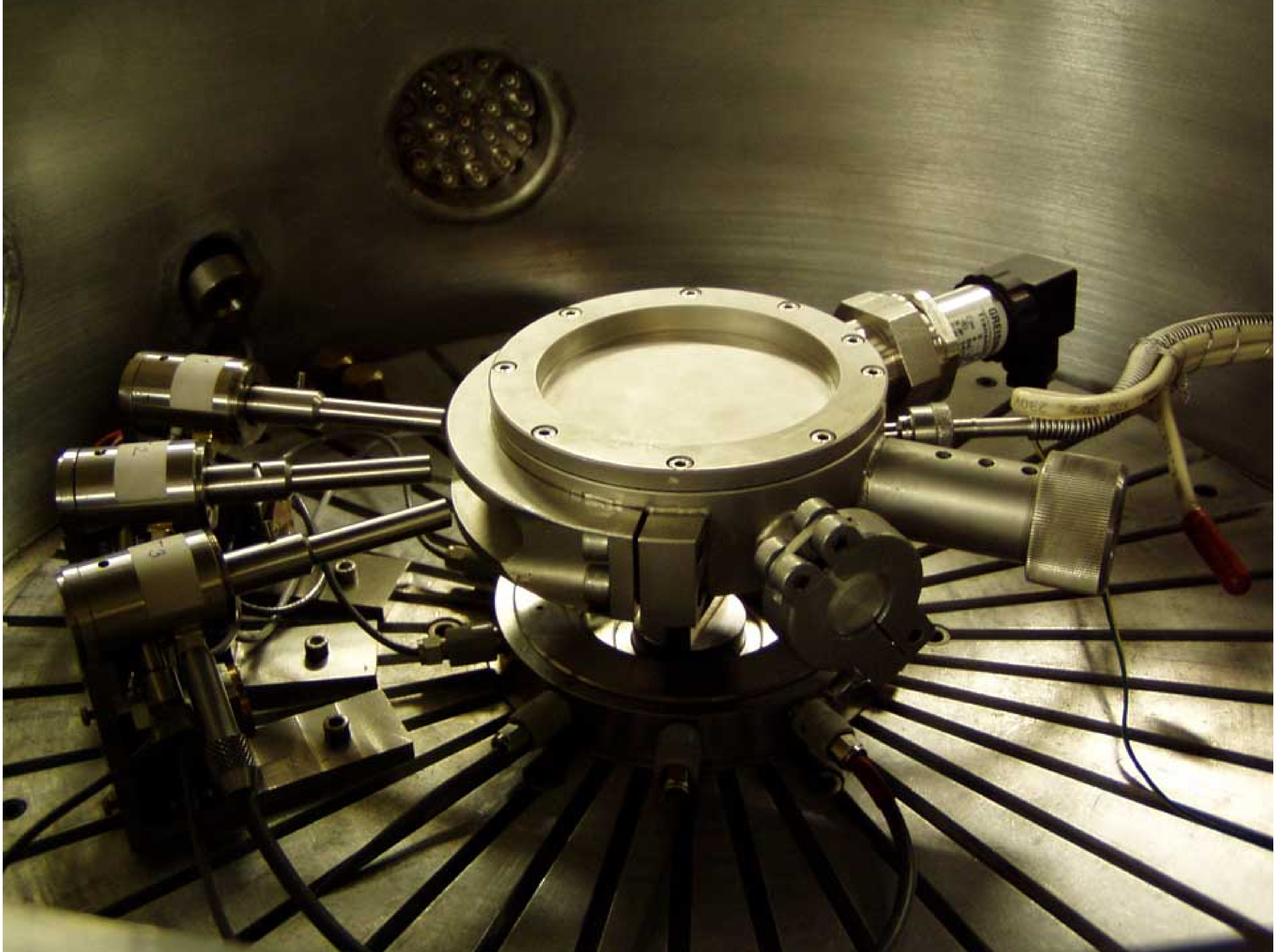
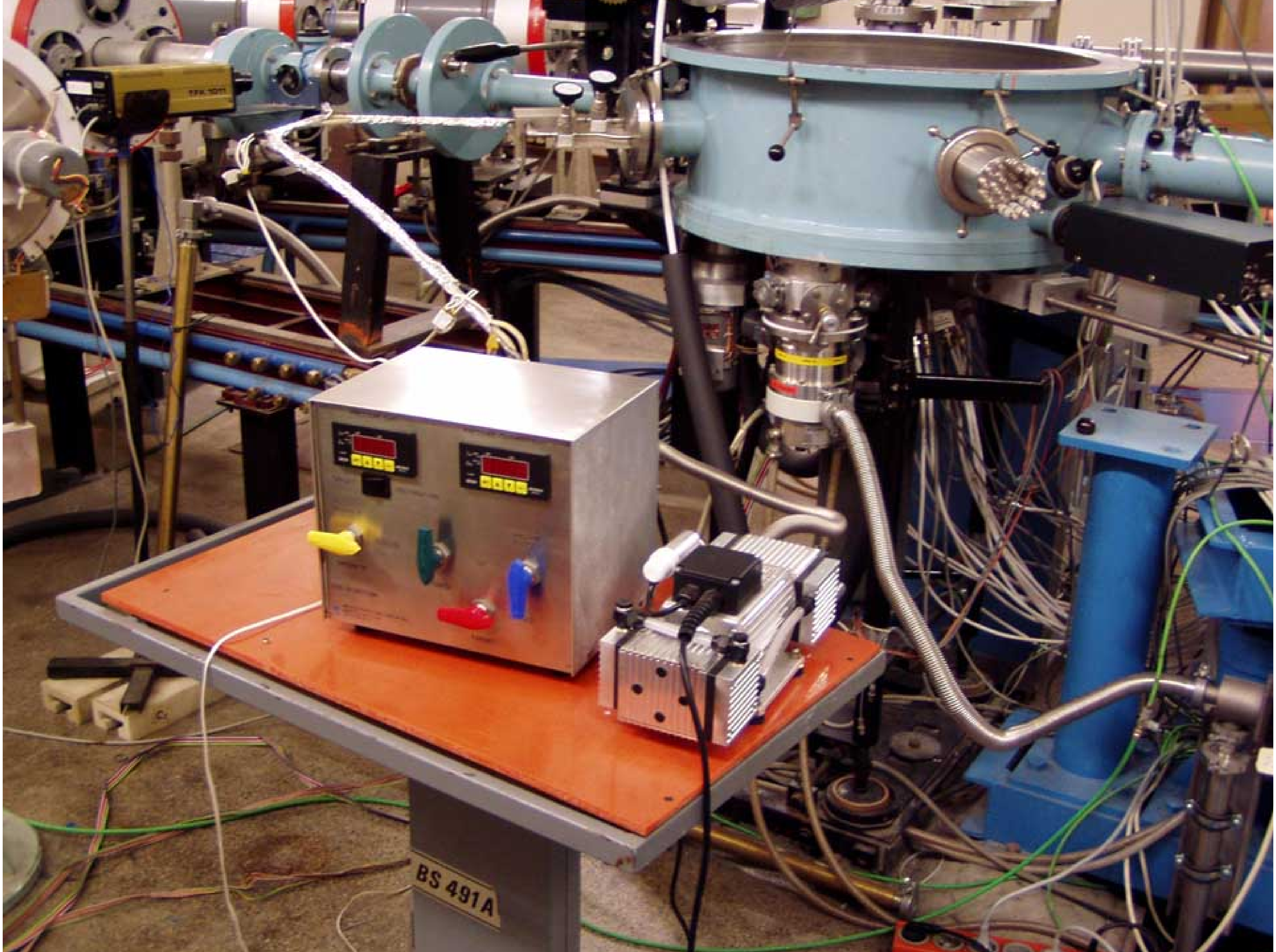
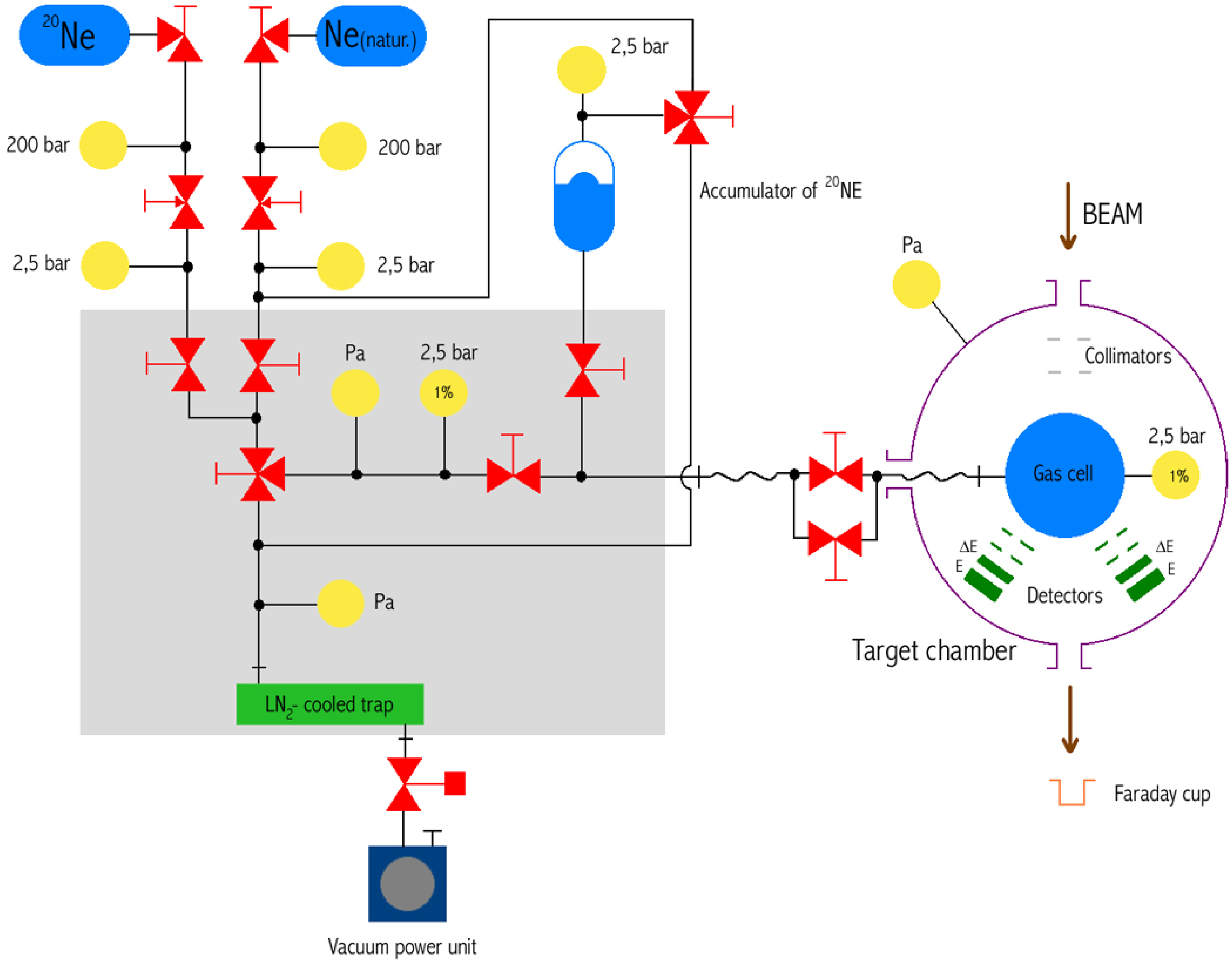
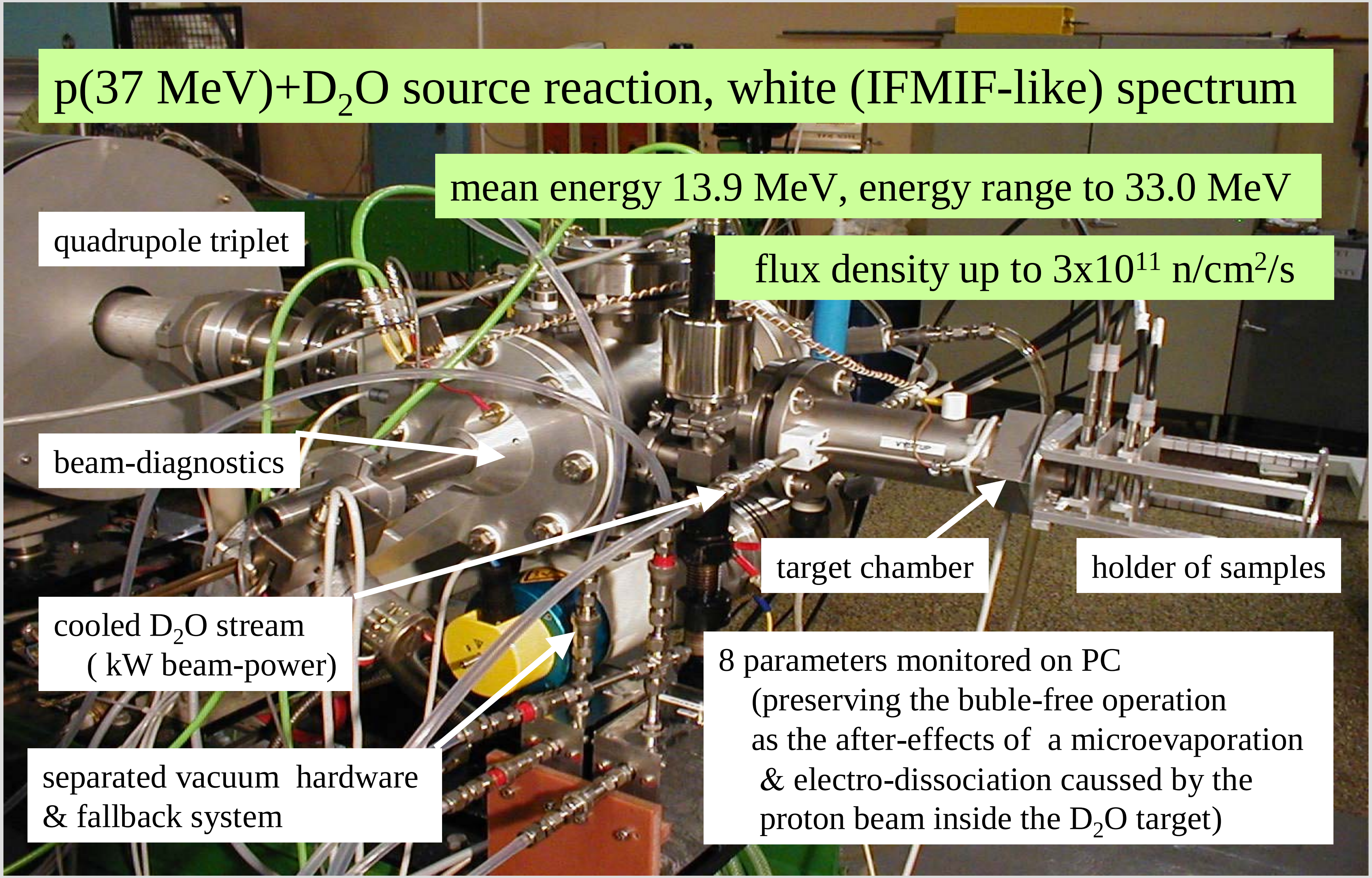



BS 491A

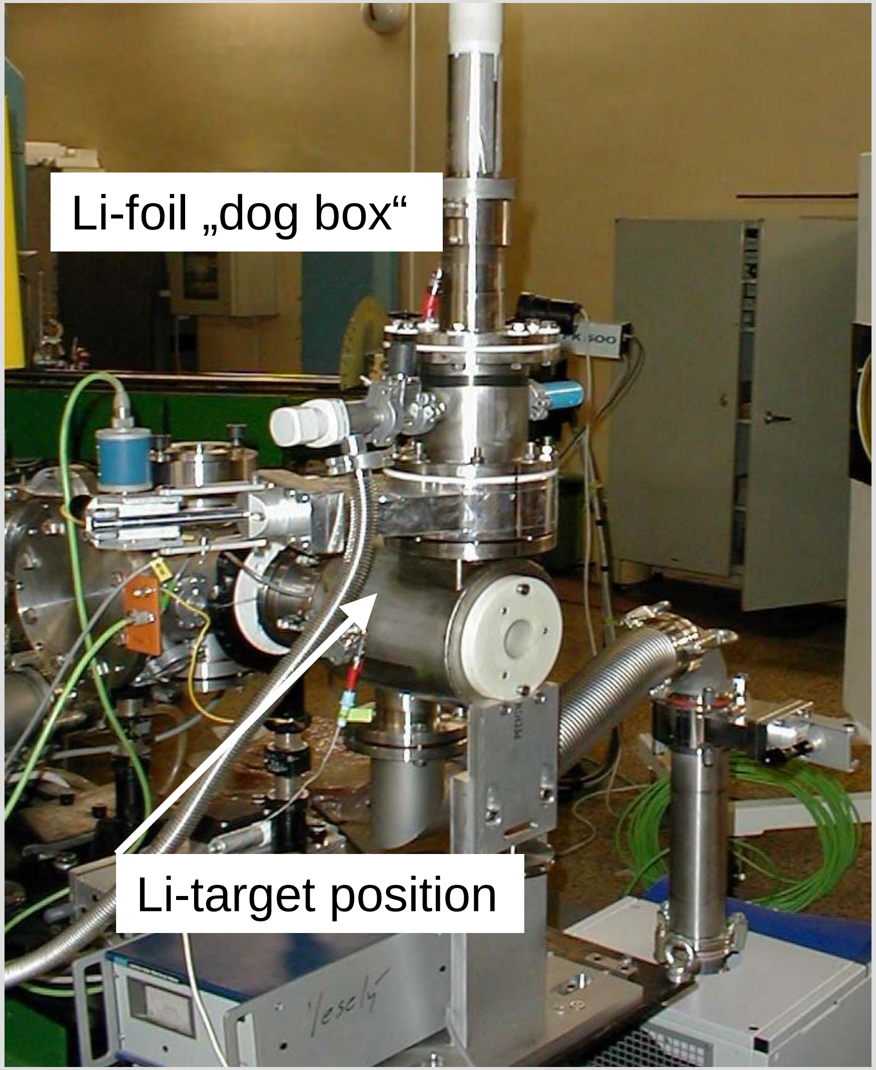
GAS TARGET CONTROL SYSTEM



NG2 target station of NPI high-power neutron source



NG2 target station of NPI quasi-monoenergetic neutron source



? p+^{7}Li(C backing) source reaction
11-37 MeV proton beam

? target set-up:
2 mm thick ^{7}Li foil
12 mm thick graphit stopper
cooling by 5^{o}C alcohol stream
300W beam-power operated

? quasi-monoenergetic spectrum
E_n = 10-35 MeV
flux density 10^9 n/cm^2/s (in peak)
calculated for 30 MeV/10 µA
at t-s distance of 50 mm

Nuclear astrophysics

The most important results for the period 1999 – 2006

Development of the new method for indirect determination of the astrophysical *S* – factors

Method of Asymptotic Normalization Coefficients was developed in cooperation with Texas A&M University

The main test of ANC method was realized in INP at Řež using $^{16}O(^{3}He,d)^{17}F$ reaction.
Publications :

Phys.Rev.C56(1997)1302

Phys.Rev.C59(1999)1149

Few-Body Syst.Suppl.12(2000)102

Czech.J.Phys.54(2001)

Determination of astrophysical *S* – factor for ^{8}B synthesis

This work was implemented on ^{7}Be radioactive beam in TAMU as a joint experiment. Reactions $^{10}B(^{7}Be,^{8}B)^{9}Be$ and $^{14}N(^{7}Be,^{8}B)^{13}C$ were studied. The necessary complementary measurements of the $^{9}Be(^{3}He,d)^{10}B$ and $^{13}C(^{3}He,d)^{14}N$ reactions were performed on the ^{3}He beam of cyclotron NPI.

The most important published results :

Phys.Rev.Lett.82(1999)3960

Phys.Rev.C60(1999)055803

Phys.Rev.C62(2000)024320

Phys.Rev.C63(2001)055803

Phys.Rev.C66(2002)027602

Phys.Rev.C73(2006)025808

Determination of the reaction rate for $^{14}N + p \rightarrow {}^{15}O$ synthesis

The reaction $^{14}N(^{3}He,d)^{15}O$ was studied on cyclotron NPI at beam energy 26.3 MeV.The direct capture to the subthreshold bound state of ^{15}O dominates in this key reaction of all CNO cycle.

Up to now,the most accurate value of the total *S* – factor for the

$^{14}N(p,\gamma)^{15}O$ radiative capture was obtained.

The main published results :

Phys.Rev.C67(2003)065804

Nucl.Phys.A718(2003)147

Nucl.Phys.A725(2003)279

Measurement of the *S* – factor for $^{11}C(p,\gamma)^{12}N$ reaction

***S* – factor was determined by the ANC method using**

the $^{14}N(^{11}C,^{12}N)^{13}C$ reaction. Effect of the distant resonances was analysed in R – matrix approach. It was shown that value of the

***S* – factor is much higher than the present theoretical predictions.**

It increases the probability of successive generating of the CNO cycle in supermassive stars and their stabilization against the gravitational collapse into a black hole. Such stars explode in the final stage of their evolution as supernovae.

The main published result :

Phys.Rev.C67(2003)015804

Determination of ANC from $^{20}Ne(^{3}He,d)^{21}Na$ reaction and *S* factor for $^{20}Ne(p,\gamma)^{21}Na$

The ANCs for $^{20}Ne(p,\gamma)$ capture were obtained on cyclotron of NPI at laboratory energy 25 MeV.

Measurements were realized on gas target of isotopic ^{20}Ne.

Analysis was given for all bound states up to the threshold.

The main results were published at international meetings :

Catania, March 20, 2003, Italy

Conf. of American Physical Society, Oct. 29, 2003, Tuscon,Arizona

and in Phys. Rev. C 73(2006)035806

Trojan-Horse Indirect method

Validity test of the T–H method on cyclotron ^{3}He beam

Coincidence measurements of $^{7}Li + p \rightarrow \alpha + \alpha$ reaction via the ^{3}He break – up

Published :

Intern. Conf. Debrecen, Hungary, 2005

Intern. Conf.FINUSTAR 2005, Kos, Greece, 2005

Accepted in European Phys. Journal

Research program until the year 2010

-proton transfer reactions of the CNO and NeNa cycles will continue on the NPI cyclotron . The main goal – to find out intensities of reactions leading to synthesis of heaviest nuclei

-transfer reactions will be studied also at TAMU with heavy ions ^{8}B, ^{12}N, ^{13}N and ^{22}Ne to determine the direct components of the capture reactions important for evolution of the supermassive stars and for relation between reactions in standard and „hot“CNO cycles

-the other indirect technique, Trojan-Horse method, was developed by Catania group. Using a ^{3}He beam of our cyclotron and in cooperation with LNS we study the possibility of absolutization of this method by its combination with ANC one.

-in LNS Catania we realized a study of alpha transfer reactions on the Li–beam to test our ANC method for the case of alpha particle captureprocesses.

-Results of ^{12}C(^{6}Li,d)^{16}O are under way

Collaborators

INP (CR) : P.Bém, V.Burjan, Z.Hons, V.Kroha, J.Novák, Š.Piskoř, E.Šimečková, J.Vincour, J.Mrázek

TAMU (USA) : A.Azhari, C.A.Gagliardi, A.M.Mukhamedzhanov, A.Sattarov, X.Tang, L.Trache, R.E.Tribble

INFN-LNS (Italy) : M.LaCognata, L.Lamia, R.G.Pizzone, S.Romano, C.Spitareli, S.Tudisco, A.Tumino

INF Debrecen (Hungary) : S.Fulop, E.Somorjai, G.Kiss

The research will be supported

by the newly accepted project of MŠMT(CR) – NSF(USA)

ME643(2007) :

Indirect Methods in Nuclear Astrophysics

principal investigators V.Kroha (NPI),R.E.Tribble (TAMU)

by grant of GAČR 202/05/0302

Astrophysical Reactions and Method of Asymptotic Normalization Coefficients

principal investigator V.Burjan (NPI)

and by Centrum of Nuclear astrophysics and Nuclear Physics (MED)

Publications 1999 – 2006

International journals :   45

International conferences : 60

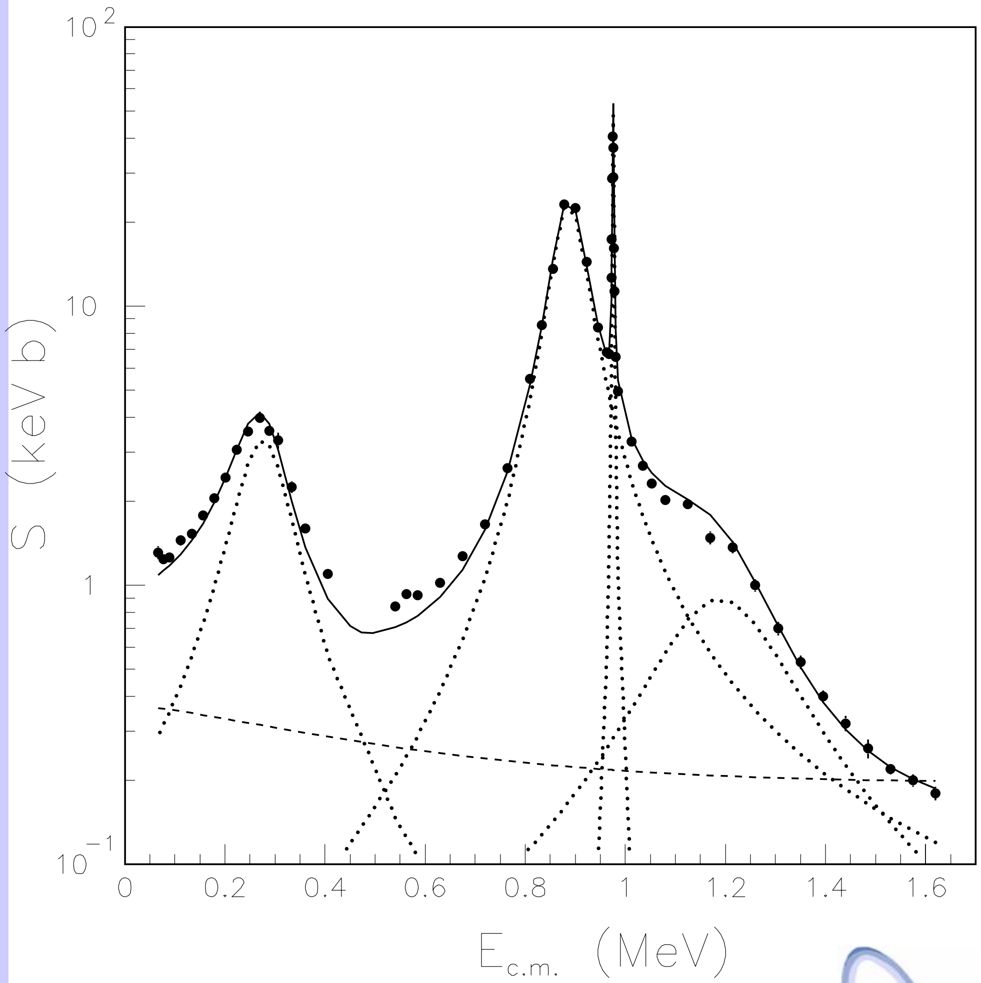
Preprints and Reports : 24

Citations 1999 – 2006

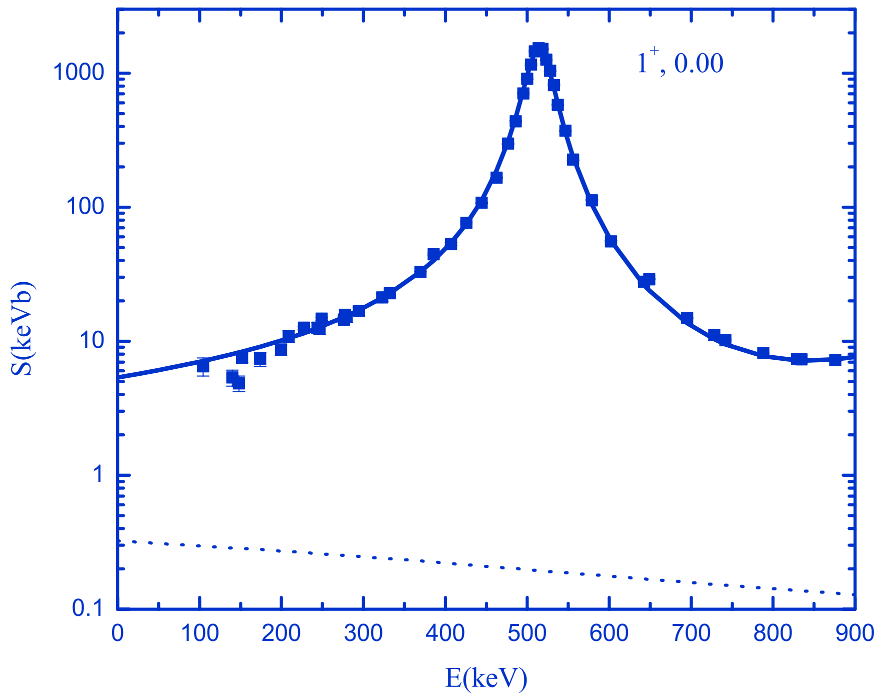
International journals : 170

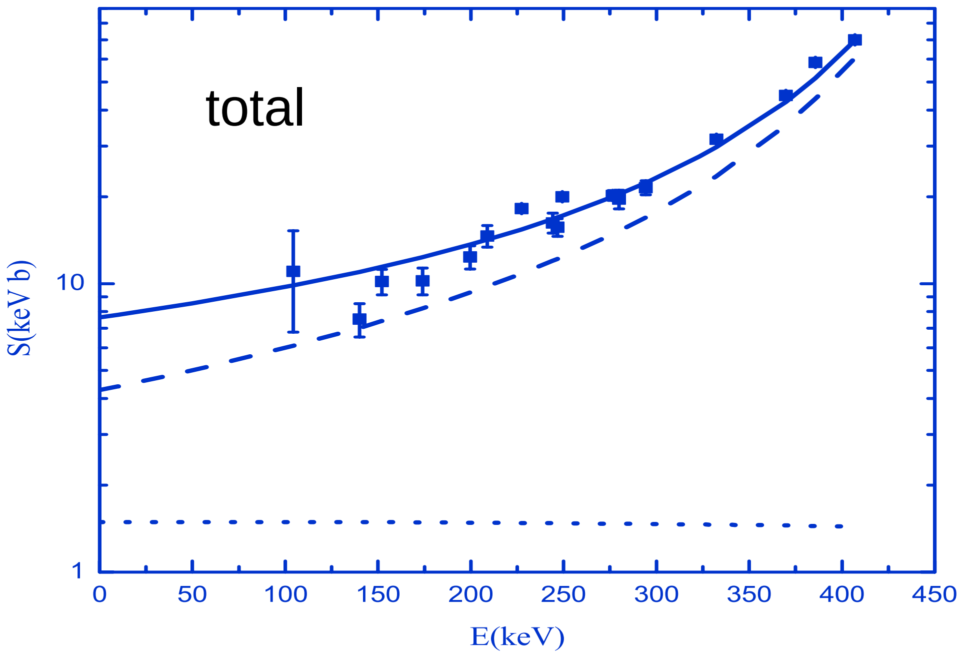
S factor for ^{9}Be(p, γ)^{10}B

- ANC's $\Leftarrow$ ^{9}Be(^{3}He,*d*)^{10}B and ^{9}Be(^{10}B, ^{9}Be)^{10}B
- R-Matrix fit to ground plus excited states (includes interference)
- Data from Zahnow, . . ., Rolfs et. al (1995)
- Uses known values for E_r and Γ_γ



S factor for $^{13}C(p,\gamma)^{14}N$

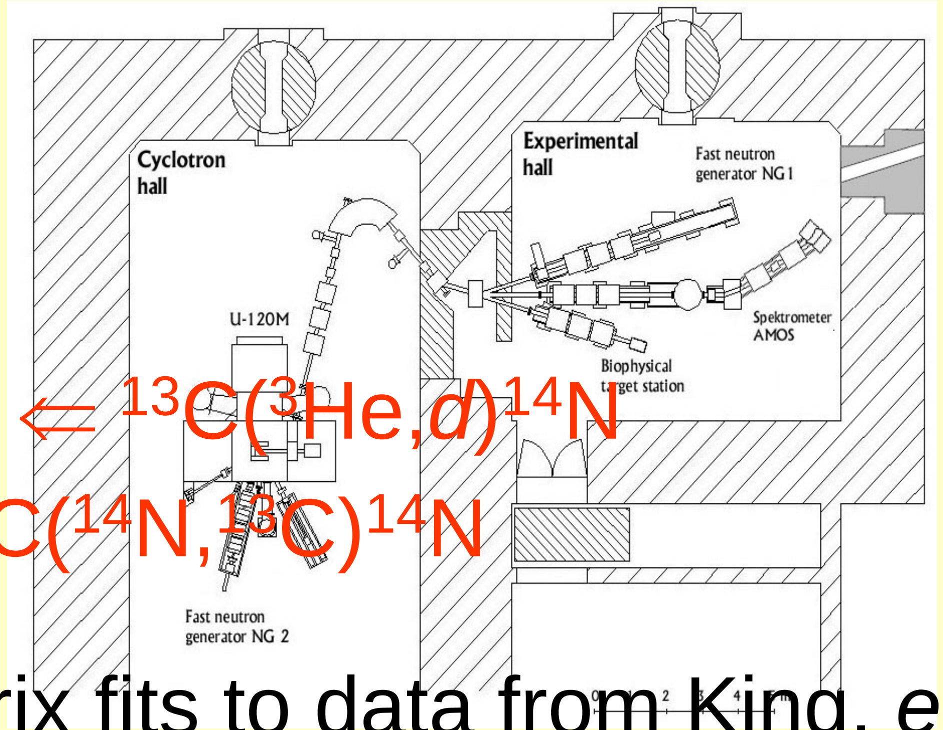




S(0) = 7.7 ± 1.1 keV·b

(R - 4.3 keV·b; D – 1.5 keV·b; INT – 1. 9 keV·b)

NPI Cyclotron-based Fast Neutron Facility

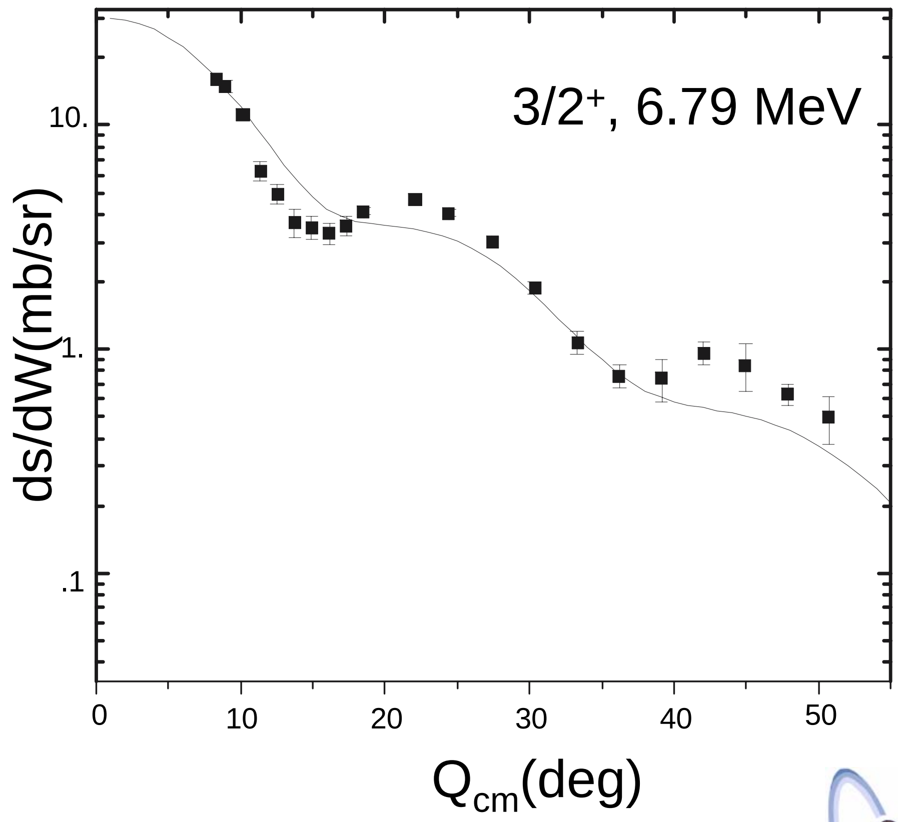


- ANC’s ⇐ $^{13}C(^{3}He,d)^{14}N$ and $^{13}C(^{14}N,^{13}C)^{14}N$
- R-Matrix fits to data from King, *et al.*

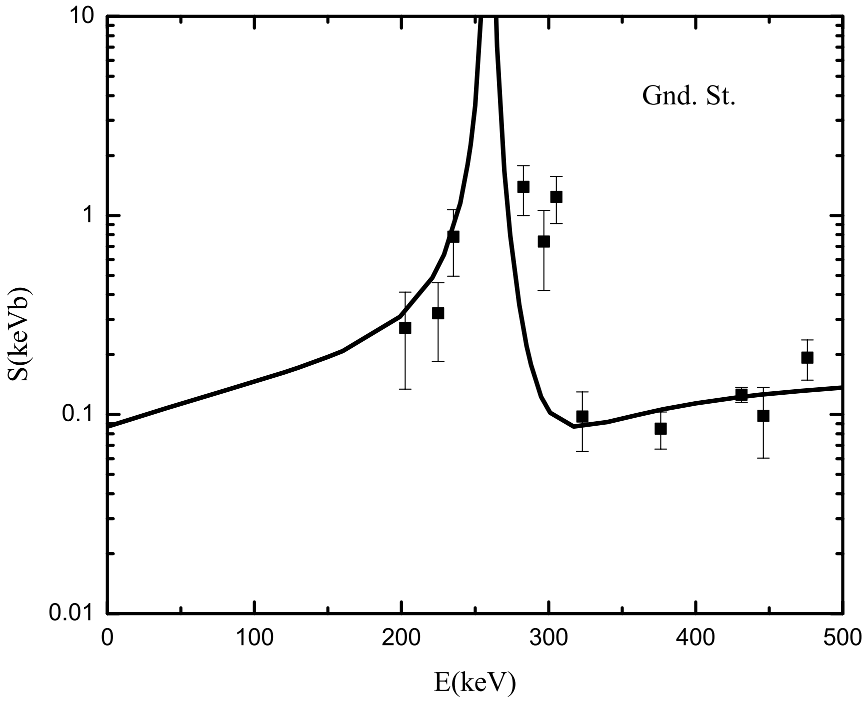
Target station	NG1	NG2
Particles energy	Protons 12-24 MeV Deuterons 12-17 MeV ^{3,4}He -ions 20-40 MeV	Protons 16-36 MeV Deuterons 8-18 MeV
Beam current up to	2 μA	20 μA
Targets	Gaseous (He,D) Thick Solid (Li, Be,) Liquid (D_2O)	Thick Solid (Be) Liquid (D_2O stream)
Neutron spectrum mean energy energy range	White 4-15 MeV ? 32 MeV	White 7 / 15 MeV ?16 / ? 33 MeV
Source strength	? $5x10^{10}$ n/s	? $3x10^{12}$ n/s

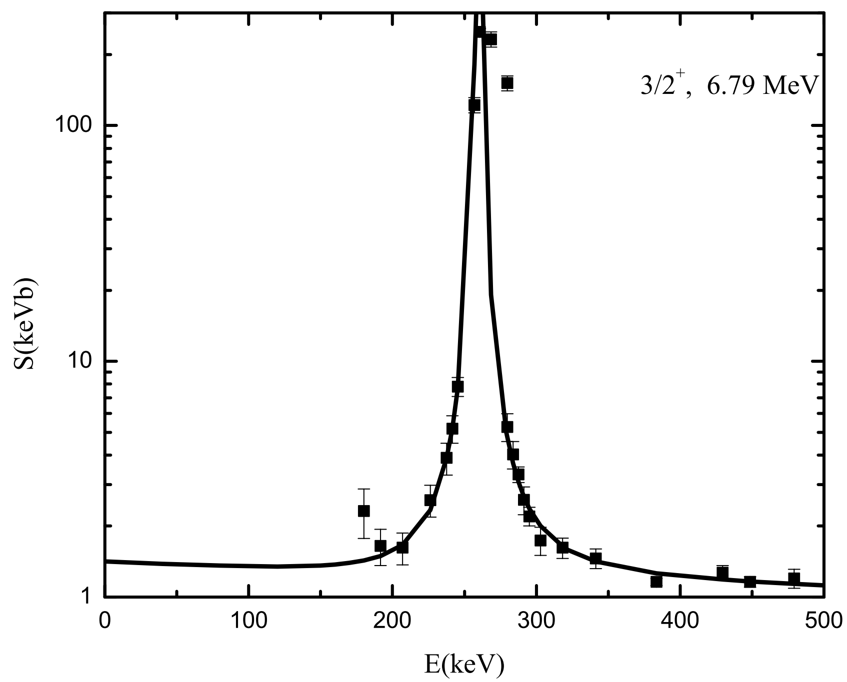
S factor for $^{14}N(p, \gamma)^{15}O$

- ANC's $\Leftarrow$ $^{14}N(^3He,d)^{15}O$
- NRC to subthreshold state at E_x = 6.79 MeV
- Subthreshold resonance width from Bertone, *et al.*
- R-Matrix fits to data from Schröder, *et al.*



S factor for $^{14}N(p,\gamma)^{15}O$





- $C^2(E_x=6.79\ \mathrm{MeV}) \approx 27\ \mathrm{fm}^{-1}$ [non-resonant capture to this state dominates S factor]
- $S(0) \approx 1.41 \pm 0.24$ keV·b for $E_x=6.79$ MeV
- $S_{tot}(0) \approx 1.62 \pm 0.25$ keV·b

ANC's via **transfer** reactions using **radioactive** (rare isotope) **beams**

- **^{7}Be + p $\leftrightarrow$ ^{8}B** [^{10}B(^{7}Be,^{8}B)^{9}Be] {TAMU}
  [^{14}N(^{7}Be,^{8}B)^{13}C] {TAMU}
  [d(^{7}Be,^{8}B)n] {Beijing}
- **^{11}C + p $\leftrightarrow$ ^{12}N** [^{14}N(^{11}C,^{12}N)^{13}C] {TAMU}
- **^{13}N + p $\leftrightarrow$ ^{14}O** [^{14}N(^{13}N,^{14}O)^{13}C] {TAMU}
- **^{17}F + p $\leftrightarrow$ ^{18}Ne** [^{14}N(^{17}F,^{18}Ne)^{13}C]
  {ORNL (TAMU collaborator)}

beams $\approx$ 10 - 12 MeV/u

ANC's for $^{11}C + p \leftrightarrow {}^{12}N$

- reaction:

$^{14}N(^{11}C,^{12}N)^{13}C$

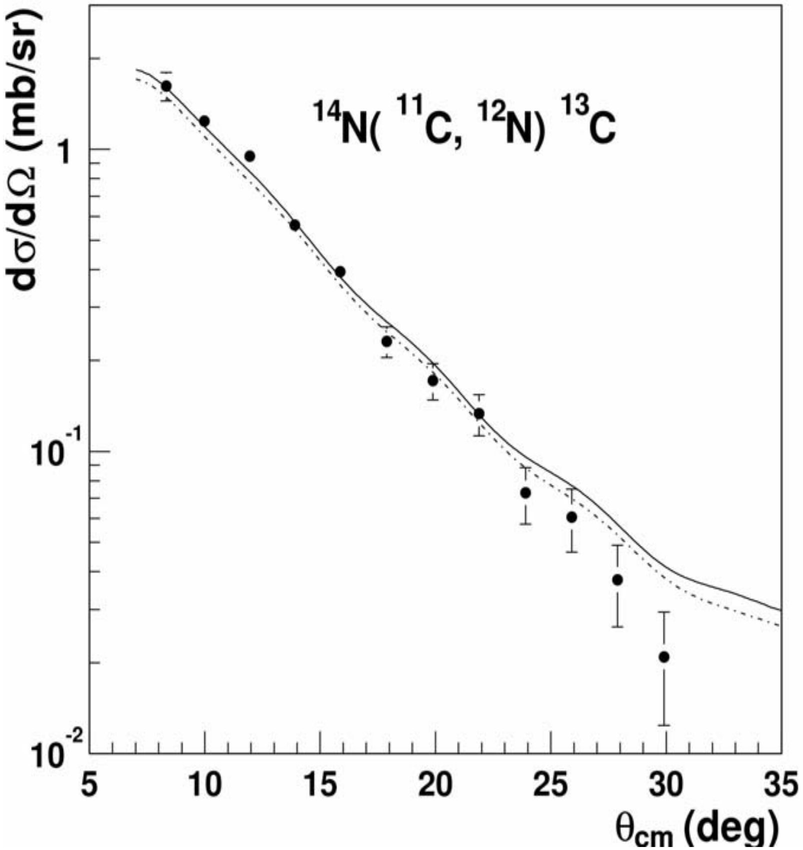
K500: ^{11}B beam $\approx$ 144 MeV

MARS: ^{11}C beam $\approx$ 110 MeV

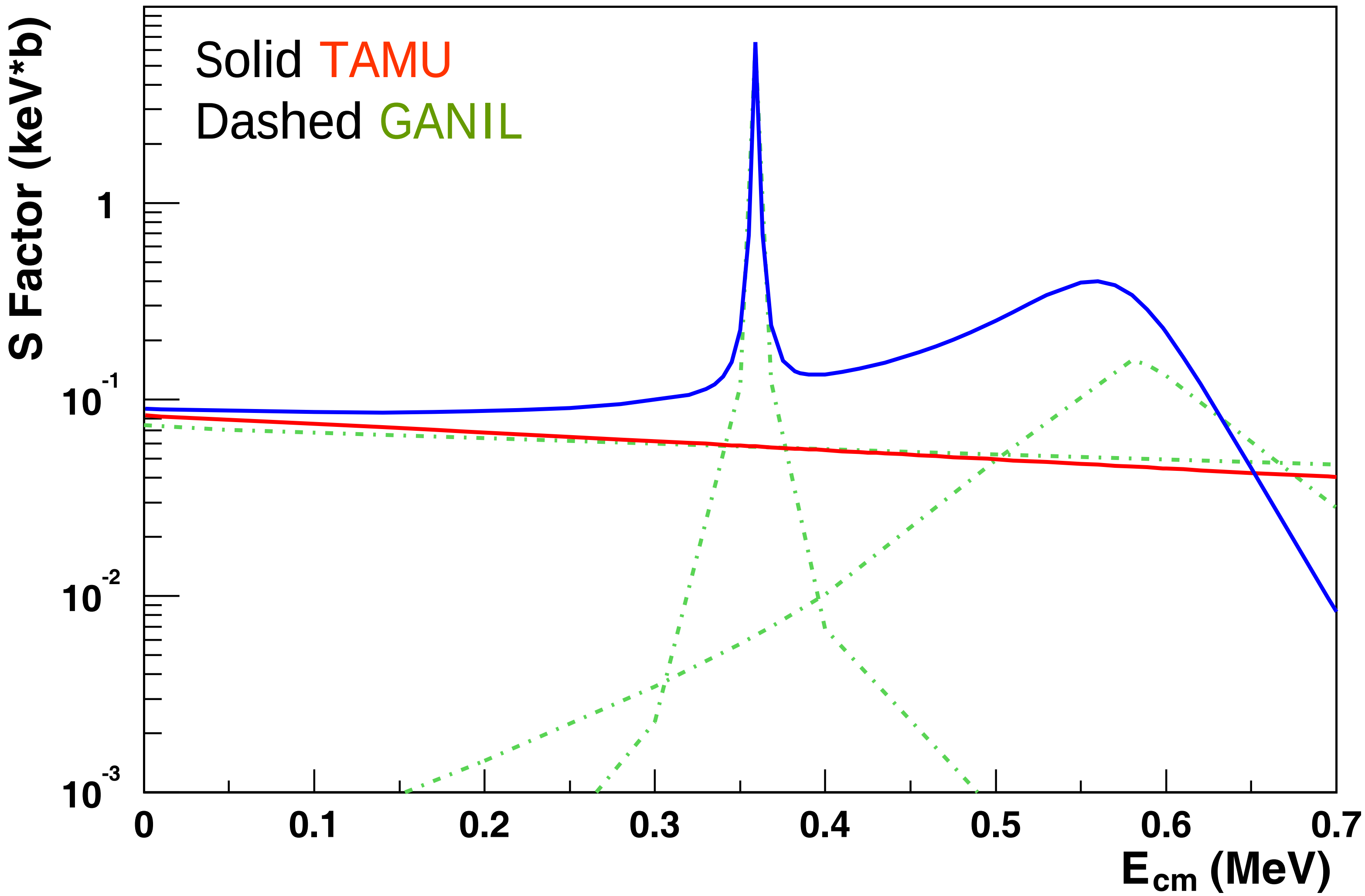
$^{14}N(^{11}C,^{12}N)^{13}C$ angular distribution

$$\frac{1}{(C^{12N}_{11Cp1\frac{1}{2}})^2} = \frac{1}{\sigma_{exp}}\left(\left(\frac{C^{14N}_{13Cp1\frac{1}{2}}}{b^{14N}_{13Cp1\frac{1}{2}}\,b^{12N}_{11Cp1\frac{1}{2}}}\right)^2\sigma^{DW}_{1\frac{1}{2}1\frac{1}{2}} + \left(\frac{C^{14N}_{13Cp1\frac{3}{2}}}{b^{14N}_{13Cp1\frac{1}{2}}\,b^{12N}_{11Cp1\frac{3}{2}}}\right)^2\sigma^{DW}_{1\frac{1}{2}1\frac{3}{2}} + \mathcal{S}\left(\frac{C^{14N}_{13Cp1\frac{1}{2}}}{b^{14N}_{13Cp1\frac{3}{2}}\,b^{12N}_{11Cp1\frac{1}{2}}}\right)^2\sigma^{DW}_{1\frac{3}{2}1\frac{1}{2}} + \mathcal{S}\left(\frac{C^{14N}_{13Cp1\frac{3}{2}}}{b^{14N}_{13Cp1\frac{3}{2}}\,b^{12N}_{11Cp1\frac{3}{2}}}\right)^2\sigma^{DW}_{1\frac{3}{2}1\frac{3}{2}}\right),$$

Normalization(beam&target)	6.5%
Optical Model	8%
ANCs of ^{14}N	6.4%
Statistical Error	3%
MC parameters	2%
Total	12.7%



S factor for $^{11}C(p,\gamma)^{12}N$



Updated Reaction rates