JÜLICH
FORSCHUNGSZENTRUM

Review on existing data / databases (and facilities)

3. December 2012 | Frank Goldenbaum

Contents

- relevance of and need for Nuclear Data (fundamental research, applications,…)
- terminology/classification (*thin/thick* targets, *invers/direct* kinematics)
- EU-FP-5,6,7 initiatives: HINDAS, EUROTRANS,…
- nuclear data/databases Services Data access
  - NEA (EXFOR: Exp. nucl. reac. data), CINDA: Bibliograpical nucl. reac. data)
  - BNL National Nuclear Data Center
  - IAEA Nuclear Data Services
    - ➢ Benchmark of Spallation Models (of interest also for GCR physics)
  - Examples (IAEA, ITEP, NEA,…)

    n-,p-,LCP-ddxs, n-multiplicities, multiplicitiy distributions, excitation functions, mass-, charge-, isotopic-distributions, residues,…
- facilities (COSY, ITEP, GSI, …)

Motivation: Nuclear data needed for…

- **nuclear physics**
  - systematics of nuclear reactions
  - equilibrium and pre-equilibrium reactions
  - spallation, fragmentation
  - medium energy fission
  - CN-, PE- and INC-models
- **accelerator technology**
  - activation of detectors
  - radiation protection
  - on-line mass separation
  - radioactive ion beams
- **dosimetry**
  - mixed nucleon fields
  - medicine
- **radionuclide production**
  - radiation therapy
- **space and aviation technology**
  - radiation protection
  - material damage
- **astrophysics**
  - abundance of heavy CR particles
  - T-Tauri and WR stars
  - p-process nucleosynthesis
- **geo- and environmental physics**
  - cosmogenic nuclides as natural tracers in geology, archeometry, climatology, hydrology, glaciology
- **planetology**
  - remote sensing of planetary surfaces
- **cosmophysics and -chemistry**
  - cosmic ray exposure history of extraterrestrial matter
  - terrestrial ages of meteorites
  - variations of cosmic radiation with space and time
- **accelerator driven systems (ADS)**
  - waste transmutation
  - energy amplification
  - spallation neutron sources

from: R.Michel, Advanced Workshop on Spallation Models|CTP-Trieste, Feb. 4-8, 2008

Motivation

Application driven aspect

- nuclear data required for ADS facilities planned: shielding layout, irradiation damage in target and structural materials, dpa, embrittlement, gas production, radioactive inventory, activation

Fundamental physics driven aspect

- decay modes of highly excited hot nuclear matter
- systematics on production cross sections for H,He,Li,Be isotopes (complex particles) in GeV pN reactions
- understanding of reaction mechanism and cluster formation (coalescence, exciton model, successive elementary reactions,…)
- decomposition of evaporative and pre-equilibrium components

⇒ systematic comprehensive data sets on angular-, energy distributions (over wide range of target nuclei) provide test grounds for model development and improvements and sensitive benchmarking

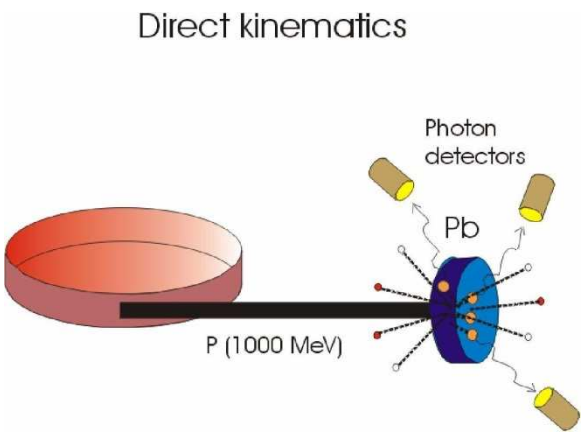
before going to the details of data/databases:

Classification/terminology targets…

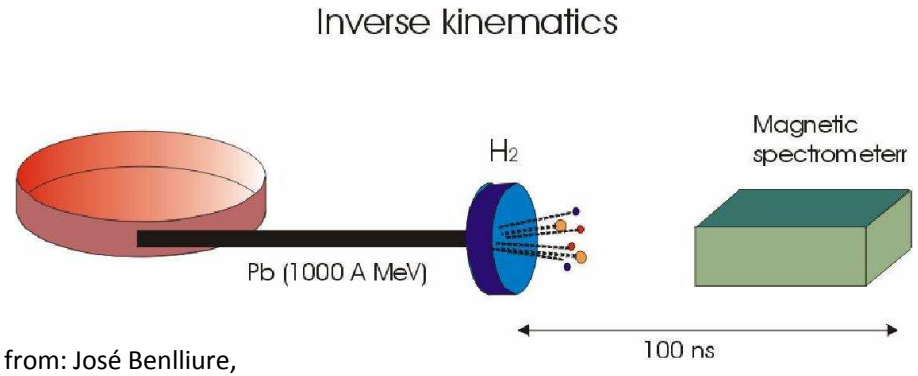
Classification of targets with thickness d in terms of the interaction length $\mu = 1/\Sigma_a$:

thin targets	$d \ll \mu$	**secondaries negligible**
thick targets	$0.1\ \mu < d < 10\ \mu$	**secondaries relevant**
extended targets	$10\ \mu \ll d$	**secondaries dominant**

Classification/terminology
invers/direct reaction kinematics



- target (almost) at rest in laboratory frame
- secondary n and p leave the target
- residues are stopped in the target
- residues are measured off-line via their decay or by mass spectrometry
- fast experiments: full excitation functions
- mostly isobaric distributions are provided
- full kinematical information more difficult



from: José Benlliure,

- target with high velocity in laboratory frame
- residues / secondaries leave target in forward direction
- residues measured on-line via Z,A identification; in-flight magnetic identification
- full isotopic identification
- only selected reactions can be investigated
- long beam times

accelerator experiments (few GeV) provide quantitative basis for model calculations by measuring relevant cross sections and by realistically simulating interactions of galactic protons with extraterrestrial matter under completely controlled conditions

Nuclear Data / exemplary EU-projects

FP5 HINDAS High- and Intermediate Energy Nuclear Data for Accelerator-Driven Systems

http://cdsweb.cern.ch/record/1212694 (147pp)

Experimental and theoretical studies on following elements

1. One shielding material: Fe (n, charged part.)
2. One target element : Pb (n, charged part., residue)
3. One actinide: U (n, residue)

Task 1 : Experiments between 20 and 200 MeV

Task 2 : large set of high-energy experimental data above 200 MeV up to 2 GeV !

Task 3 : Theory (TALYS, INCL, ABLA) and evaluation

FP6 EUROTRANS, (EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System)

www.nuklear-server.ka.fzk.de/eurotrans

NUDATRA

(Nuclear data for transmutation of nuclear waste).

Goal: improve nuclear data evaluated files and models which involves sensitivity analysis and validation of simulation tools, low and intermediate energy nuclear data measurements, nuclear data libraries evaluation at low and medium energies, and high energy experiments and modeling.

…so how to access these data?

http://www.oecd-nea.org/dbdata/databases.htm

NEA Nuclear Energy Agency

NEA search engine Go

OECD

Nuclear Data Services

Nuclear Data Services Databases Access

Database	JANIS*	Description
EVA	YES	A large number of complete evaluated data libraries are available from the EVA database, including JEFF-3.1, JENDL-4.0, ENDF/B-VII, BROND-2.2, CENDL-3.1 and many more. Index and description of libraries in EVA
EXFOR	YES	Contains neutron-induced experimental data, as well as charged-particle and photon-induced data. In addition to storing the data and it's bibliographic information, experimental information, including source of uncertainties, is also compiled.
CINDA	YES	The Computer Index of Nuclear Data contains bibliographical references to measurements, calculations, reviews and evaluations of neutron and charged particle reactions and other microscopic data; it includes cross-references to the EXFOR data base of numerical reaction data.
ENSDF	NO	The Evaluated Nuclear Structure Data File database contains evaluated structure information, including nuclear level properties, radiations, radioactive decay, and reaction data for all known nuclides. For masses A ≥ 45, this information is documented in the *Nuclear Data Sheets*; for A < 45 ENSDF is based on compilations published in the journal *Nuclear Physics*.
NUDAT	NO	The NUclear DATa database contains evaluated numeric data containing adopted levels and gammas, ground and metastable state properties, nuclear half-lives, decay radiations, thermal neutron cross-section data, and resonance integrals.
NSR	NO	The Nuclear Science References database contains bibliographic information on low and intermediate energy nuclear physics, covering the period 1910 to the present.

N.B. The three databases; ENSDF, NUDAT and NSR, are hosted by Brookhaven National Laboratory, USA

JANIS* : Accessible with JANIS software

Last reviewed: 5 October 2012

Projects

Nuclear data
JEFF project
WPEC
HPRL
NRDC

Software

Janis

JANIS 3.4

Services and Resources

JANIS Book

Databases
- EVA
- EXFOR
- CINDA

CD/DVD

Processed data

EXFOR…

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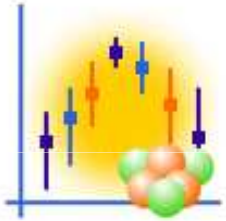
NEA Nuclear Energy Agency

NEA search engine

Nuclear Data Services



EXFOR: Experimental Nuclear Reaction Data

Simple User Form - Advanced Exfor Form (HELP)

Other Databases: EVA, CINDA, Program abstracts
Display software: JANIS

Target	
Element (Z)	Isotope (A)
Not selected	

Constraints		
Energy limits	From (eV)	To (eV)
(eg: 1.3e6)		
Date limits	From (YYYY)	To (YYYY)

(IN,OUT)
Incident particle: Not selected
Outgoing particle: Not selected x (ie: 2 for n,2n)
OR process code: Not selected
OR Reaction string

Retrieve Reset

CINDA: Bibliographical nuclear reaction data

Search form (Cinda manual)

Other Databases: EVA, EXFOR, Program abstracts
Display software: JANIS

Retrieve Reset

Target material

Element (Z):

Isotope (A): select isomer

Compound: select compound

Reaction

(IN,OUT)Q

Incident particle | Outgoing particle

Reaction Quantity
CS Cross section data
CSP Partial cross section data
CST Temperature dependent cross section data
DA Differential data with respect to angle
DAE Differential data with respect to angle and energy
DAP Partial differential data with respect to angle
DE Differential data with respect to energy

(Use the control key to select multiple values)

select OLD reaction type for backwards compatibility

Energy

Min (eV)

Max (eV)

Reference date

From (yyyymm) | To (yyyymm)

First Author:

Reference type: select reference type

Specify a Publication code

From: Journal codes or Book codes or Report codes

Work type: select work type

Laboratory:

Use the 3 letter code from the lab dictionary

Country select country of the work

EXFOR number:

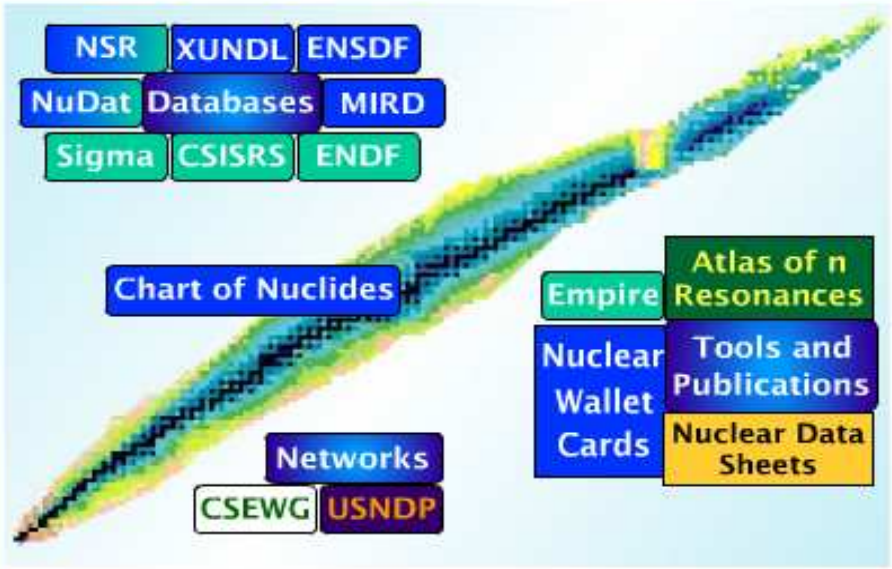
Output presentation: Short
(Default is 'Short')

Output Sort order: Z-A-Reaction-Lab
(Default is 'Z-A-Reaction-Lab')

NNDC National Nuclear Data Center

BROOKHAVEN NATIONAL LABORATORY

Site Index - Go



CSEWG/USNDP November 5-9 2012

CSEWG/USNDP 2012 presentations

ND2013 Abstract Submission closed

Nuclear Wallet Cards for your Android phone!

Nuclear Wallet Cards (8th Edition) Release

http://www.nndc.bnl.gov/

Main | Structure & Decay | Reactions | Bibliography | Networks & Links | Publications | Meetings

AMDC Atomic Mass Data Center, ***Q-value Calculator***

Atlas of Neutron Resonances Parameters & thermal values

CapGam Thermal Neutron Capture γ-rays

Chart of Nuclides Basic properties of atomic nuclei

Covariances of Neutron Reactions

CSEWG Cross Section Evaluation Working Group

CSISRS alias EXFOR Nuclear reaction experimental data

Empire Nuclear reaction model code system, *Reference* ***paper***

ENDF Evaluated Nuclear (reaction) Data File, ***Sigma***

ENSDF Evaluated Nuclear Structure Data File

IRDF International Reactor Dosimetry File

MIRD Medical Internal Radiation Dose

NMMSS & DoE NMIRDC Safeguards & inventory decay data standards

NSR Nuclear Science References

Nuclear Data Sheets Nuclear structure & decay data journal, ***Special Issues*** *on reaction data*

Nuclear Wallet Cards Ground & isomeric states properties, ***Homeland Security*** *version*

NucRates MACS & Astro-physical reaction rates

NuDat Nuclear structure & decay Data

USNDP U.S. Nuclear Data Program

USNDP/CSEWG GForge Collaboration Server

XUNDL Experimental Un-evaluated Nuclear Data List

Help » EXFOR-Manual | NNDC-Help | CSISRS/EXFOR History Submit » Your Data Databases » ENDF | CINDA | NSR

Experimental Nuclear Reaction Data (EXFOR)

Database Version of November 01, 2012

Software Version of 2012.09.19

News

2012/07 Sort by publications with extended view [example]
2012/07 Searching reactions: n,xp; p,xg, etc. [example]
2012/02 Improvements and extensions:
1) Automactic data re-normalization (optional: for plots and output data only) [video]
2) Web-ZVView plotting: clipboard copy/paste
2011/12 Search in CINDA (+NSR) if data not found in EXFOR
[History]

The EXFOR library contains an extensive compilation of experimental nuclear reaction data. Neutron reactions have been compiled systematically since the discovery of the neutron, while charged particle and photon reactions have been covered less extensively.
The library contains data from 19633 experiments (see statistics and recent updates).

Request

Examples: 1 2 3 4 5 6 7 ...

Submit Reset Help

Target
Reaction
Quantity
Product
Energy from to eV
Author(s)
Publication year
Accession #

Extended
Keywords
Expert

Submit Reset

Options
Ranges (Z,A)
Reaction Sub-Fields
Feedback and User's Input
Comments/Questions?
Previously submitted comments

Clone Request:
CINDA ENDF

Tip of the day: video-guide

Note:
- all criteria are optional (selected by checking ☑)
- selected criteria are combined for search with logical AND
- criteria separated in a field by ";" are combined with logical OR
- criteria starting with "^" will be used as logical NOT
- wildcards (*) and intervals (..) are available


International Atomic Energy Agency
Nuclear Data Services
قسم البيانات النووية مقدمة من
http://www-nds.iaea.org/
IAEA.org | NDS Mission
Search
Hot Topics » ENDF/B-VII.1 • TENDL-2011 • JENDL-4 • IBANDL
News » 2012/09/19 JENDL-4.0u Update 2012 of Japanese evaluated nuclear data library 2010
Request
CD/DVD with documentation, data, codes, etc.
Quick Links
NGATLAS
NSR
NuDat 2.6
PADF 2007
PGAA
PHSP
POINT2012
PREPRO
Photon and Electron Interaction Data
Photonuclear
Q-values, Thresholds
RIPL
RNAL
SIGACE
Safeguards Data
SigmaCalc
Spallation models
Specialized Evaluated Libraries
Standards
Stopping Power Data for Light Ions
NEW
JENDL-4.0u Update 2012 of Japanese evaluated nuclear data library 2010 [page] [list] [retrieve]
IRDFF - International Reactor Dosimetry and Fusion File v1.02 [page] [archive] [retrieve]
TENDL-2011 TALYS Evaluated Nuclear Data Library [page] [retrieve]
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ENDF
Evaluated nuclear reaction libraries
ENSDF
evaluated nuclear structure and decay data (+XUNDL) **
NSR
Nuclear Science References *
NuDat 2.6
selected evaluated nuclear structure data **
RIPL
reference parameters for nuclear model calculations
IBANDL
Ion Beam Analysis Nuclear Data Library
Charged particle reference cross section
Beam monitor reactions
PGAA
Prompt gamma rays from neutron capture
FENDL-2.1
Fusion Evaluated Nuclear Data Library, Version 2.1
Photonuclear
cross sections and spectra up to 140MeV
IRDFF
International Reactor Dosimetry and Fusion File
NAA
Neutron Activation Analysis Portal
Safeguards Data
recommendations, August 2008
Medical Portal
Data for Medical Applications
Standards
- Neutron cross-sections, 2006
- Decay data, 2005
*Database at the IAEA, Vienna
**Database at the US NNDC
IAEA Nuclear Data Section
IAEA-NDS Mission, Staff and more
A+M
Atomic and Molecular Data
Meetings Workshops
Newsletters
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NRDC
Nuclear Reaction Data Center Network
NSDD
Nuclear Structure & Decay Data Network
Technical Documents INDC Reports Publications
Computer Codes

International Atomic Energy Agency

Nuclear Data Services

Section Données Nucléaires, AIEA

http://www-nds.iaea.org/spallations/

IAEA.org | NDS Missio

Search

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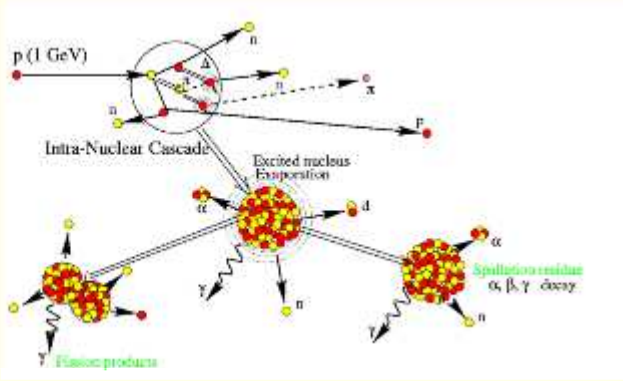
IAEA Benchmark of Spallation Models

Introduction



Spallation reactions are nuclear reactions playing an important role in a wide domain of applications ranging from neutron sources for condensed matter and material studies, transmutation of nuclear waste and rare isotope production to astrophysics, simulation of detector set-ups in nuclear and particle physics experiments, and radiation protection near accelerators or in space.

The simulation tools developed for these domains use nuclear model codes to compute the production yields and characteristics of all the particles and nuclei generated in these reactions. The codes are generally Monte-Carlo implementations of Intra-Nuclear Cascade (INC) or Quantum Molecular Dynamics (QMD) models followed by de-excitation (principally evaporation/fission) models.

The International Atomic Energy Agency (IAEA) and the Abdus Salam International Centre for Theoretical Physics (ICTP) have recently organised an expert meeting on model codes for spallation reactions. The experts have discussed in depth the physics bases and ingredients of the different models in order to understand their strengths and weaknesses. Since it is of great importance to validate on selected experimental data the abilities of the various codes to predict reliably the different quantities relevant for applications, it has been agreed to organise an international benchmark of the different models developed by different groups in the world. The specifications of the benchmark, including the set of selected experimental data to be compared to models, have been fixed during the workshop.

The benchmark is organised under the auspices of IAEA in 2008 and the analysis of the results will be done with the help of an International Advisory Board. The first results discussed at the next Accelerator Applications conference (AccApp'09) to be held in Vienna in May 2009.

Objectives

- **To assess the prediction capabilities of the spallation models** used or that coud be used in the future in high-energy transport codes.
- **To understand the reason for the success or deficiency of the models** in the different mass and energy regions or for the different exit channels
- **To reach a consensus, if possible,** on some of the physics ingredients that should be used in the models.

IAEA Benchmark of Spallation Models – Specifications + Experimental Nuclear Data

- Participation (rules…)
- Domain N + A, 20 MeV to 3 GeV, A≥12, i.e.
  - nucleon-induced reactions on nuclei from C to U
  - mostly >100 MeV, but with a few sets at low incident energies down to 20 MeV, (certain isotopes) 20-150 MeV libraries are not available for all isotopes
  - test physics models (also implemented in high-energy transport codes to compute the production yields and properties of particles and nuclei emitted in a fundamental spallation interaction.

    ⇒ only comparisons with elementary exp. data on thin targets considered
- Model ingredients and parameters

http://www-nds.iaea.org/spallations/spal_spc.html

IAEA Benchmark of Spallation Models – Specifications + Experimental Nuclear Data

Observables of the data base /data and formatting

- particle cross sections ($d^2\sigma/d\Omega dE$ of n, p, π, d, t, ^{3}He, alphas, etc.)
- multiplicities (M_n, M_p , M_π , M_d, M_t, M_{He}, M_{IMF}), + multiplicity distributions
- isotope production (isotopic distributions) Z, A, σ (mb), error (mb) in direct and inverse kinematics
- production cross sections up to 3 GeV (excitation functions)
- isotope production cross sections (isomers)

units energies in MeV, cross-sections and errors in mb

http://www-nds.iaea.org/spallations/spal_spc.html

IAEA Benchmark of Spallation Models – Specifications + Experimental Nuclear Data

JÜLICH FORSCHUNGSZENTRUM

http://www-nds.iaea.org/spallations/spal_spc.html

Observables of the data base /data and formatting

- particle cross sections ($d^2\sigma/d\Omega dE$ of n, p, π, d, t, ^{3}He, alphas, etc.)

Energy		**Angle 1**		**Angle 2**		**...**		**Angle integrated**	
Energy [MeV]	Energy bin [MeV]	$d^2\sigma/d\Omega/dE$ [mb/sr/MeV]	error [mb/sr/MeV]	$d^2\sigma/d\Omega/dE$ [mb/sr/MeV]	error [mb/sr/MeV]	.	.	$d\sigma/dE$ [mb/MeV]	error [mb/MeV]
E1	ΔE1	.	.	.	.	.	.	.	.
E2	ΔE2	.	.	.	.	.	.	.	.
...	...	.	.	.	.	.	.	.	.
Energy integrated $d\sigma/d\Omega$[mb/sr] error[mb/sr]		.	.	.	.	.	.	**Energy and Angle integrated** σ[mb] error[mb]	

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IAEA Benchmark of Spallation Models - Experimental Data

Participants should preferably calculate the whole set of quantities (highlighted in the tables below) for which experimental data are given. The following list has been chosen as limited as possible but covering the full range of energy, mass and reaction channels considered appropriate for the present benchmark.

Full archives: [mandatory][additional]

Double differential cross section (neutron)

Proj.	Targ.	E (MeV)	Reference	Lab.	EXFOR	Figure
n	^{nat}Fe	65	E.L.Hjort et al., Phys.Rev.C.53(1996)237	UC Davis, USA	13522	[fig]
p	^{nat}Fe	800	W.B.Amian et al., Nucl.Sci.Eng.112(1992)78	LANL, USA	C0170	[fig]
p	^{nat}Fe	800	S.Leray et al., Phys.Rev.C65(2002)044621	Saturn, France	O0977	[fig]
p	^{nat}Fe	1200	S.Leray et al., Phys.Rev.C65(2002)044621	Saturn, France	O0977	[fig]
p	^{nat}Fe	1600	S.Leray et al., Phys.Rev.C65(2002)044621	Saturn, France	O0977	[fig]
p	^{nat}Fe	3000	K.Ishibashi et al., J.Nucl.Sci.Tech.34(1997)529	KEK, Japan	E1762	[fig]
p	^{nat}Pb	256	M.M.Meier et al., Nucl.Sci.Eng.110(1992)289	LANL, USA	C0168	[fig]
p	^{nat}Pb	800	W.B.Amian et al., Nucl.Sci.Eng.112(1992)78	LANL, USA	C0170	[fig]
p	^{nat}Pb	800	S.Leray et al., Phys.Rev.C65(2002)044621	Saturn, France	O0977	[fig]
p	^{nat}Pb	1200	S.Leray et al., Phys.Rev.C65(2002)044621	Saturn, France	O0977	[fig]
p	^{nat}Pb	1600	S.Leray et al., Phys.Rev.C65(2002)044621	Saturn, France	O0977	[fig]
p	^{nat}Pb	3000	K.Ishibashi et al., J.Nucl.Sci.Tech.34(1997)529	KEK, Japan	E1762	[fig]
p	^{208}Pb	63	A.Guertin et al., Eur.Phys.J.A23(2005)49	Louvain, Belgium	O1146	[fig]

Double differential cross section (proton)

Proj.	Targ.	E (MeV)	Reference	Lab.	EXFOR	Figure
n	^{209}Bi	542	J.Franz et al., Nucl.Phys.A510(1990)774	PSI, Switzerland	22173	[fig]
p	^{197}Au	1200	A.Budzanowski et al., Phys.Rev.C78(2008)024603	COSY, Germany	D0512	[fig]
p	^{197}Au	2500	A.Bubak et al., Phys.Rev.C76(2007)014618	COSY, Germany	D0514	[fig]
p	^{197}Au	2500	A.Letourneau et al., Nucl.Phys.A712(2002)133	COSY, Germany	D0579	[fig]
p	^{209}Bi	62	F.E.Bertrand et al., Phys.Rev.C8(1973)1045	ORNL, USA	O0294	[fig]
p	^{56}Fe	62	F.E.Bertrand et al., Phys.Rev.C8(1973)1045	ORNL, USA	O0294	[fig]
p	^{nat}Ni	175	S.V.Fortsch et al., Phys.Rev.C43(1991)691	iTHEMBA, South Africa	O0173	[fig]
p	^{nat}Ni	175	A.Budzanowski et al., Phys.Rev.C80(2009)054604	COSY, Germany	C1763	[fig]
p	^{208}Pb	63	A.Guertin et al., Eur.Phys.J.A23(2005)49	Louvain, Belgium	O1146	[fig]
p	^{208}Pb	800	R.E.Chrien et al., Phys.Rev.C21(1980)1014	LANL, USA	C0665	[fig]

IAEA Benchmark of Spallation Models - Experimental Data

- Double differential cross sections (n, p, d, t, ^{3}He,^{4}He, π^{-}, π^{+})
- Mass distributions
- Charge distributions
- Isotope distributions
- Neutron multiplicity distributions
- Excitation functions (isotopic, mass, charge)
- …

Website and tools to analyze results fully operational

⇒ Continue benchmark in a dynamic way,
i.e. add new experimental data, new versions of models
(in progress OECD/NEA framework for next benchmark…)

Few examples of Evaluated Results
Benchmark data/calculations

Specification of the 1997 NEA International Codes and Model Intercomparison for Intermediate Energy Activation Yields

R. Michel: cross section data base for production rates of cosmogenic nuclides and production rate ratios

O-16 Be-7, Be-10, C-11, C-14

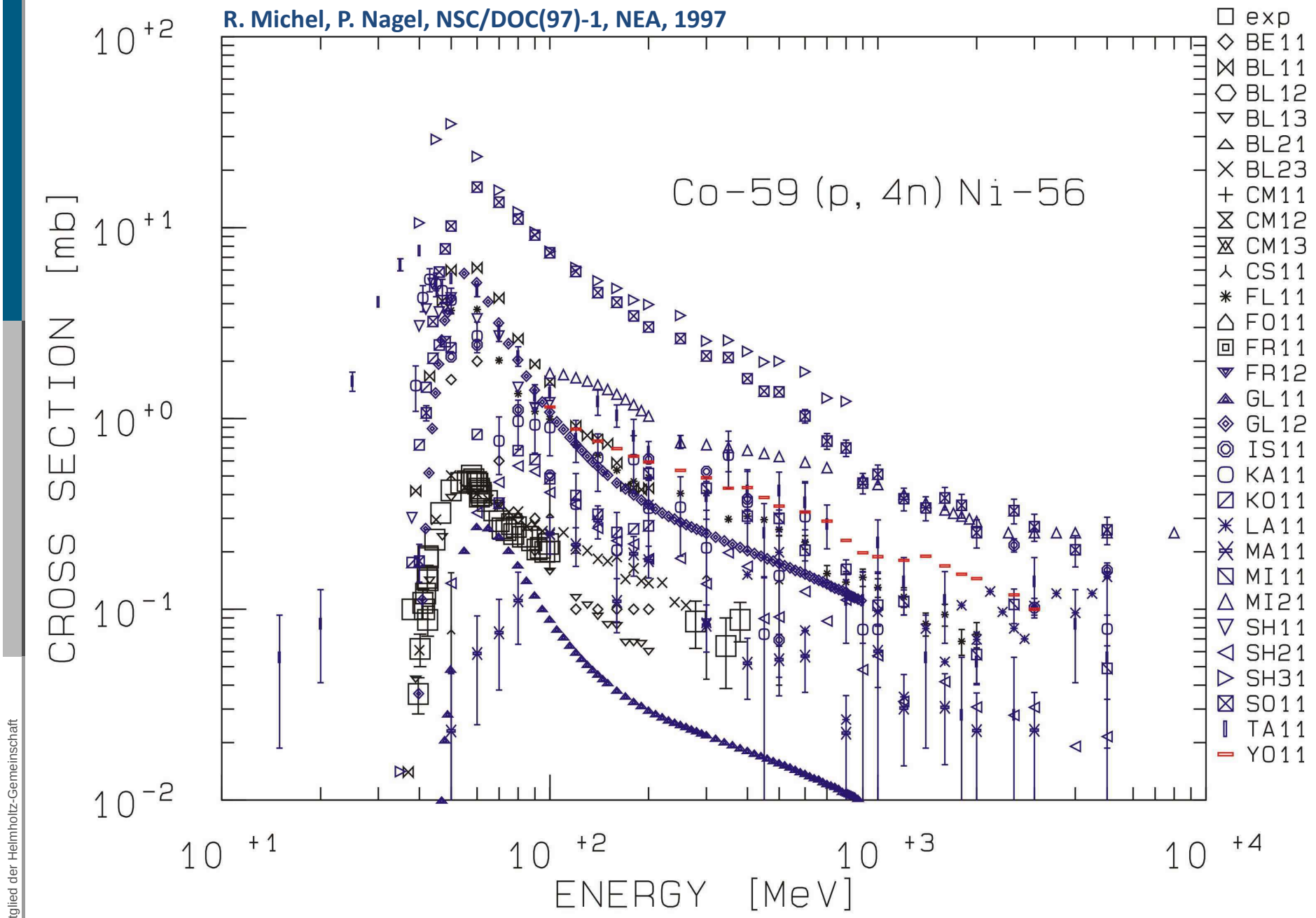
Al-27 H-3, He-3, He-4, Be-7, Be-10, Na-22 (Mg-22), Na-24 (Ne-26), (Si-26)

Fe (nat) H-3, He-3, He-4, Be-7, Be-10, Ne-20 (all mass 20 nuclides), Ne-21 (all mass 21 nuclides),Ne-22 (F-22), Na-22 (Mg-22), Na-24 (Ne-24), Mg-28 (Na-28), Al-26 (Si-26), Cl-36, Ar-36 (K-36, Ca-36), Ar-38 (all mass 38 nuclides), Sc-46, V-48 (Cr-48), Cr-51 (Mn-51, Fe-51),Mn-52m+g (Fe-52), Mn-53 (Fe-53, Co-53), Mn-54, Fe-55 (Co-55, Ni-55), Co-56

Co-59 Co-56, Co-57, Co-58, Ni-56, Ni-57

Zr (nat) Be-7, Na-22 (Mg-22), Sc-46, V-48, (Cr-48)), Cr-51 (Mn-51, Fe-51), Mn-54, Co-56 (Ni-56),Co-58, Co-60, Zn-65 (Ga-65, Ge-65), Ga-67 (Ge-67, As-67), Ge-69 (As-69, Se-69), As-71(Se-71, Br-71, Kr-71) As-74, Se-75 (Br-75, Kr-75, Rb-75), Br-77 (Kr-77, Rb-77, Sr-77), Kr-78(Br-78, Rb-78), Kr-79 (Rb-79, Sr-79), Kr-80 (Br-80, Rb-80, Sr-80, Y-80), Kr-81 (Rb-81, Sr-81,Y-81, Zr-81), Kr-82 (Br-82, Rb-82, Sr-82, Y-82, Zr-82), Kr-83 (all mass 83 nuclides), Kr-84(Br-84, Se-84, Rb-84), Kr-85 (Se-85, Br-85), Kr-86 (Se-86, Br-86, Rb-86), Rb-83 (Sr-83, Y-83, Zr-83), Rb-84, Rb-86, Sr-82 (Y-82, Zr-82), Sr-83 (Y-83, Zr-83), Sr-85 (Y-85, Zr-85, Nb-85), Y-86 (Zr-86, Nb-86), Y-86m, Y-87 (Zr-87, Nb-87), Y-87m, Y-88 (Zr-88, Nb-88), Zr-86(Nb-86), Zr-88 (Nb-88), Zr-89 (Nb-89), Zr-95 (Y-95), Nb-90, Nb-92m, Nb-95, Nb-95m, Nb-96

Au-197 Be-7, Na-22 (Mg-22), Na-24 (Ne-24), Sc-46, V-48 (Cr-48), Mn-54, Fe-59 (Mn-59), Co-56 (Ni-56), Co-58, Co-60, Zn-65 (Ga-65, Ge-65), As-74, Se-75 (Br-75, Kr-75, Rb-75), Rb-83 (Sr-83,Y-83, Zr-83), Rb-84, Rb-86, Sr-85 (Y-85, Zr-85, Nb-85), Y-87 (Zr-87, Nb-87), Y-88 (Zr-88, Nb-88), Zr-88 (Nb-88), Zr-89 (Nb-89), Zr-95 (Y-95), Nb-95 (Rb-95, Sr-95, Y-95, Zr-95), Tc-96,Ru-103 (Nb-103, Mo-103, Tc-103), Rh-102, Ag-105 (Cd-105, In-105), Ag-110m, Ag-110,Sn-113 (Sb-113, Te-113, I-113, Xe-113), Te-121 (I-121, Xe-121, Cs-121, Ba-121), Te-121m,Te-121m+g, Xe-127 (Cs-127, Ba-127, La-127), Ba-131 (La-131, Ce-131), Ce-139 (Pr-139,Nd-139, Pm-139, Sm-139), Eu-145 (Gd-145), Eu-147 (Gd-147, Tb-147), Eu-148, Eu-149 (Gd-149, Tb-149, Dy-149, Ho-149), Gd-146 (Tb-146), Gd-147 (Tb-147, Dy-147), Gd-149 (Tb-149,Dy-149, Ho-149), Gd-151 (Tb-151, Dy-151, Ho-151), Gd-153 (Tb-153, Dy-153, Ho-153),Tb-149 (Dy-149, Ho-149), Tb-151 (Dy-151, Ho-151), Tb-153 (Dy-153, Ho-153), Tm-165 (Y-165, Lu-165, Hf-165), Tm-166 (Y-166, Lu-166, Hf-166, Ta-166, W-166), Tm-167 (Y-167, Hf-167, Ta-167), Tm-168, Yb-166 (lu-166, Hf-166, Ta-166), Yb-169 (Lu-169, Hf-169, Ta-169) ,Lu-169 (Hf-169, Ta-169), Lu-170 (Hf-170, Ta-170), Lu-171 (Hf-171, Ta-171), Lu-172 (Hf-172,Ta-172), Lu-173 (Hf-173, Ta-173), Hf-172 (Ta-172, W-172, Re-172), Hf-173 (Ta-173, W-173),Hf-175 (Ta-175, Re-175, Os-175), Re-181 (Os-181, Ir-181), Re-182 (Os-182, Ir-182, Pt-182),Re-183 (Os-183, Ir-183, Pt-183, Au-183), Os-182 (Ir-182, Pt-182, Au-182, Hg-182), Os-185(Ir-185, Pt-185, Au-185, Hg-185), Os-191 (Re-191), Ir-185 (Pt-185, Au-185, Hg-185), Ir-186(Pt-186, Au-186, Hg-186), Ir-187 (Pt-187, Au-187, Hg-187), Ir-188 (Pt-188, Au-188, Hg-188),Ir-189 (Pt-189, Au-189, Hg-189), Ir-190, Ir-192, Pt-188 (Au-188, Hg-188), Pt-191 (Au-191,Hg-191), Au-193 (Hg-193), Au-194 (Hg-194), Au-195 (Hg-195), Au-196, Hg-193, Hg-194,Hg-195, Hg-195m, Hg-197, Hg-197m



ITEP (Moscow) experiments with targets irradiated by upto 2.6GeV protons

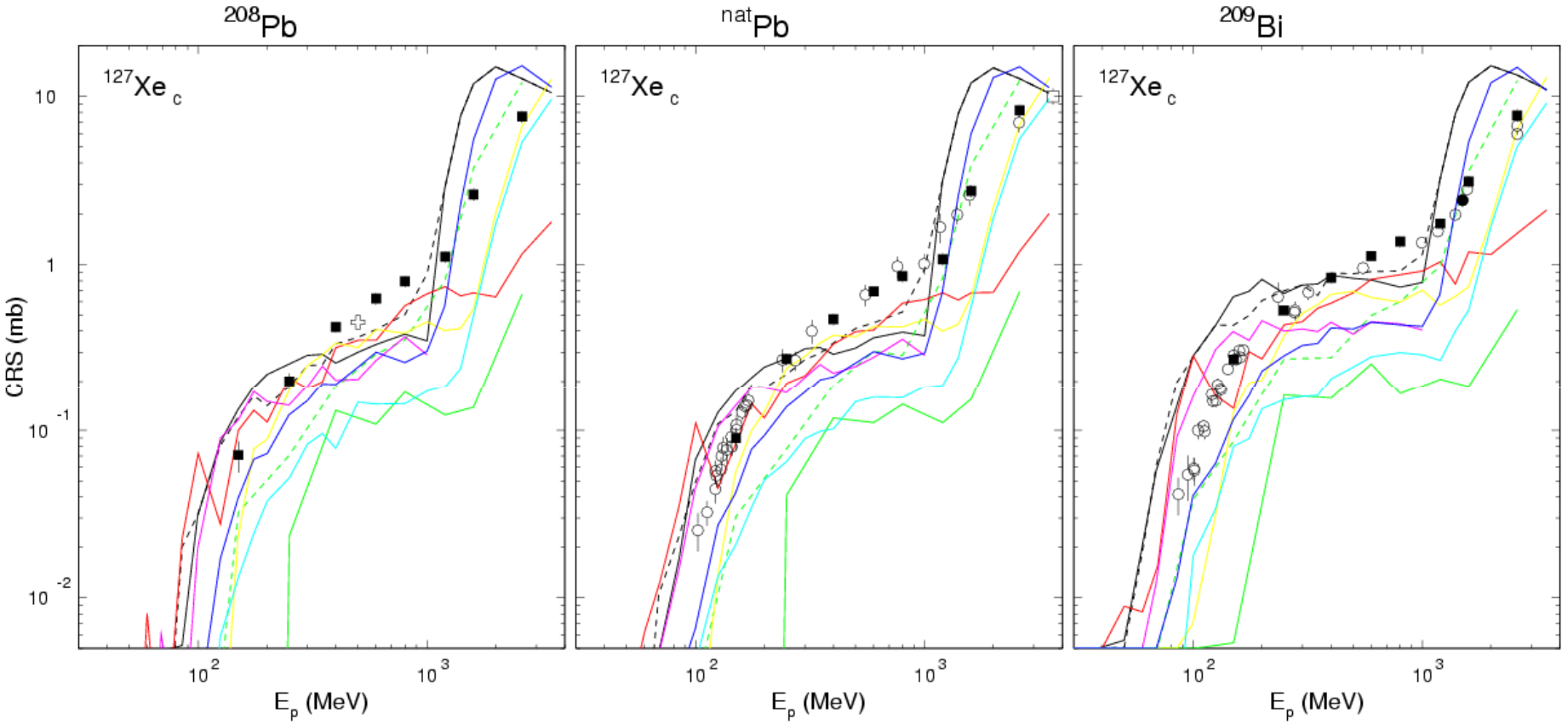
	THIN Targets	THICK Targets	Critical experiments (fuel cycle, …)
ISTC Projects	#839-0, #839 (1997-2001) #2002 (2002-2004) #3266 (2006-2009)	#1145 (1999-2001) #2405 (2005-2007)	#017 (1994-1996) #1145 (1999-2001)
Current Results	More than 10000 CRS's measured and published in IAEA and OECD web sites. Data are used for: 1)designs 2)physics models verification	More than 2500 reaction rates measured. Data are used for activation excitation functions verification	• ^{237}Np RI's; • Th-cycle major reactions; • Subcriticality • MA fission rates were measured.
Perspectives	Mo, Ti, Zr, Th&U?	1)Pb-target activation. 2)Actinide(n,f) CRS in ADS-spectrum	Th-cycle in ADS

Major facilities at ITEP:

- Proton synchrotron (E_p=40-2600MeV, $<I_p>$~10^{11}p/s
- MAKET critical facility (heavy water zero-power reactor, ~100W power)

Trieste08_Titarenko 10000...data fission...

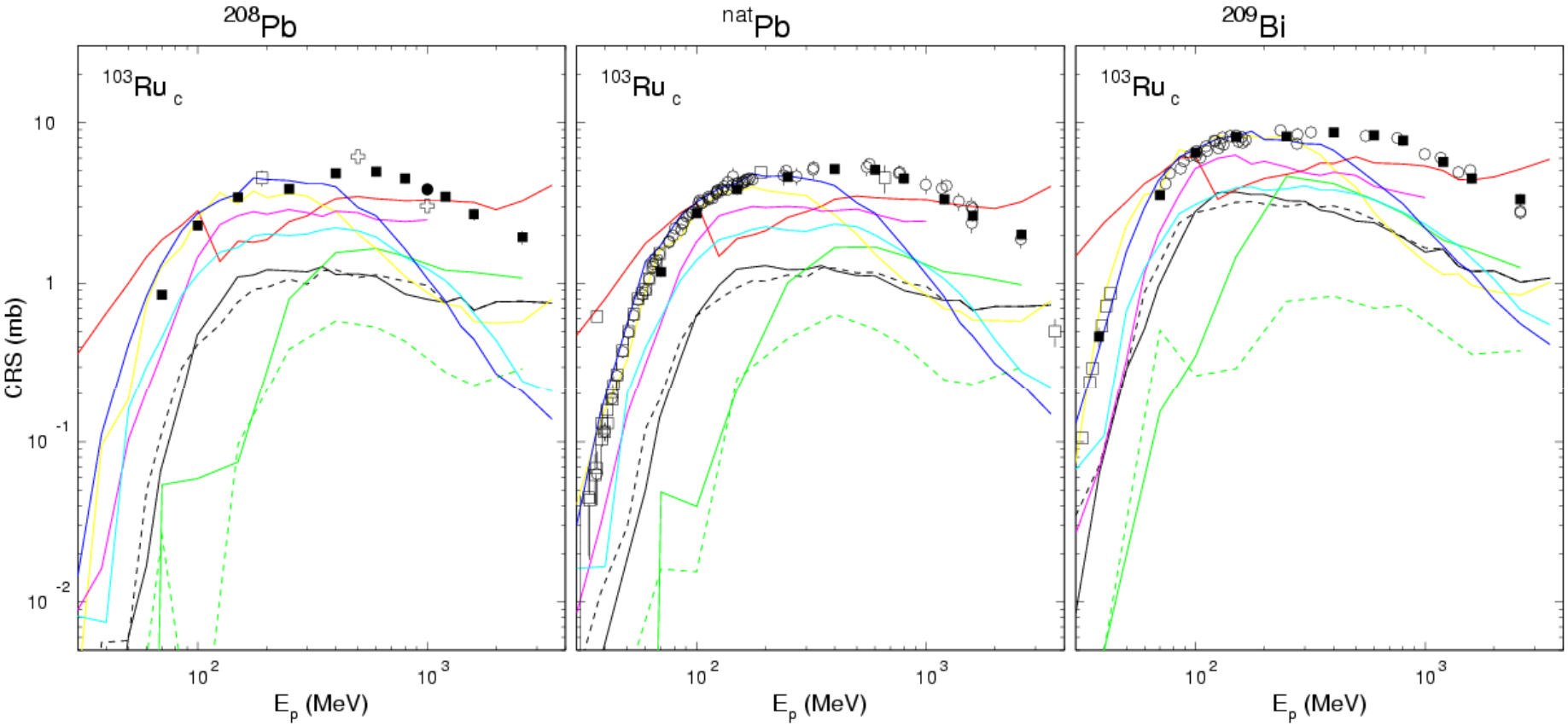
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Spallation+Fission products



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✣ - *GSI*, □ - *others*

^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fission products



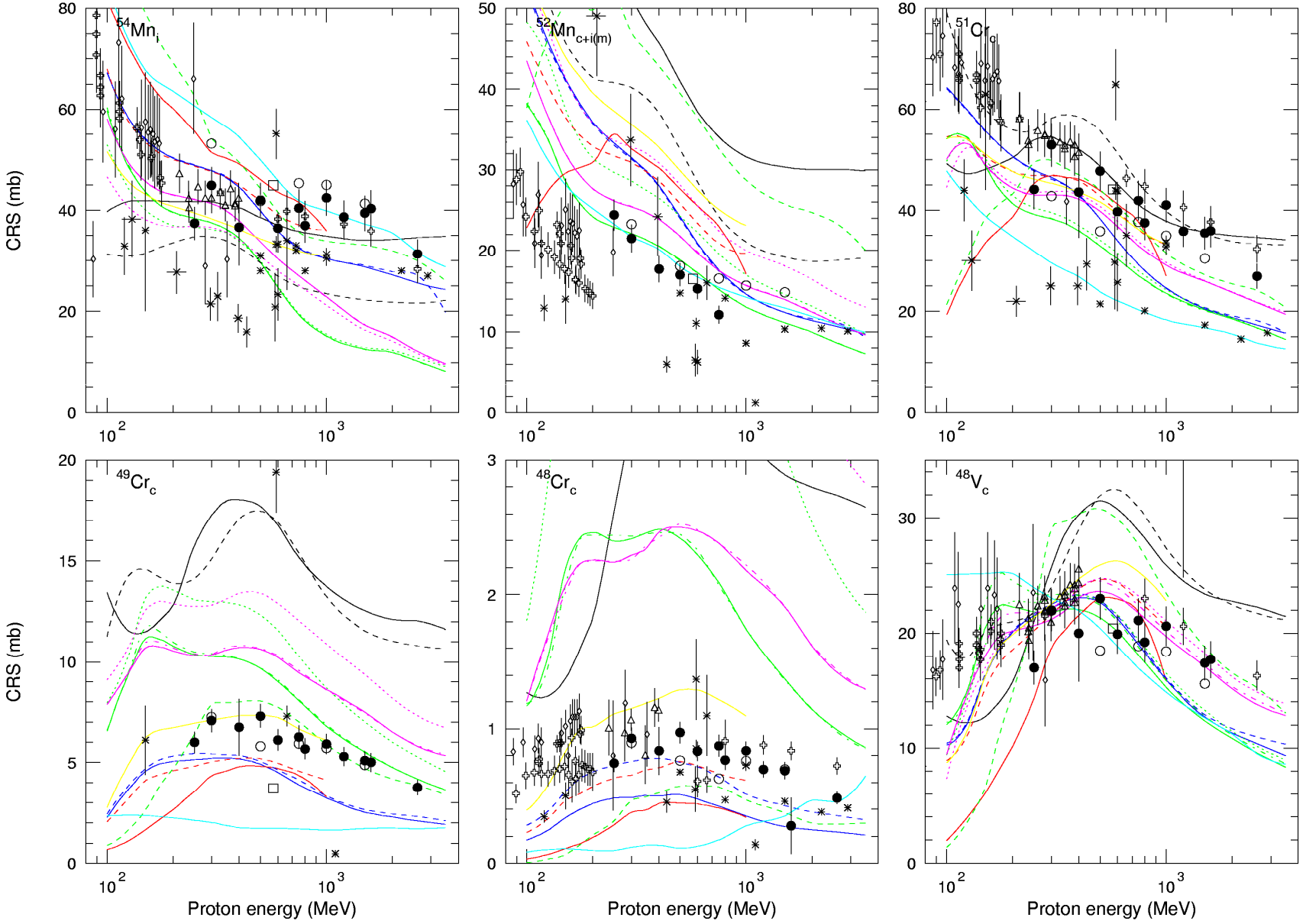
LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✣ - *GSI*, □ - *others*

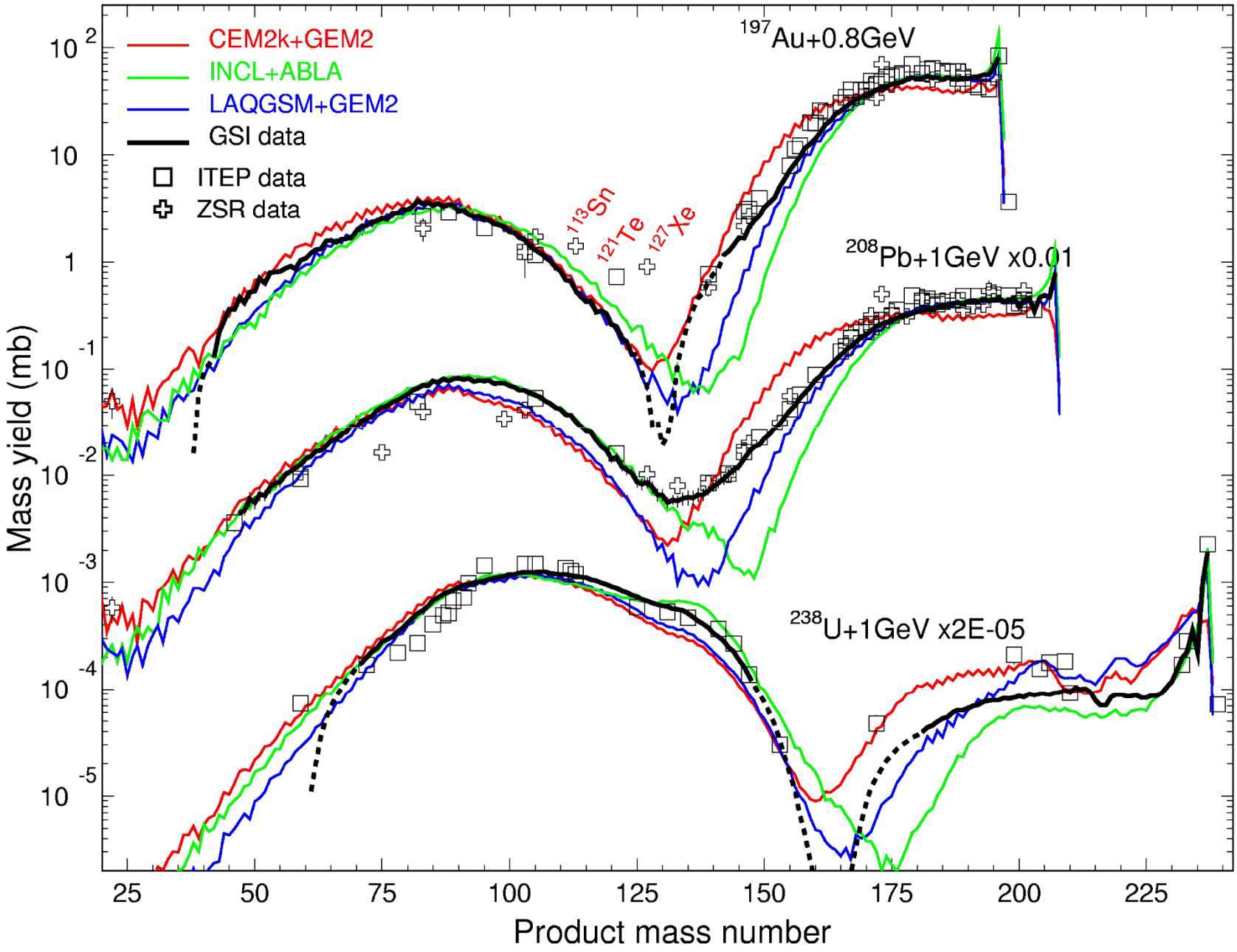
^{56}Fe(p,x)

INCL/MCNPX (solid) BRIEFF (dashed)
CEM03.01 (solid) CEM2k/MCNPX (dashed) CEM03.G1 (dotted) CEM03.S1 (dashed-dotted)
BERTINI (MCNPX - solid, LAHET- dashed)
ISABEL (MCNPX - solid, LAHET- dashed)
LAQGSM03.01 (solid) LAQGSM03.G1(dotted) LAQGSM03.S1(dashed-dotted)
CASCADE-2004
LAHETO

- ITEP (This work)
- GSI (C. Villagrasa-Canton et al.)
- ZSR (R. Michel et al.)
- Th. Schiekel et al.
- M. Fassbender et al.
- SATURNE (W.R. Webber et al.)
- Others



Product mass distributions (GSI, ITEP, ZSR)

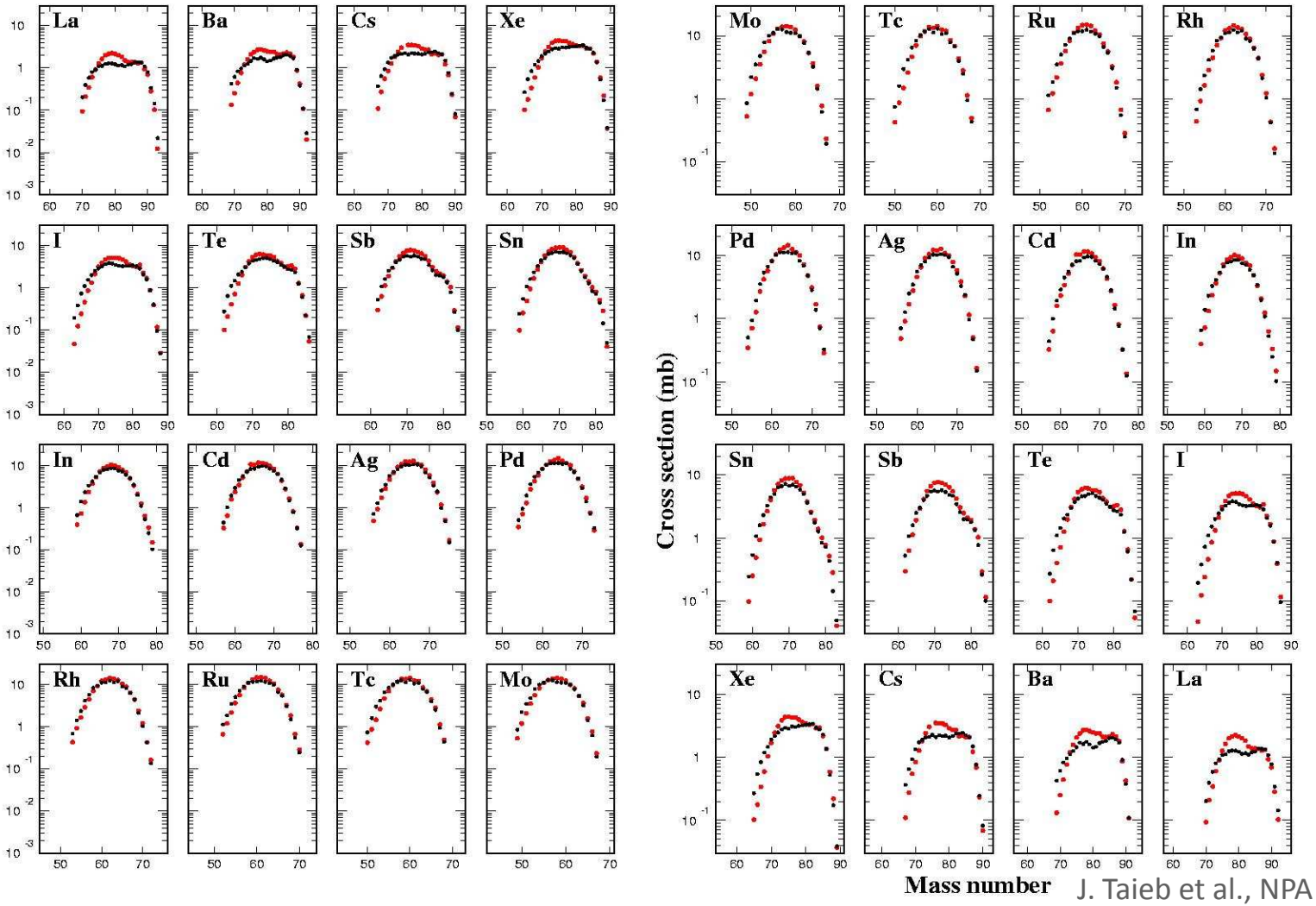


Isotopic Production Cross Sections

Fission residues

^{238}U(1 A GeV) + p

^{238}U(1 A GeV) + d

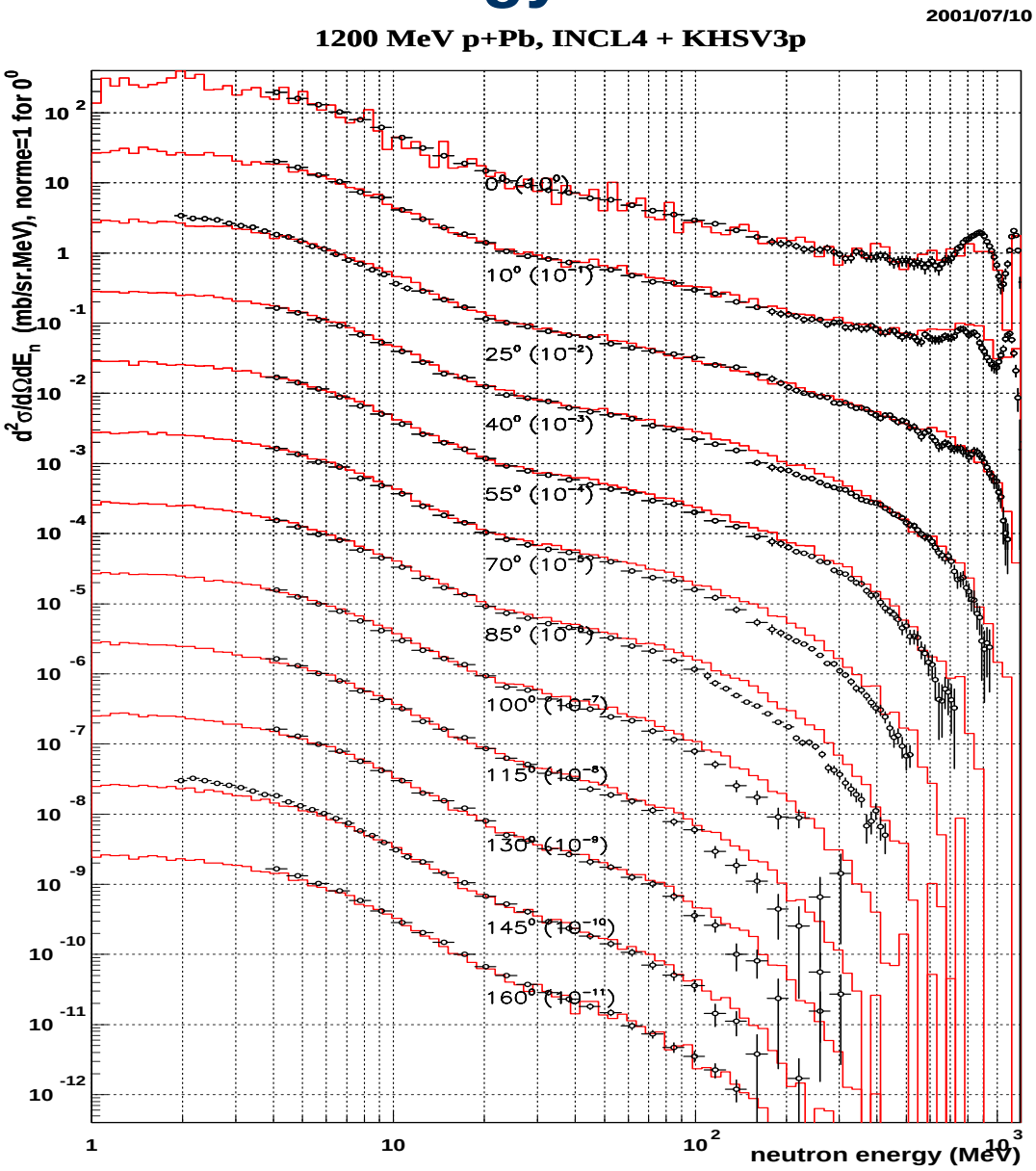


J. Taieb et al., NPA 724 (2003) 413

J. Pereira et al., PRC 75 (2007) 014602

from: José Benlliure, Advanced Workshop on Spallation ModelsICTP-Trieste, Feb. 4-8, 2008

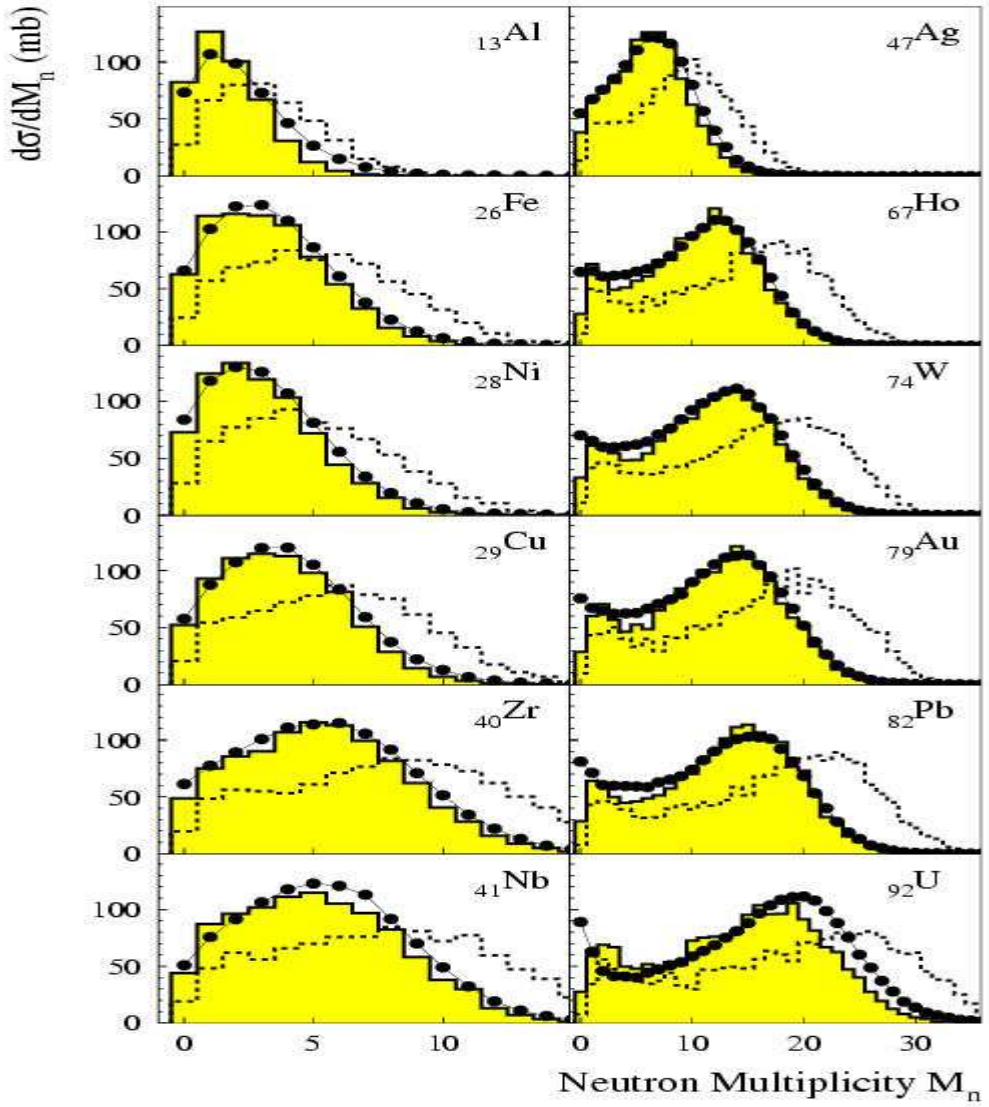
Neutron energy ddxs 1.2GeV p+Pb



Neutrons:
Generally good
Agreement with
Model desciption

Saturne Data 1.2GeV p +Pb
INCL4.2

Neutron multiplicity distributions for 1.2 GeV p+Al,...,U

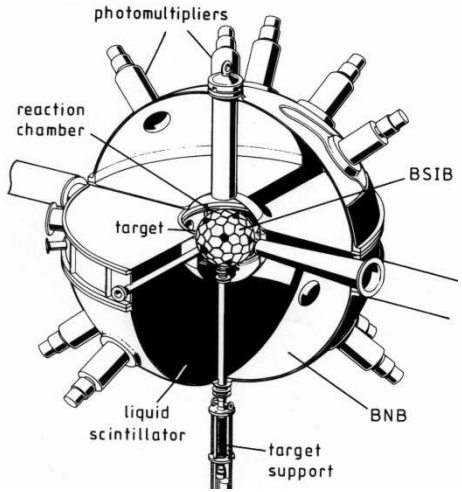


measured (symbols) and calculated (histograms) neutron multiplicity distributions.

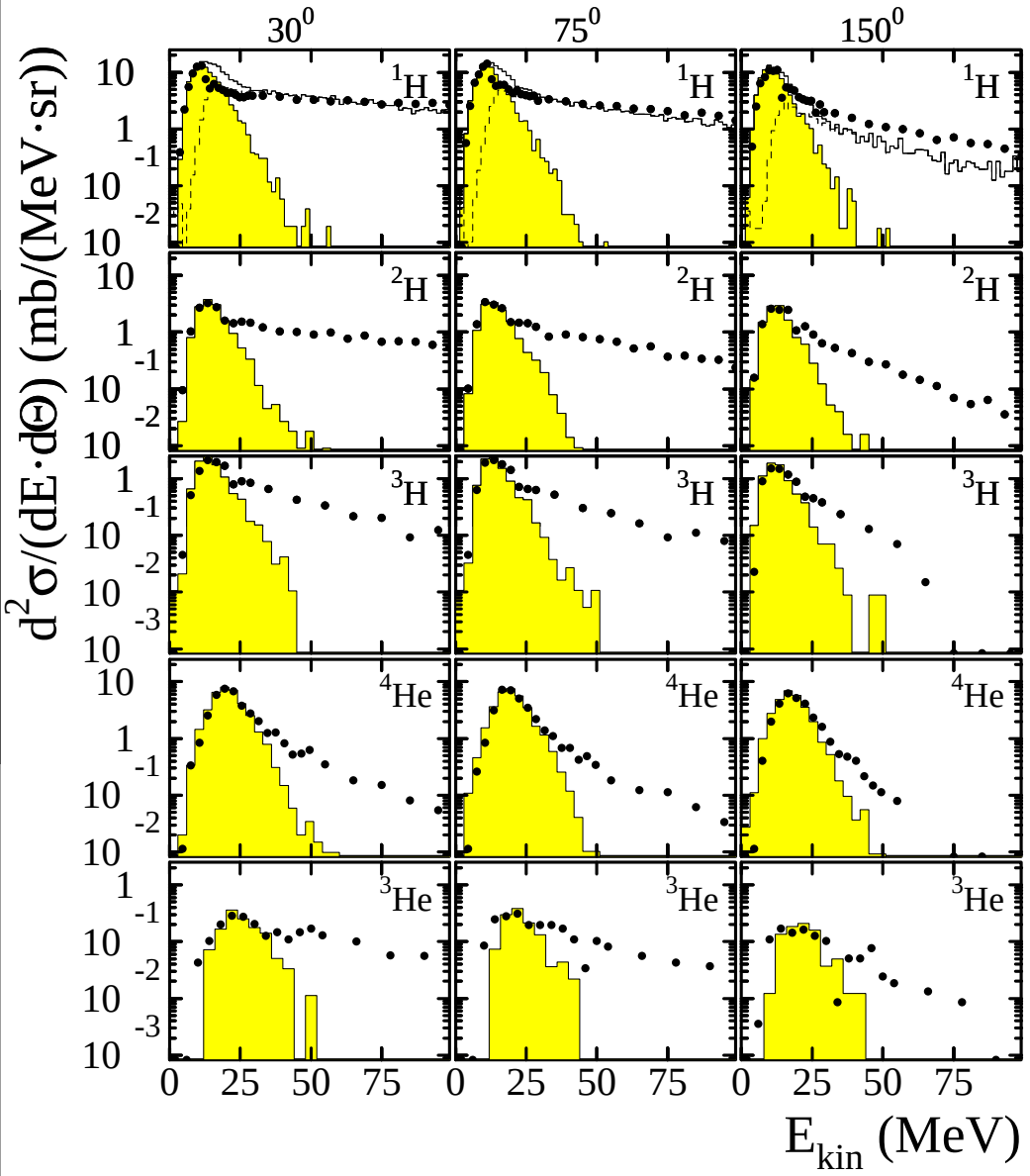
calculated (INCL+GEMINI) distributions are shown before (dashed histogram) and after (shaded histogram) folding with the neutron energy dependent detector efficiency.

note different M_n scales for the left and the right panels.

Neutrons:
Generally good
Agreement with
Model desciption



Energy spectra of ^{1,2,3}H and ^{3,4}He (NESSI)



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1.2 GeV p+Ta

@30, 75 and 150⁰ for the reaction 1.2 GeV p +Ta

dots: experimental data
→ clearly feature two components!

shaded histos: calculated evaporation spectra

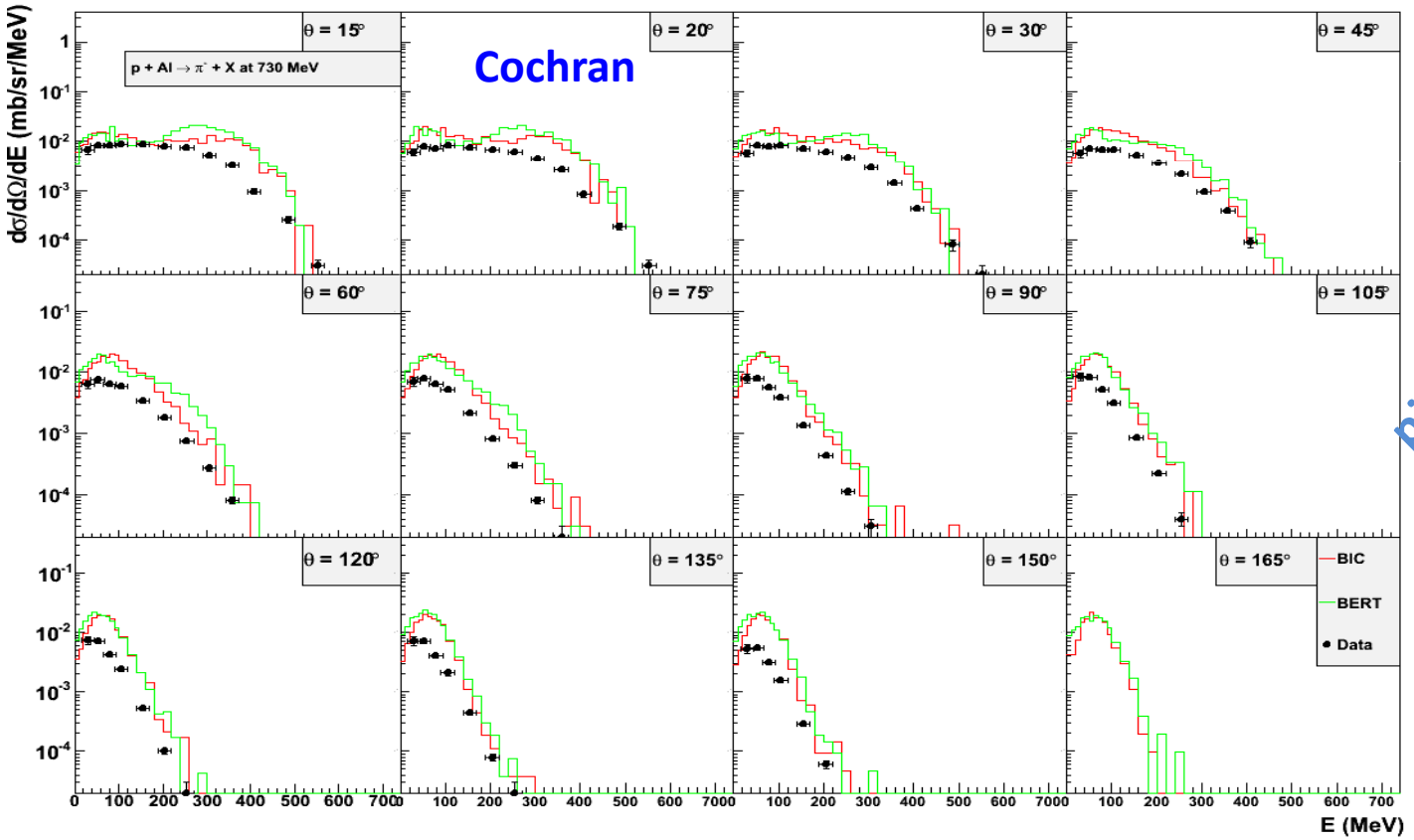
dashed histo: INC-protons

LCPs:
Generally less good Agreement (i.p. tails!) with Model desciptions

see talk by Alain Boudard

Pion data

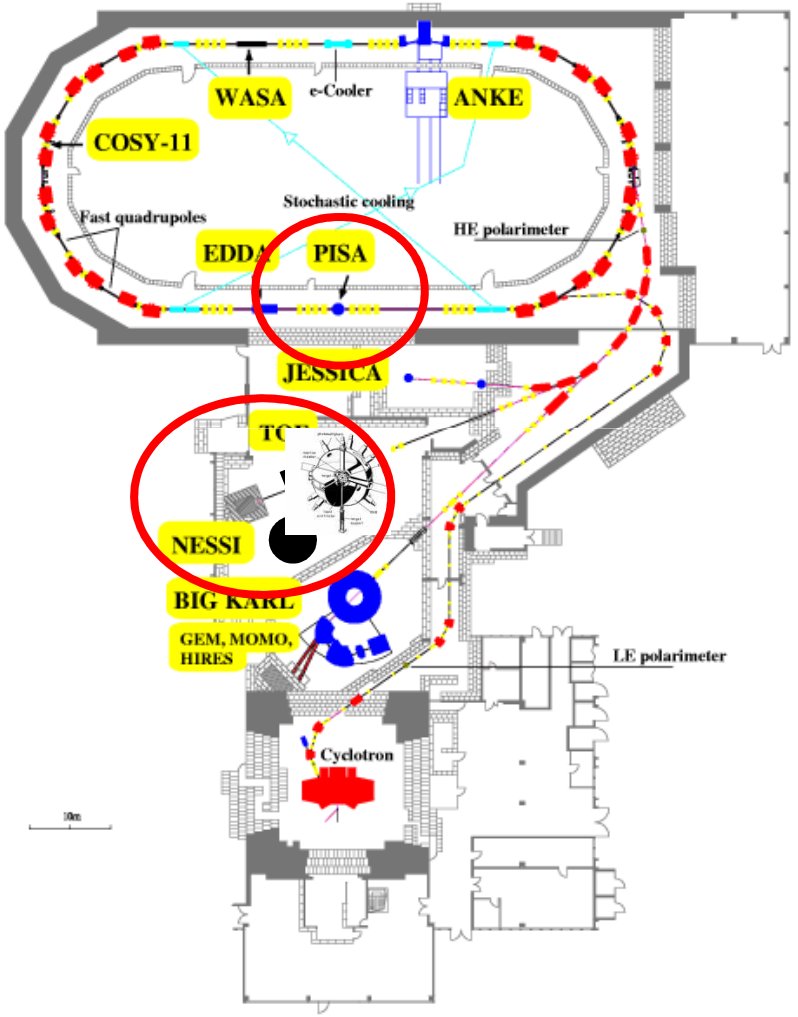
- **Pion double differential cross-sections (p,xπ)**
  - ➢ **Cochran data p, π+, π-, 743 MeV, Phys. Rev. D 6, 3085 (1972)**
  - ➢ **PSI 590 MeV π+, π- several targets**
  - ➢ **H. En'yo et al., 3 GeV/c, Phy. Lett B159, Issue 1, 12 (1985)**



pions: scarce information found in literature

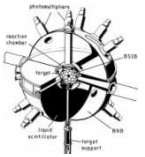
Facilities

Schematic layout of the COSY (FZJ, Germany) (COoler SYnchrotron) facility (p,d<2.5GeV)



NESSI (external experiment)

NEutron
Scintillator and
SIlicium detector

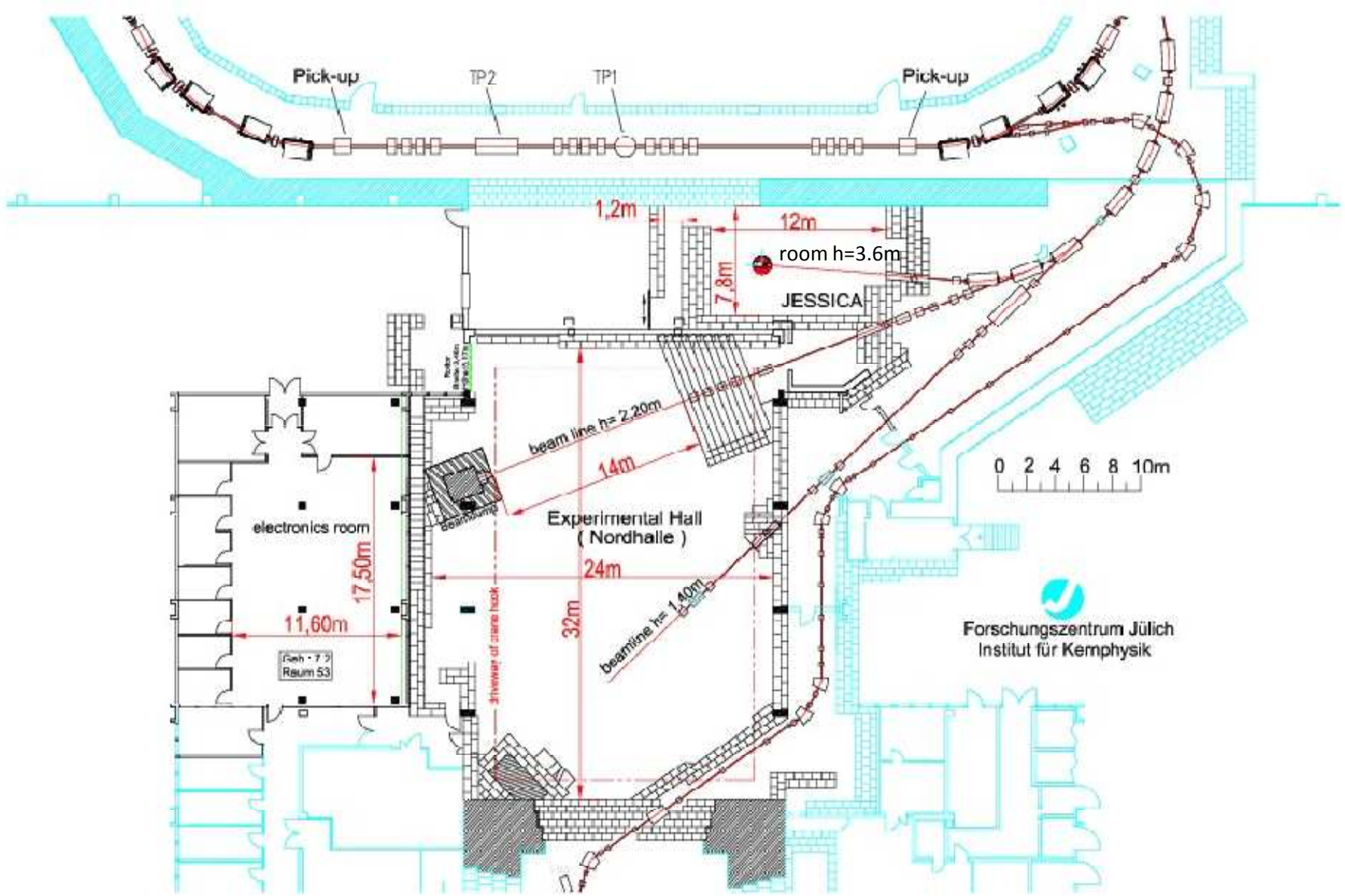


PISA (internal experiment)

Proton
Iinduced
SpAllation

- Energy range: 150 MeV – 2.5GeV
- Luminosity: $6.6*10^{34}$ $cm^{-2}s^{-1}$
- Low absorption, small energy loss of ejectiles due to target thicknesses (down to 50 µg/cm^2)

External beam areas



COSY Beam Parameters:

Energy range
0.045 – 2.8 GeV (p)
0.023 – 2.3 GeV (d)
(momentum 3.7 GeV/c)

Cooling (transverse & longitudinal)
2 methods:
electron, stochastic
$\Delta p/p \leq 5 \cdot 10^{-5}$

Polarization
p, d beams & targets

Beams
internal, extracted

Activities, Experiments, detectors
ANKE, TOF, WASA, EDM, PAX, …

COSY Beam Parameters… cont'd

- **beam quality:**
  - without cooling: $\Delta p/p \sim 2 \cdot 10^{-4}$
  - electron cooling: $\Delta p/p \leq 5 \cdot 10^{-5}$ p_p<0.6 GeV/c
  - stochastic cooling: $\Delta p/p \leq 5 \cdot 10^{-5}$ p_p>1.5 GeV/c

    $\varepsilon = \pi$ mm mrad 1mmØ·0,18°
- **beam intensities (cooled):**
  - protons, unpolarized: $1 \cdot 10^{11}$
  - protons, polarized: $1 \cdot 10^{10}$
  - deuterons, unpolarized: $1 \cdot 10^{11}$
  - deuterons, polarized: $6 \cdot 10^{9}$ (by stacking)

- **extracted beam:**
  - 10^5 ... 10^9 protons/s in spill
  - slow extraction: 10 s ... > 10 min spill, quasi-DC beam

    10(5) s inter-spill (un)cooled
  - fast extraction: $2 \cdot 10^9$ protons in 200 ns, every 15 s

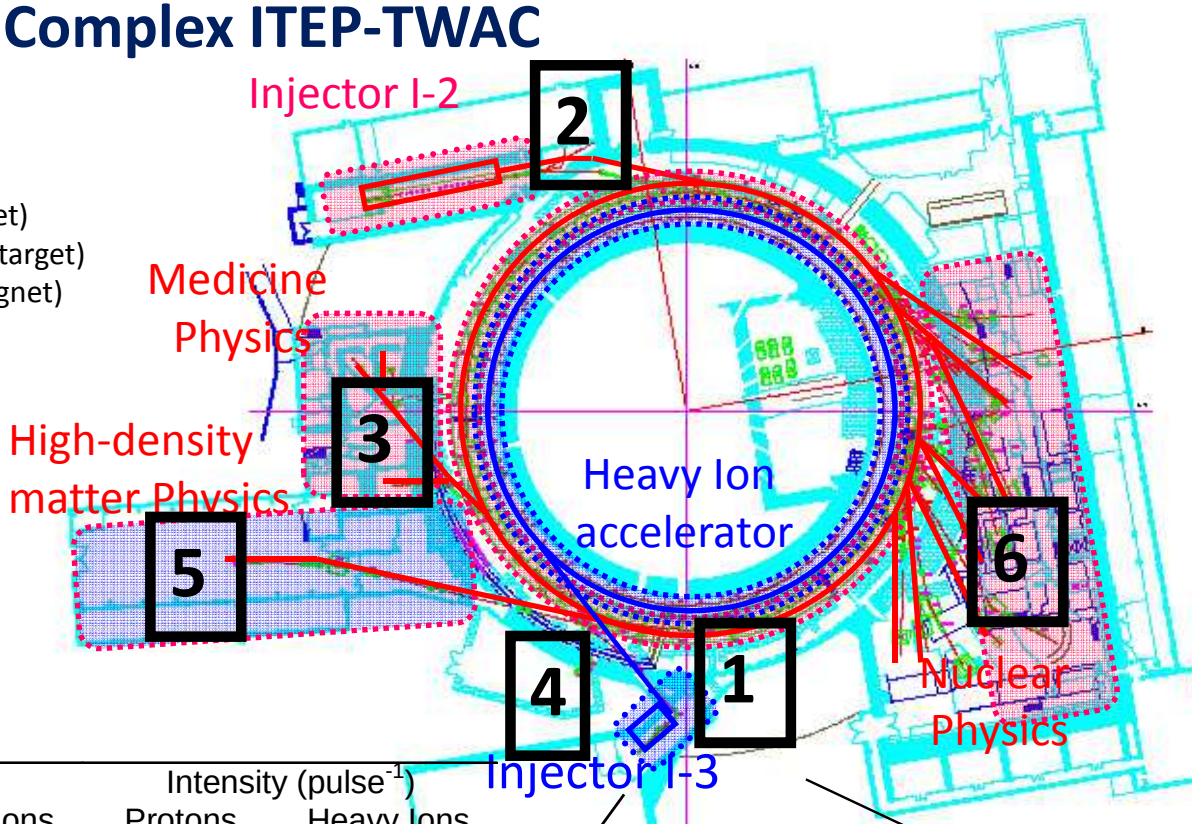
Accelerator-Accumulator Complex ITEP-TWAC

Main parameters:

Energy:	Any from 25MeV to 9.3GeV
Intensity:	<1E12 p/pulse (fast via kicker magnet)
	~1E5-1E6 p/pulse (slow via internal target)
	~1E10 p/pulse (slow via septum magnet)
Pulse rate:	~15pulses/min
Pulse	~100ns (fast)
Duration:	up to ~500ms (slow)

Species:

Proton – since 1961
^{12}C – since 2002
^{27}Al – to be put in ~Dec2007
^{56}Fe – to be put in ~Mar2008
^{238}U – to be put ~Dec2008



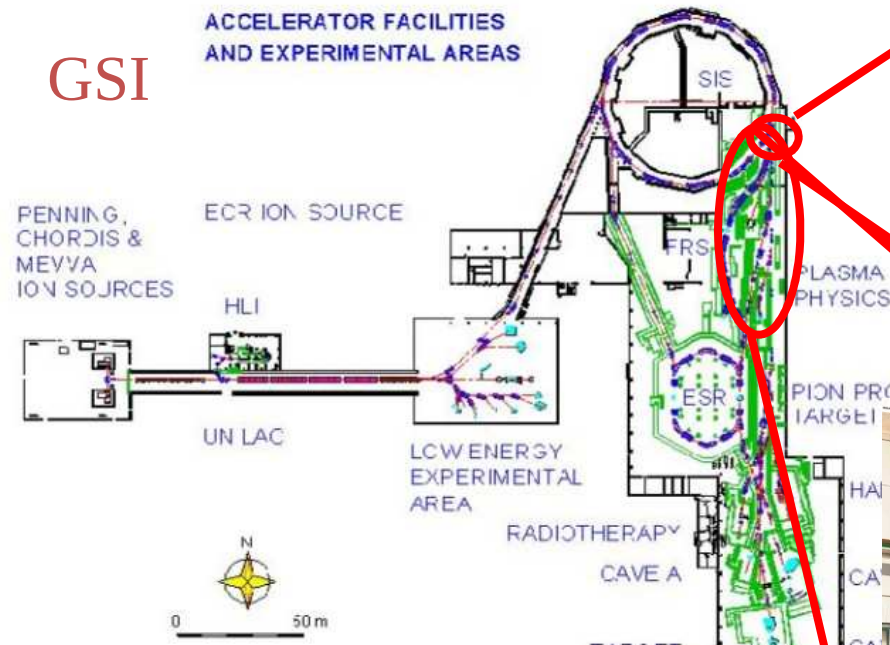
Beam parameters:

№	Site	Energies		Intensity (pulse^{-1})	
		Protons	Heavy Ions	Protons	Heavy Ions
1	I-3: Heavy Ion injector	-	$^{12}C^{6+}$, $^{56}Fe^{15+}$, $^{238}U^{28+}$, 0.1-2 MeV/A	-	~10^9 -10^{11}
2	I-2: Proton Injector	<25MeV	-	~1*10^{12}	-
3	Medical beam	<250MeV	-	≤1*10^{10}	-
4	Fast extraction , Magnet Hall	<4GeV/c	<4ZGeV/c	≤1*10^{12}	~10^9 -10^{11}
5	Fast extraction , Experimental Hall #120	<4GeV/c	<4ZGeV/c	-	~1*10^8 (up to 1*10^{10} in future)
6	Slow extraction, Main Exp Hall	<10GeV/c	<10ZGeV/c	10^5-10^6	-/-

Experimental technique: setup

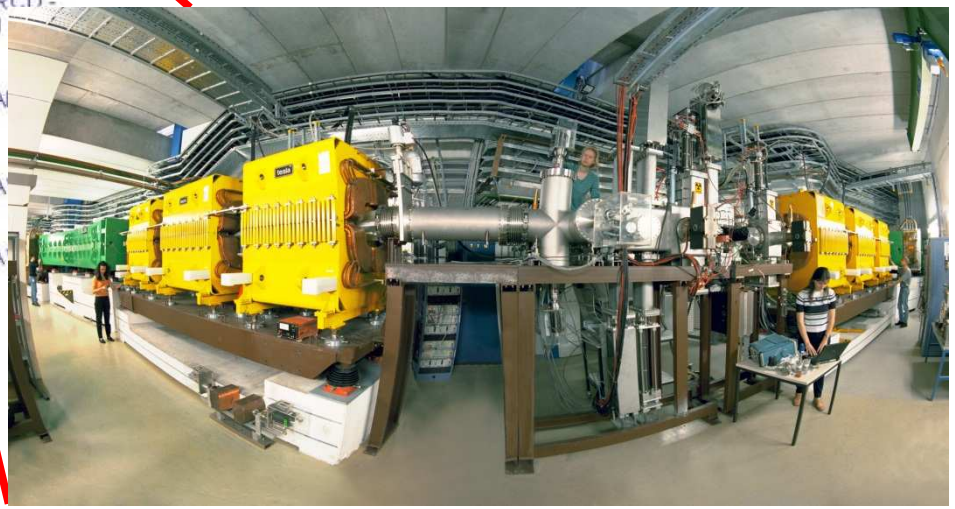
Gesellschaft fur Schwerionenforschung (GSI)

Relativistic heavy-ion beams
- pulsed beams (~ 4 s spill, 8 s cycle)
- 200 A MeV – 1000 A MeV



Secondary Electron Monitor (SEETRAM)

Cryogenic target (1 cm thickness)
- 1 cm thick., Ti windows (36 mg/cm2)
- H_2 (87 mg/cm_2), D_2 (201 mg/cm^2)



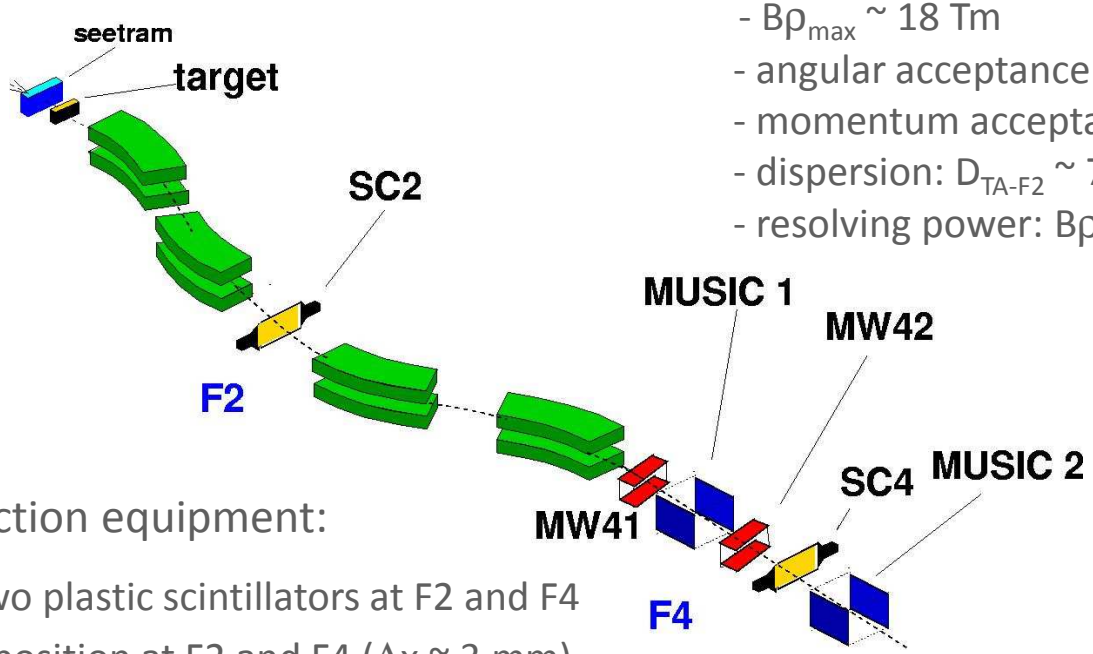
from: José Benlliure, Advanced Workshop on Spallation Models ICTP-Trieste, Feb. 4-8, 2008

Experimental technique:setup

FRagment Separator (FRS)

Two-stage, zero degree achromatic spemetrometer:

- $B\rho_{max}$ ~ 18 Tm
- angular acceptance: $\Delta\theta$ ~ 15 mrad
- momentum acceptance: $\Delta p/p$ ~ 3%
- dispersion: D_{TA-F2} ~ 7 cm/% (F2 image plane ~ 20 cm)
- resolving power: $B\rho/\Delta B\rho$ ~ 1500



Detection equipment:

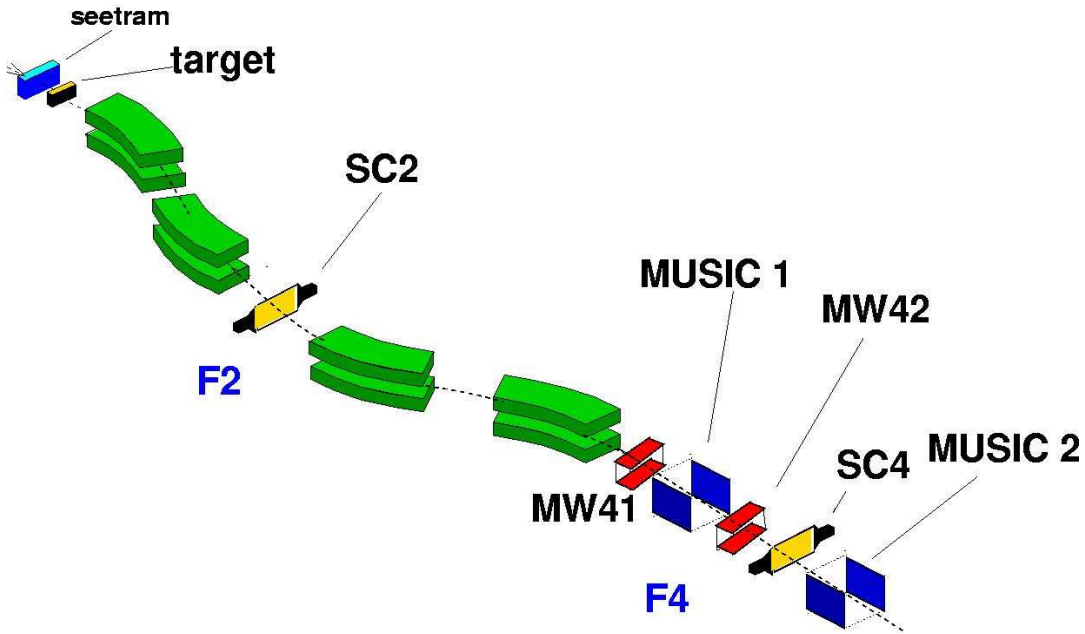
- Two plastic scintillators at F2 and F4
  position at F2 and F4 (Δx ~ 3 mm)
  F2-F4 Time of Flight (ΔToF ~ 150 ps)
- Multi-Sampling Ionisation Chamber (MUSIC)
  dE/dx, position and angle
- Multi-wire chambers for position calibrations

$$\frac{A}{Q} \propto \frac{B\rho}{\beta\gamma}$$

from: José Benlliure, Advanced Workshop on Spallation ModelsICTP-Trieste, Feb. 4-8, 2008

Experimental technique:setup

Fragment Separator (FRS)



✓ (A/Z) identification: $\frac{A}{Z} \propto \frac{B\rho}{\beta\gamma}$

$$\begin{cases} B\rho = (B\rho)_0 \cdot \left(1 - \frac{x_2 - M_2 x_4}{D_1}\right) \\ \beta\gamma = \frac{L}{c \cdot ToF} \cdot \left(1 - \frac{L^2}{c^2 \cdot ToF^2}\right)^{-1/2} \end{cases}$$

✓ Z identification: $Z \propto \sqrt{dE/dx}$

✓ Longitudinal velocities:

$$v \rightarrow \beta\gamma = \frac{Z}{A} B\rho$$

from: José Benlliure, Advanced Workshop on Spallation ModelsICTP-Trieste, Feb. 4-8, 2008

Summary

- ✓ large data sets on n-,p-,LCP-ddxs, n-multiplicities, multiplicitiy distributions, excitation functions, mass-, charge-, isotopic-distributions, residual nuclei in spallation reactions have been obtained at GSI, ZSR, FZJ, ITEP, Saturne, LANL, KEK, BNL, Lovain, PSI, ...

- ✓ Several 10000 cross sections have been determined with an accuracy between 5 and 30%

- ✓ Comprehensive, sytematic and representative coverage of particle
  - types: protons, neutrons, He-4
  - target elements: from C,N,O,… to U
  - product nuclides: $1 \leq A \leq AT + 1$
  - energies: 10 – 10,000 MeV

- ✓ NEA intercomparison, Hindas, Eurotrans, IAEA-benchmark, ITEP initiatives…

It will not be possible to measure all data needed. One has largely to rely on calculated data.

To do:
Solve discrepancies between different sets of data (composite LCP, residues)
Solve deficiencies of models…