# Neutron production in neutron induced reaction at 96 MeV on iron and lead

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# Neutron production in neutron-induced reactions at 96 MeV on iron and lead

## Introduction – Motivation

## Experimental setup

- DECOI-DEMON
- CLODIA-SCANDAL

## Experimental results

- Double Differential Cross Section
- Elastic Cross Section
- Angular distributions
- Energy distributions

## Theoretical calculations

## Cross section analysis

## Conclusion - Summary

# Introduction – Motivation

Accelerator-Driven System
intense proton beam + spallation target + subcritical reactor core

large amount of products : neutron & light charged particles
from some MeV to the GeV region

under 20 MeV : nuclear data libraries ~ complete
above 200 MeV : Intra Nuclear Cascade / experimental data

from 20 to 200 MeV : few high-quality data
particularly for (n,Xn) measurements

## Introduction – Motivation

French research program
- GEDE(PE)ON

European research program
- HINDAS (5$^{th}$ PCRD)
- EUROTRANS-NUDATRA (6$^{th}$ PCRD)

**Double Differential Cross Section**
**for neutrons and light charged particles production**
**in neutron or proton-induced reactions**
**on lead, iron and uranium**
**in the 20-200 MeV energy range**

## Introduction – Motivation

~ Cyclone (Louvain-la-neuve, Belgium)
n & p @ 63 MeV on Fe, Pb and U (n & p d t $^{3}$He $^{4}$He)

~ TSL (Uppsala, Sweden)
n @ 96 MeV on Fe, Pb and U (p d t $^{3}$He $^{4}$He)

~ KVI (Groningen, Nederland)
p @ 140 MeV on Fe, Pb and U (p d t $^{3}$He $^{4}$He)

**~ TSL (Uppsala, Sweden)**
**n @ 96 MeV on Fe and Pb (n)**

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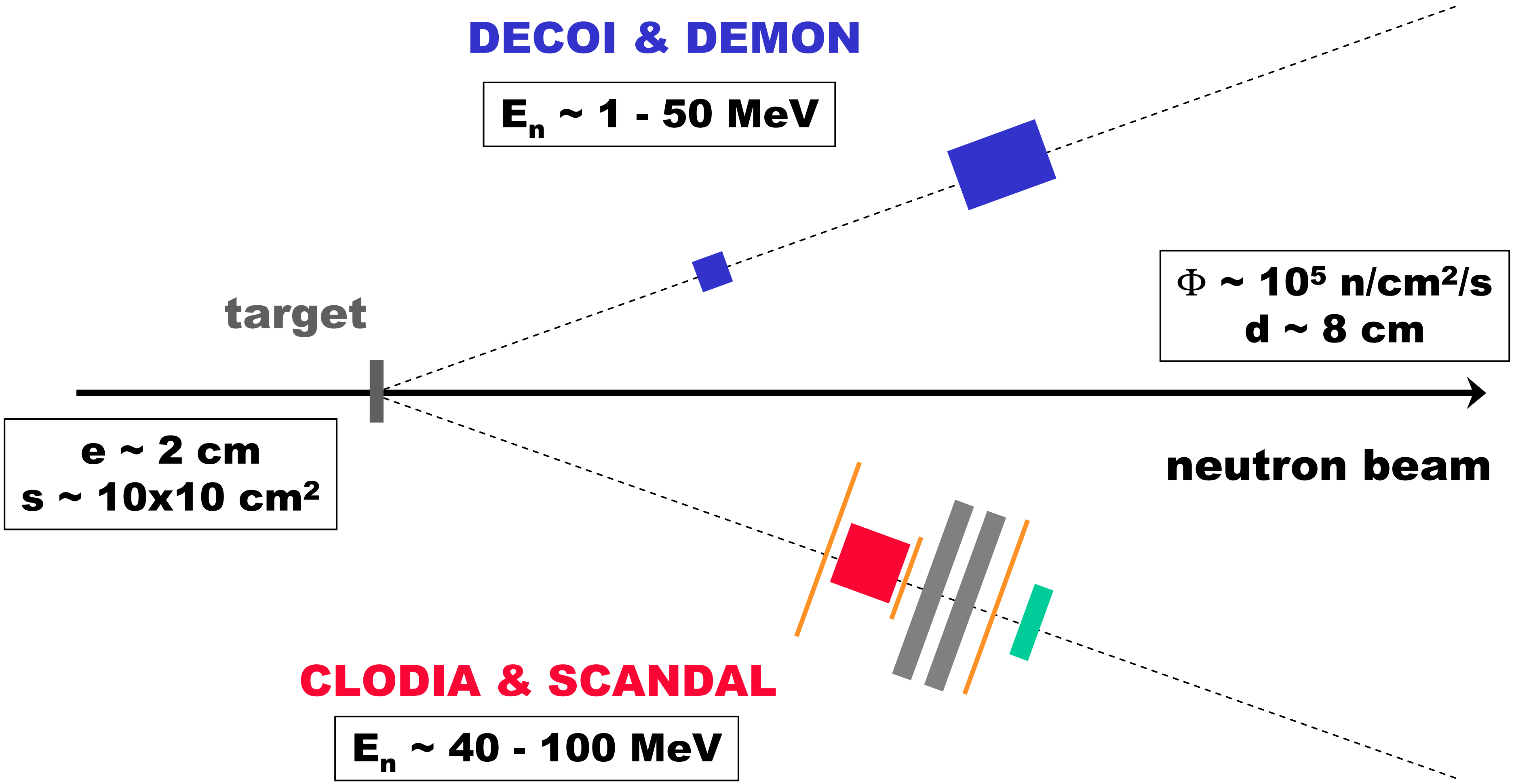
## Experimental setup



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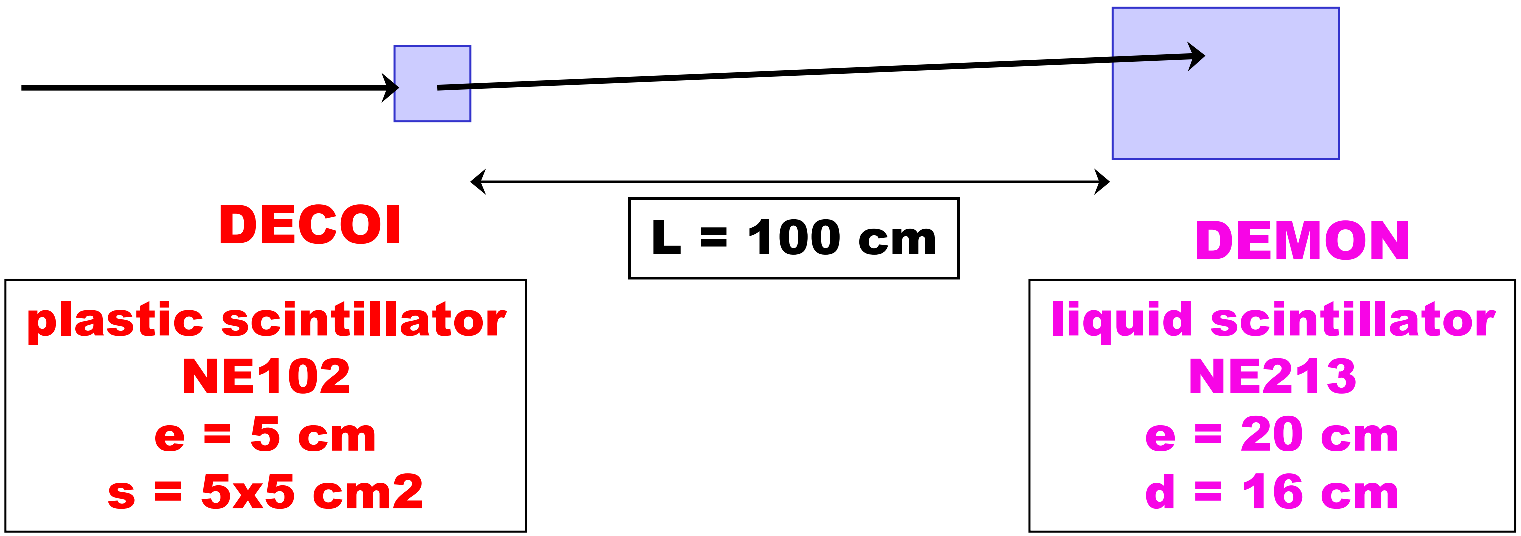
## Experimental setup : DECOI-DEMON (1 – 50 MeV)

~ detection principle : H(n,n) reaction (DECOI)

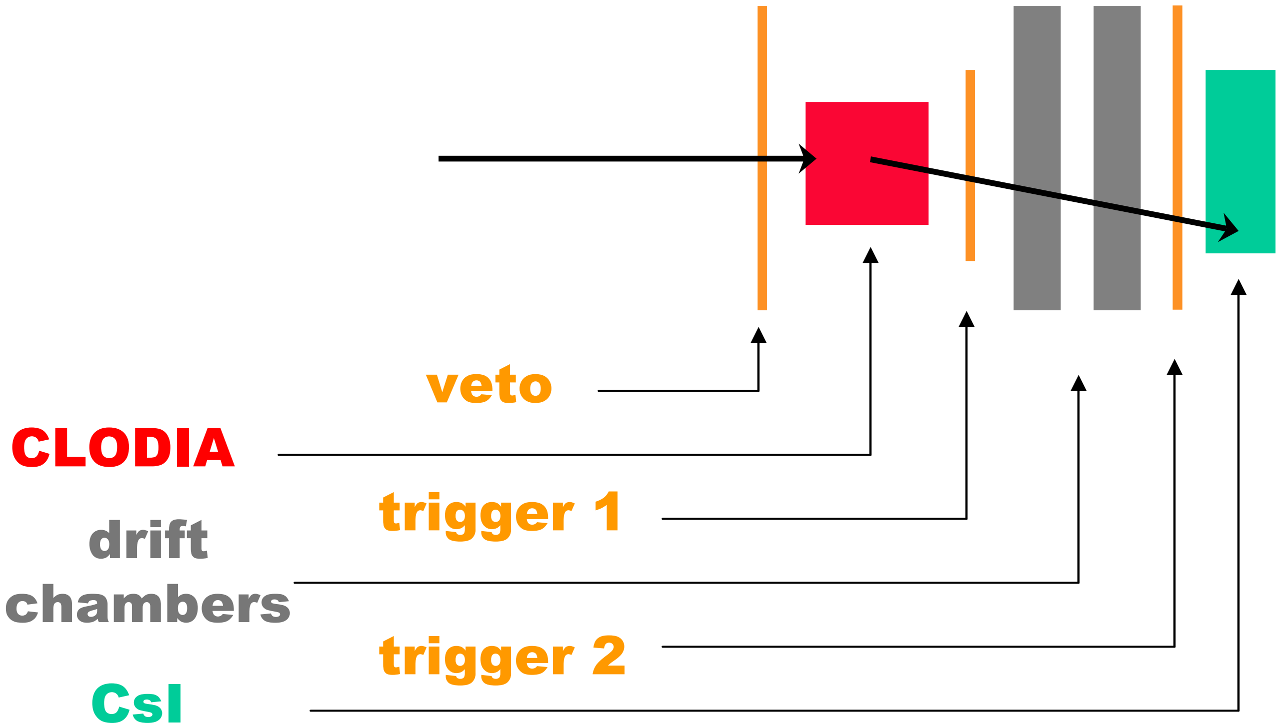
~ energy measurement : time-of-flight (DECOI-DEMON)



# Experimental setup : CLODIA-SCANDAL (40 – 100 MeV)

~ detection principle : H(n,p) reaction (CLODIA)

~ energy measurement : recoiling proton (SCANDAL)



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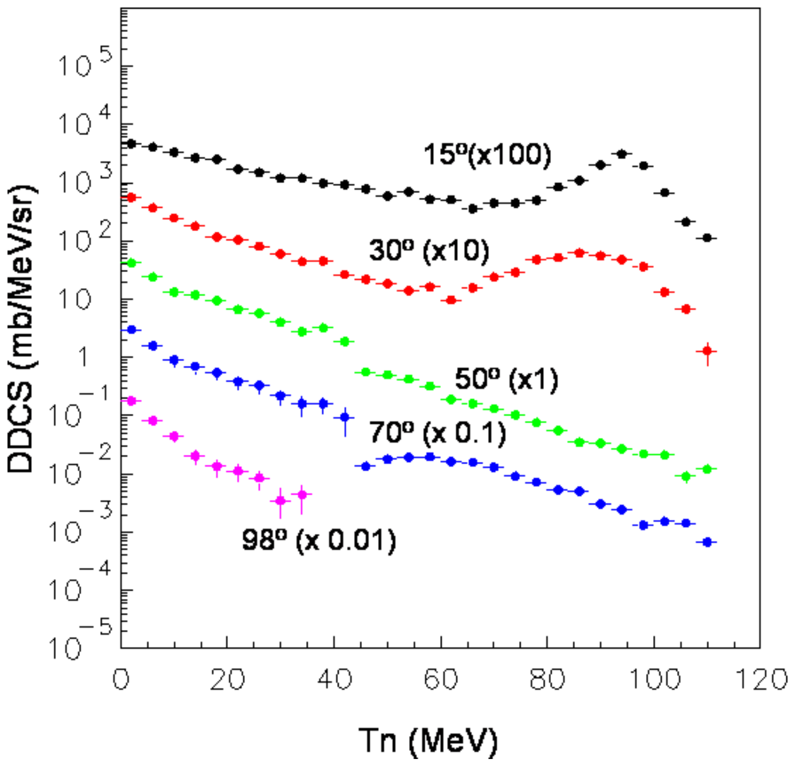
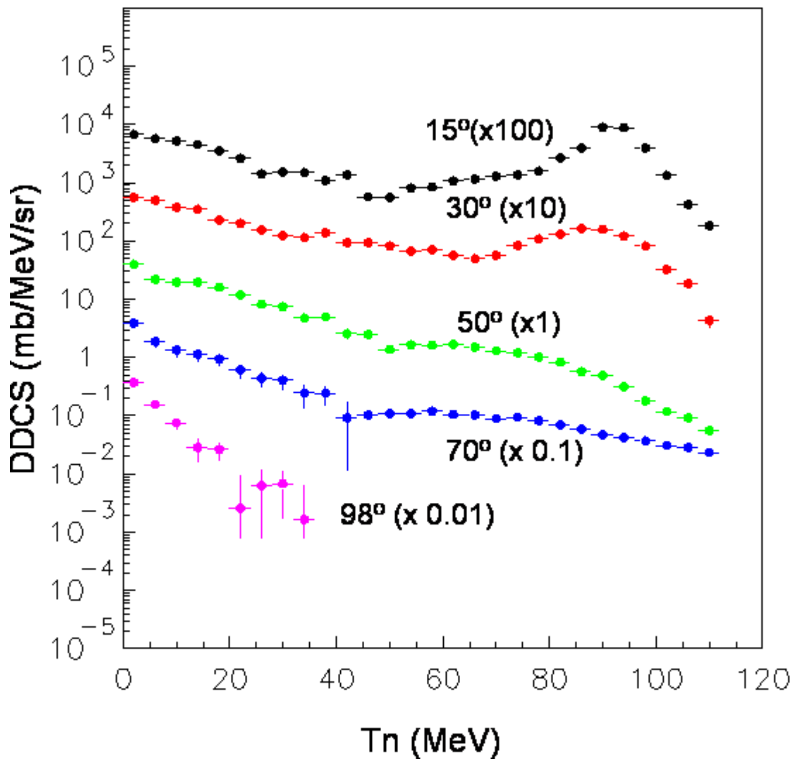
# Experimental results : Double differential cross section

iron

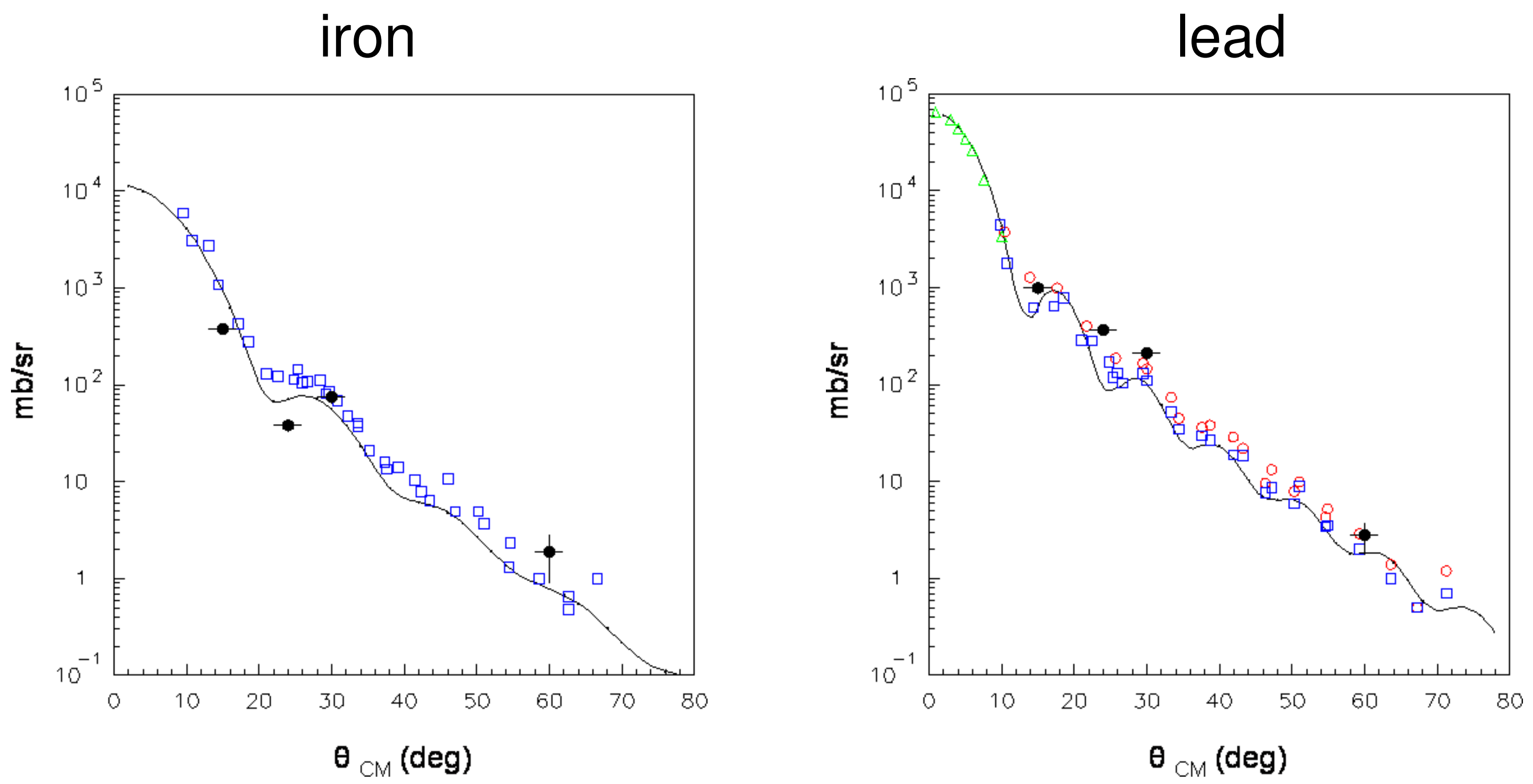



lead




evaporation + pre-equilibrium + direct processes

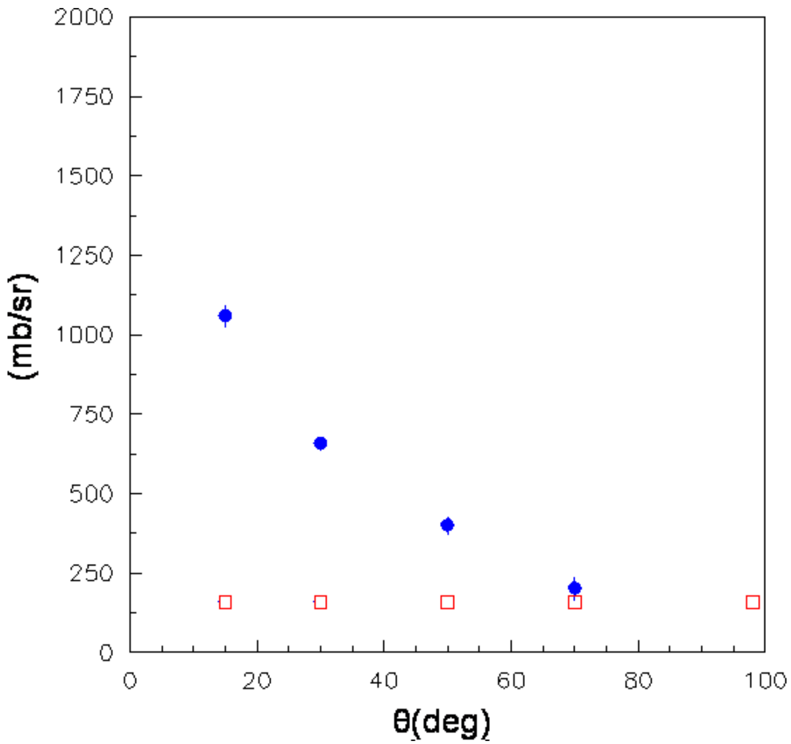
# Experimental results : Elastic cross section



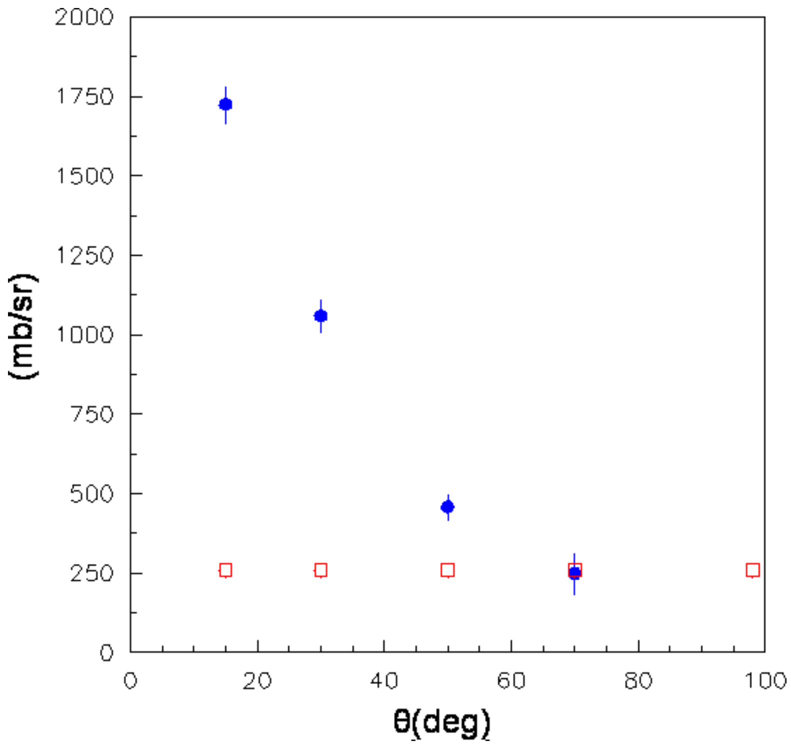

validation of the normalization procedure

# Experimental results : Angular distributions

iron

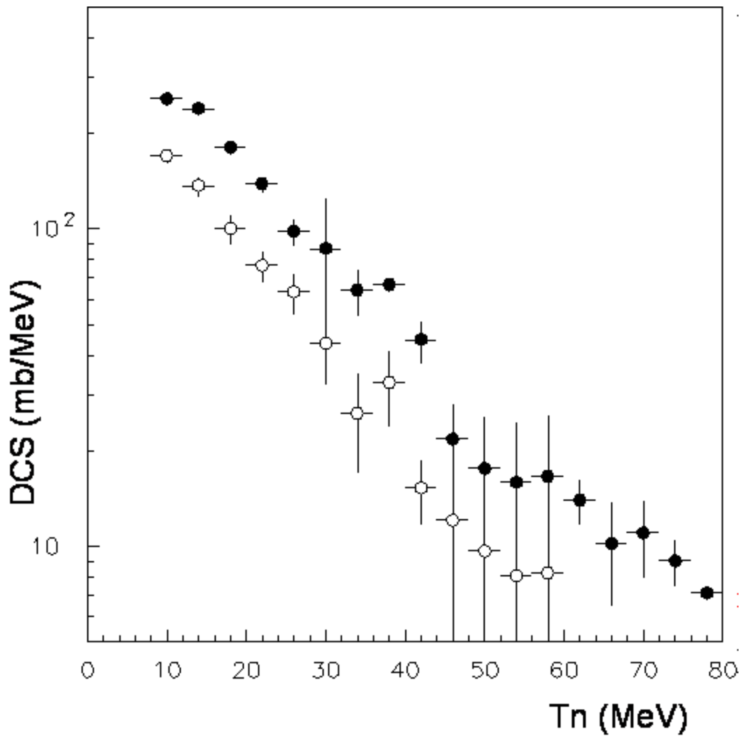



lead




DDCS : elastic + evaporation (98°) + pre-equilibrium

# Experimental results : Energy distributions




lead = filled symbols
iron = open symbols

using
the Kalbach parameterization

(without the elastic contribution)

Total Inelastic Cross Section
$s_{Fe}$ ~ 4304 mb
$s_{Pb}$ ~ 6132 mb

# Theoretical Calculations

MCNPX with GNASH and INCL4/ABLA

GEANT with GHEISA and FLUKA

TALYS

PHITS with QMD and SDM

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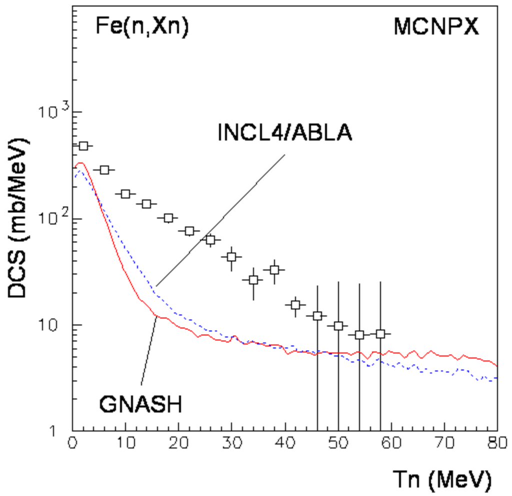
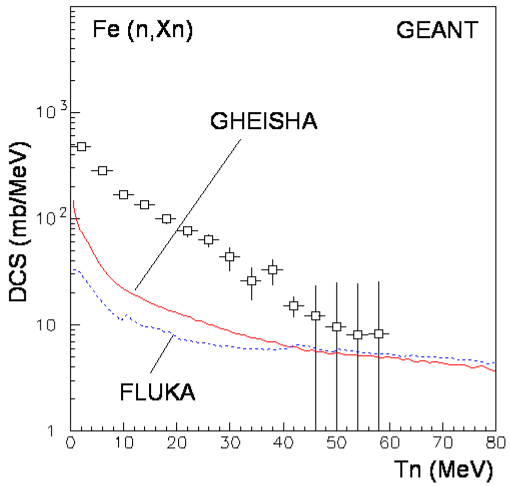
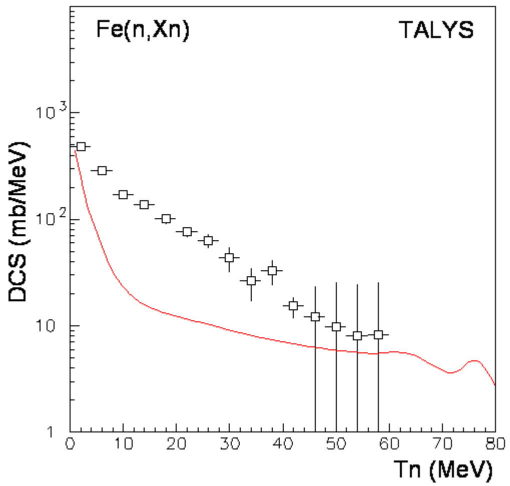
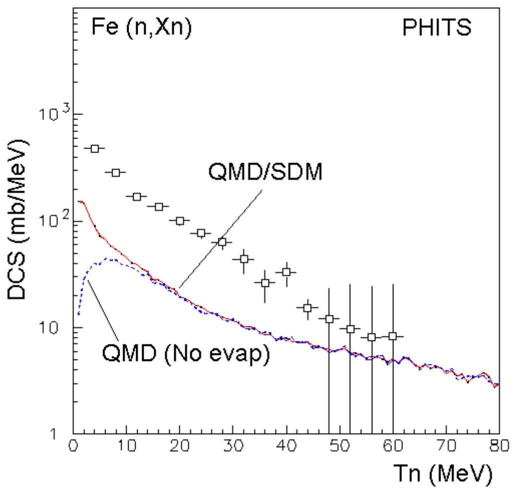
# Theoretical Calculations



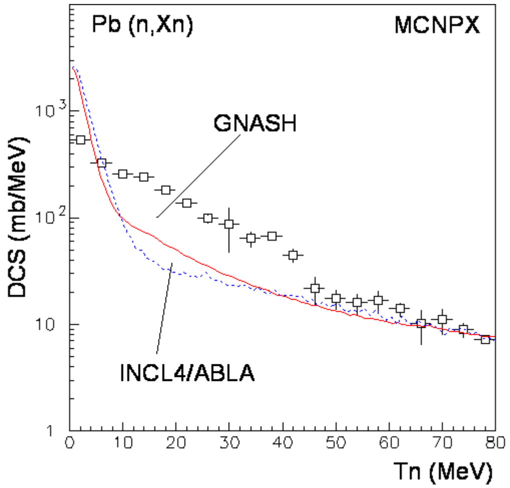



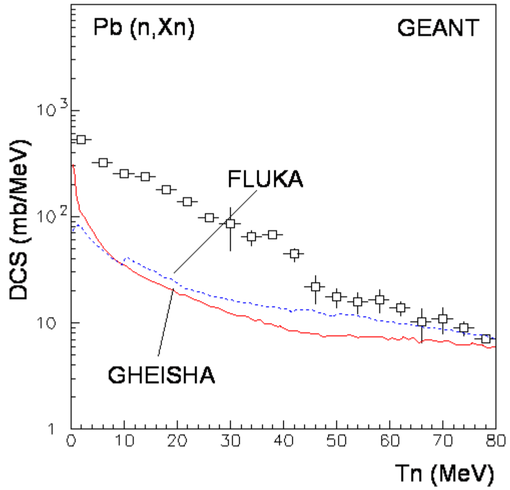

## Fe(n,Xn)

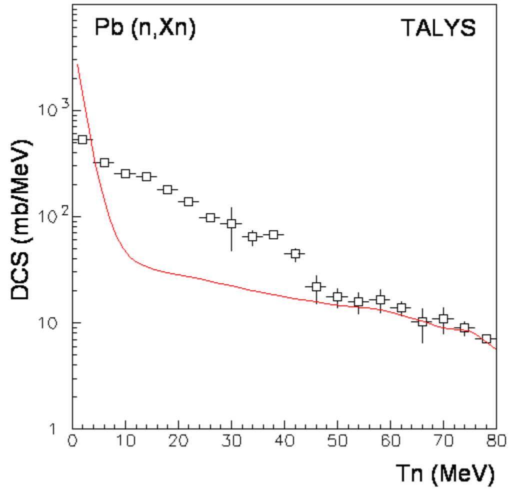
systematic underestimation
shape

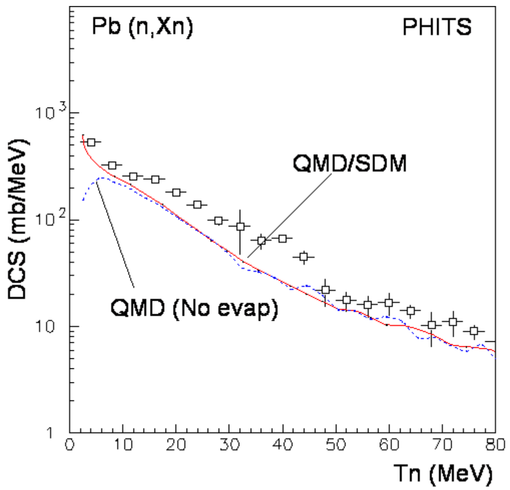
## Neutron production in neutron-induced reactions at 96 MeV on iron and lead

# Theoretical Calculations




## Pb(n,Xn)

systematic underestimation < 50 MeV
agreement > 50 MeV
shape... PHITS…

## Neutron production in neutron-induced reactions at 96 MeV on iron and lead

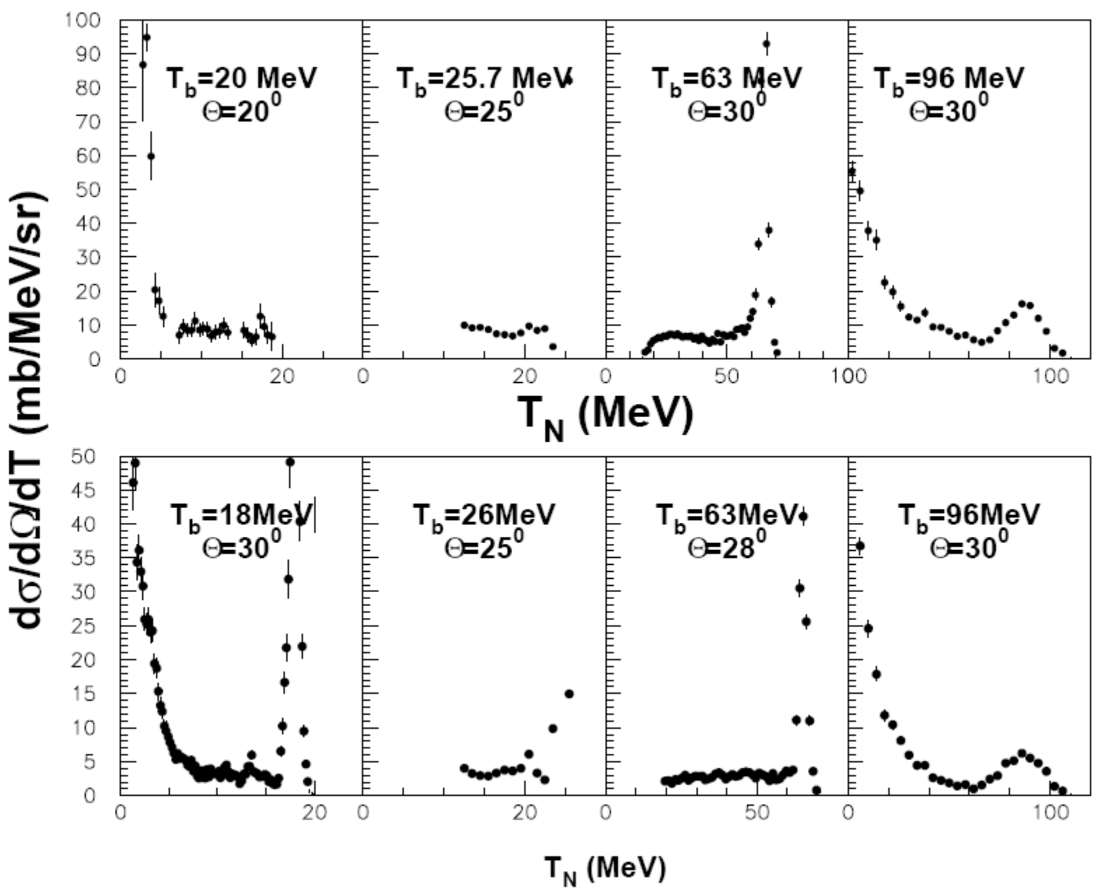
# Cross section analysis

| Beam energy ($T_b$) | Targets | Quantity | Angular range | Energy threshold |
|---|---|---|---|---|
| $65\,MeV$ | Fe, Sn, Pb | $\frac{d^2\sigma}{dTd\Omega}$ | $9.5^o < \theta < 24^o$ | $20\,MeV$ |
| $26\,MeV$ | V, Fe, Cu, Nb, W, Bi | $\frac{d^2\sigma}{dTd\Omega}, \frac{d\sigma}{dT}$ | $25^o < \theta < 145^o$ | $12\,MeV$ |
| $20\,MeV$ | Nb, Ho, Ta, Bi | $\frac{d^2\sigma}{dTd\Omega}, \frac{d\sigma}{dT}$ | $15^o < \theta < 154^o$ | $2.5\,MeV$ |
| $18\,MeV$ | Al, Fe, Ni, Zr, Nb, Cu, Bi | $\frac{d^2\sigma}{dTd\Omega}, \frac{d\sigma}{dT}$ | $30^o < \theta < 150^o$ | $1\,MeV$ |

# EXFOR Data Base – (n,Xn) between 20 and 200 MeV

E.L. Hjort et al, Phys. Rev. C53 (1996)
A. Marcinkowski et al, Nucl. Phys. A402 (1983); J. NSE 83 (1983)
A. Marcinkowski et al, Nucl. Phys. A530 (1991)
S. Ijima et al, Proc. Int. Conf. Nuclear Data, MITO (1988)

## Cross section analysis




Pb(n,Xn)

Fe(n,Xn)

DDCS
20 – 30°
beam energy

pre-equilibrium
is not very sensitive
to beam energy

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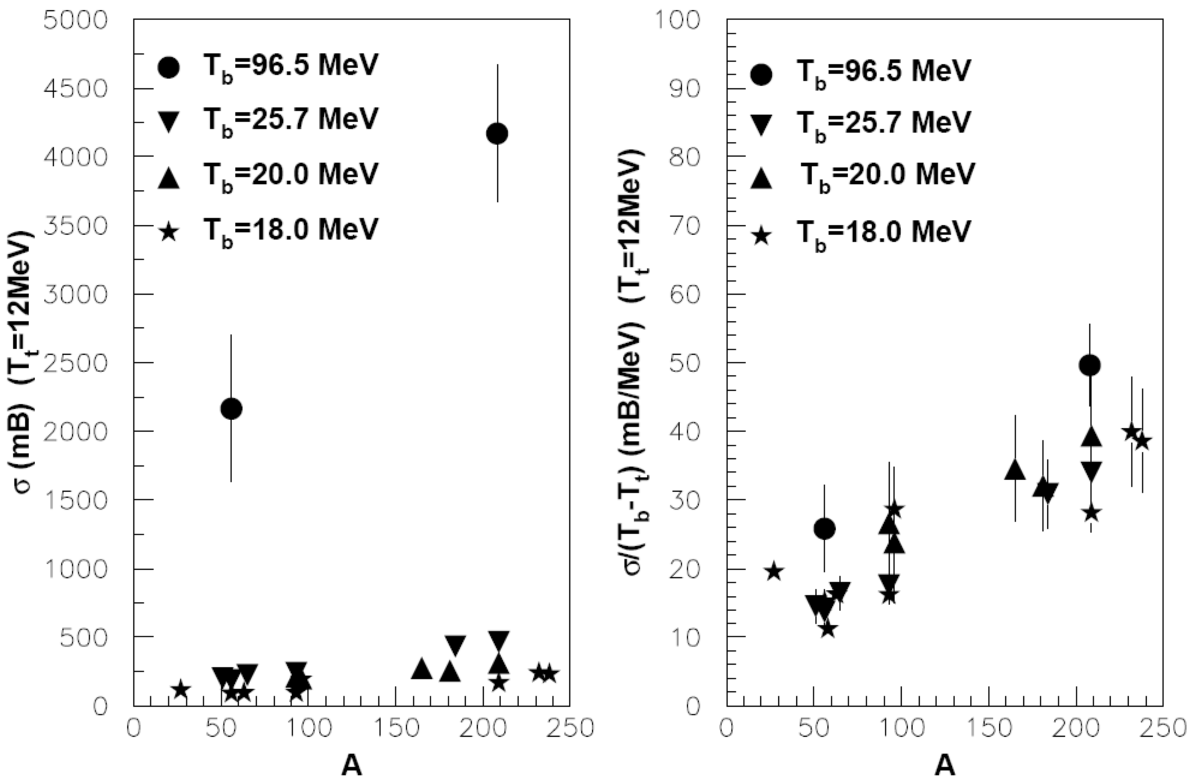
# Cross section analysis




partial pre-equilibrium cross section

...

per incident MeV

$\sigma / (T_b - T_t)$

$T_t$ = 12 MeV

strong correlation

# Conclusion - Summary

DDCS – (n,Xn) at 96 MeV neutron on iron and lead (15° - 100° & 1 – 100 MeV)

DDCS – Elastic cross section – Fe(n,n) and Pb(n,n)
in good agreement with existing data and optical model calculation

DDCS – Inelastic cross section – Fe(n,Xn) and Pb(n,Xn)
angular distributions and energy distributions

Energy distributions vs Theoretical calculations
MCNPX, GEANT, TALYS, PHITS
disagreement in shape and in magnitude… except…

Cross section analysis
pre-equilibrium is not very sensitive to neutron beam energy
strong correlation between $\sigma$ / ($T_b$ – $T_t$) and A