EUROfusion
WPBB-S.05.02-T005-D006

16th INTERNATIONAL CONFERENCE ON
NUCLEAR REACTION MECHANISMS
June 11-16, 2023, Varenna, Italy

Due consideration of breakup and stripping mechanisms within (d, p), (d, 2p), and (d, xn) reactions

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1. Motivation
2. Calculation' tools: Nuclear Models & Codes
3. Reactions competition in (d,xp), (d,xn) processes
4. Conclusions

Deuteron-nucleus interaction analysis

Motivation: Nuclear Data Needs: ITER, IFMIF, SPIRAL2, SARAF, Medical Installations

DEUTERONS BEAM

Associated Research Projects: New data & Updated theory

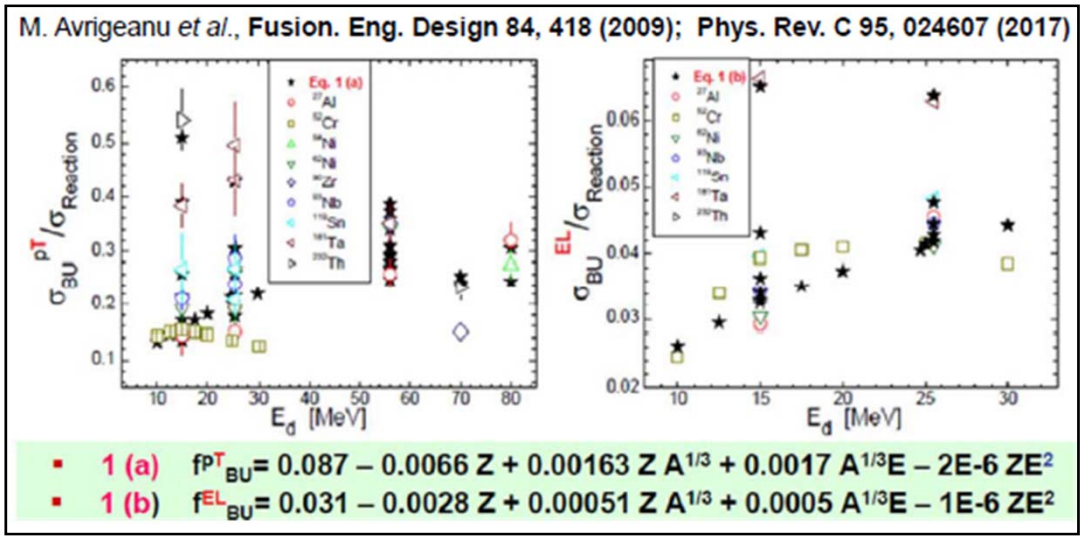
FENDL, EURATOM, F4E, EUROfusion

- **Breakup – in TALYS-1.96, option breakupmodel 2:** M. Avrigeanu *et al.*, **Eur. Phys. J. A (2022) 58:3**

  BREAKUP [M. Avrigeanu, V. Avrigeanu]

  - parametrization of total BU protons & elastic-breakup c.s.:

  - inelastic breakup enhancement brought by **breakup-nucleons** reactions



- **Direct reactions**

  FRESCO (Version **FRES 2.9**) [I.J. Thompson]

  - stripping & pick-up, DWBA : (d,p), (d,n), (^{3}He,d), (d,t), (d,α), (d,^{3}He)

- **Composite system equilibration for both deuteron and breakup-nucleon reactions**

  STAPRE-H95 [V. Avrigeanu, M. Avrigeanu] (updated)

  - OMP:SCAT2000; preequilibrium: **GDH / EXCITON;** evaporation: **Hauser-Feshbach**

  TALYS - 1.0 - 1.96 [A. Koning, S. Hilaire, S. Goriely]

  - OMP:ECIS'97; breakup, preequilibrium: **MSD / EXCITON;** evaporation: **Hauser-Feshbach**

Dedicated projects to IFMIF and ITER: EURATOM, F4E, EUROfusion

PHYSICAL REVIEW C **79**, 044610 (2009)

Low and medium energy deuteron-induced reactions on ^{27}Al

PHYSICAL REVIEW C **84**, 014605 (2011)

Low and medium energy deuteron-induced reactions on ^{63,65}Cu nuclei

PHYSICAL REVIEW C **88**, 014612 (2013)

Low-energy deuteron-induced reactions on ^{93}Nb

PHYSICAL REVIEW C **89**, 044613 (2014)

Low energy deuteron-induced … on Fe isotopes

PHYSICAL … 014606 (2016)

Deute… reactions on Ni isotopes up to 60 MeV

PHYSICAL REVIEW C **98**, 034606 (2018)

…stent account of deuteron-induced reactions on ^{nat}Cr up to 60

PHYSICAL REVIEW C **101**, 024605 (2020)

Deuteron-induced reactions on manganese at low energies

PHYSICAL REVIEW C **104**, 044615 (2021)

Deuteron-induced reactions on ^{nat}Zr up to 60

Priority list of IFMIF-DONES candidate materials

EURATOM

d+Al,
d+Cu,
d+Nb

GRT-168 of **Fusion for Energy (F4E)**

d+Fe
d+Ni

EUROfusion

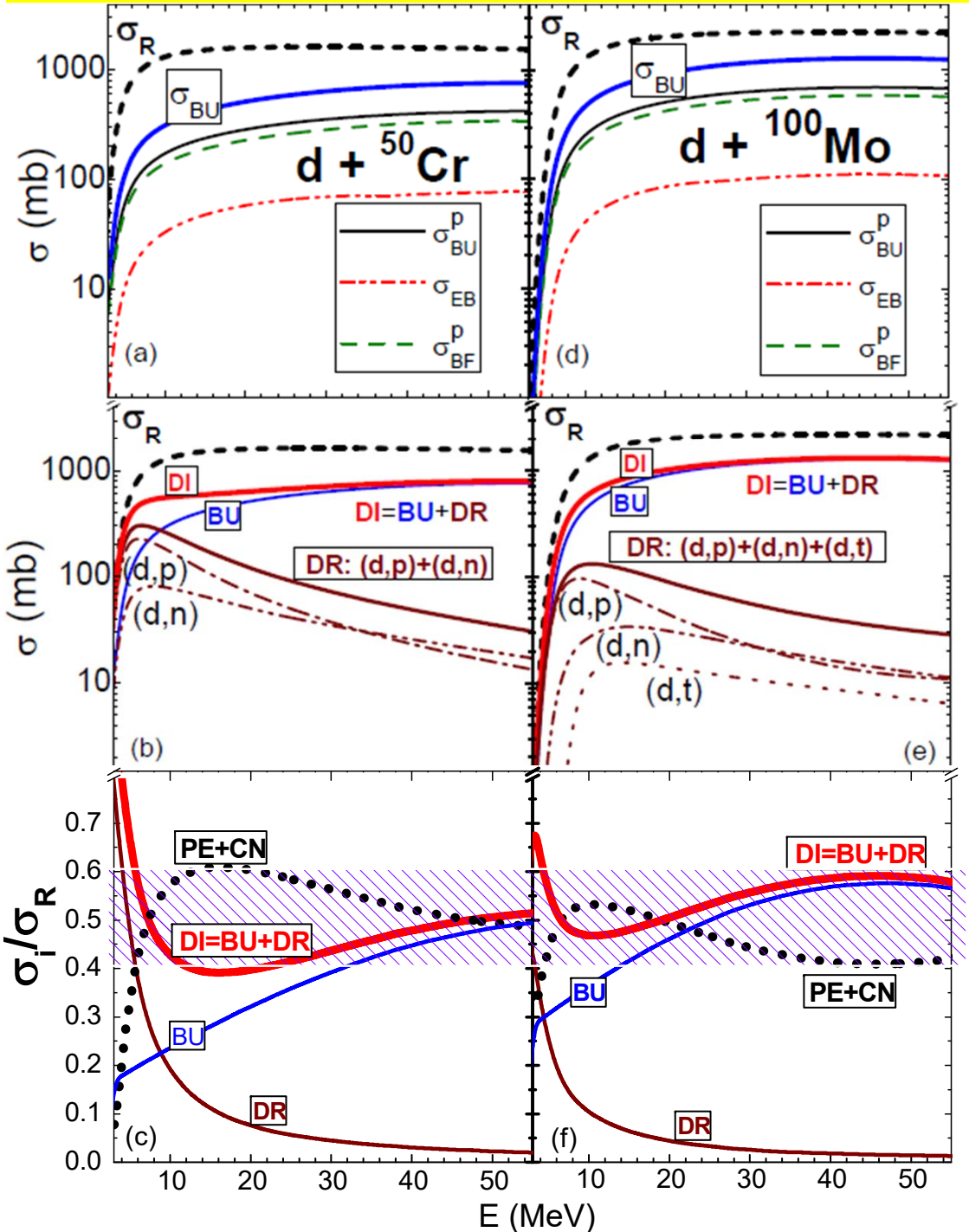
d+Cr
d+Mn

SPIRAL 2

d+Zr

DIRECT INTERACTIONS (DI): Breakup & Direct Reactions versus PE+CN

balance around half of deuteron reaction cross section σ_R



Eur. Phys. J. A (2022) 58:3 TALYS-1.96 , breakupmodel 2
https://doi.org/10.1140/epja/s10050-021-00659-6

- nucleon BU cross sections (total, elastic, inelastic)

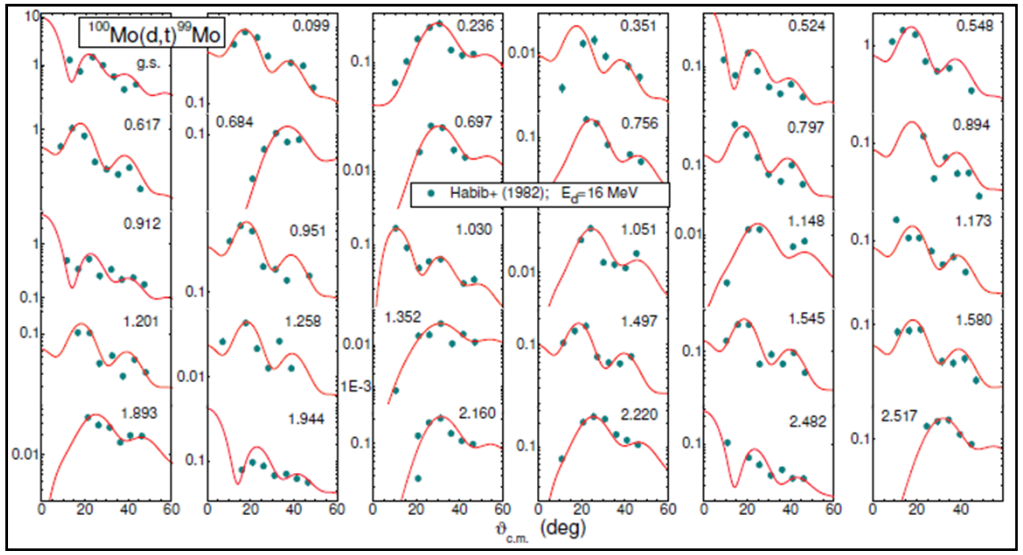
[Eqs. (2)-(5), Phys. Rev. C 89, 044613]

$$\sigma_{BU}^{p/n} = [0.087 - 0.0066Z + 0.00163ZA^{1/3} + 0.0017A^{1/3}E - 0.000002ZE^2]\sigma_R,$$

$$\sigma_{EB} = [0.031 - 0.0028Z + 0.00051ZA^{1/3} + 0.0005A^{1/3}E - 0.000001ZE^2]\sigma_R,$$

[Eq. (7), Phys. Rev. C 89, 044613]

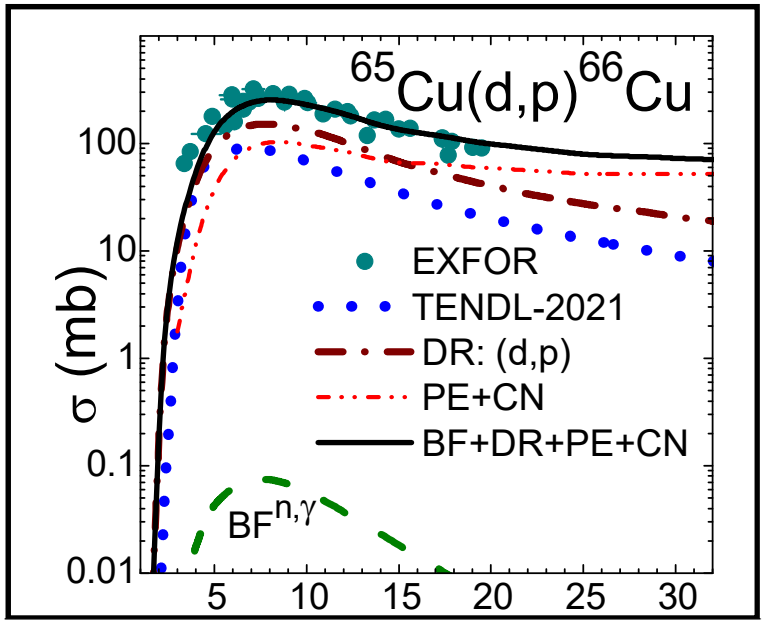
$$\sigma_{BF}^{p/n} = \sigma_{BU}^{p/n} - \sigma_{EB} \qquad \sigma_{BF}^{p,x}(E_d) = \sigma_{BF}^{p}(E_d) \int dE_p \frac{\sigma_{(p,x)}(E_p)}{\sigma_R^p} \frac{1}{(2\pi)^{\frac{1}{2}} w} exp[-\frac{(E_p - E_p^0(E_d))^2}{2w^2}]$$



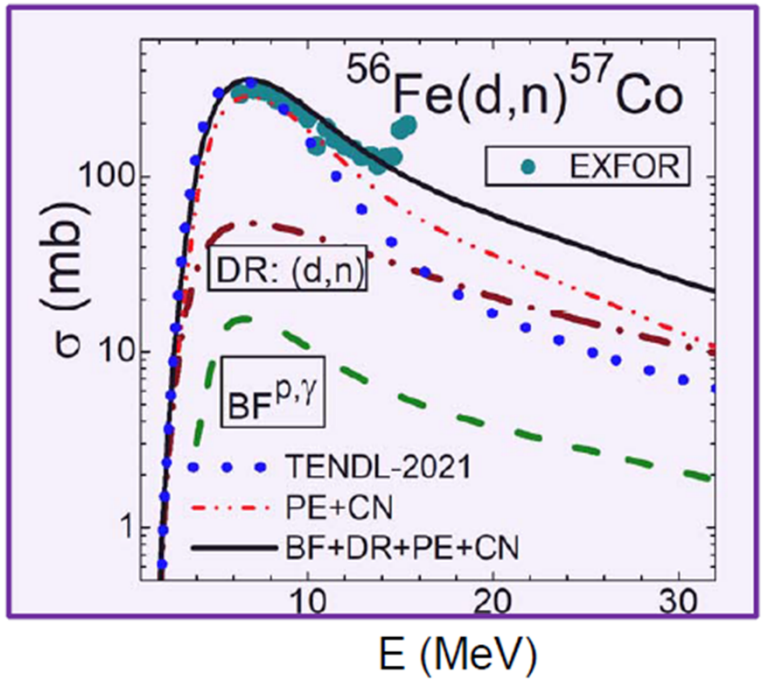
deuteron reaction cross section, σ_R, remaining available for PE+CN

$$1 - \frac{\sigma_{BU} + \sigma_{DR}}{\sigma_R} = 1 - \frac{\sigma_{DI}}{\sigma_R} = \frac{\sigma_{PE} + \sigma_{CN}}{\sigma_R}.$$

Reaction Mechanisms involved in (d,p) , (d,n) processes (1)

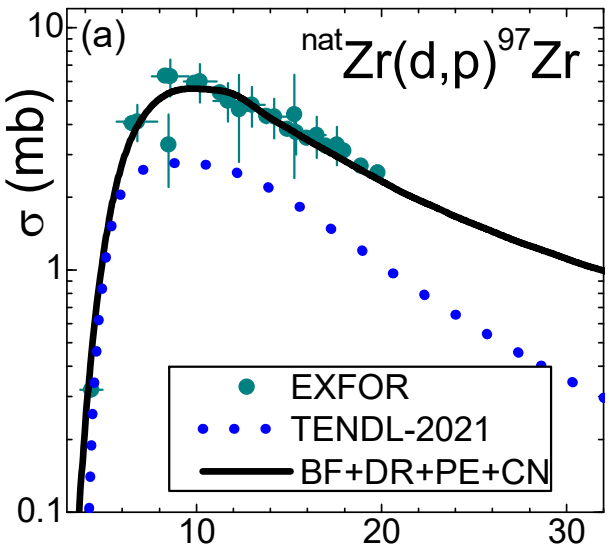


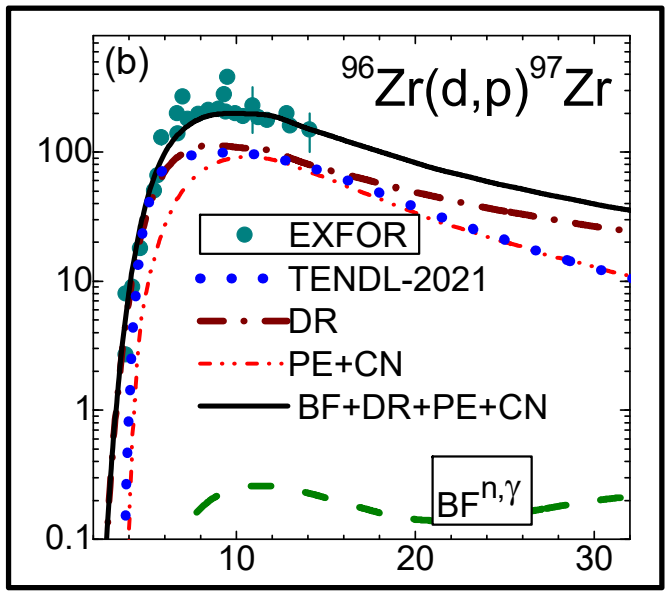
PHYSICAL REVIEW C **84**, 014605 (2011)

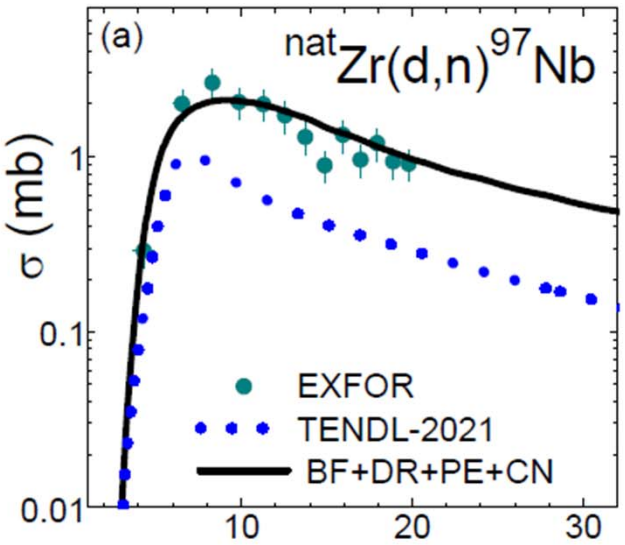


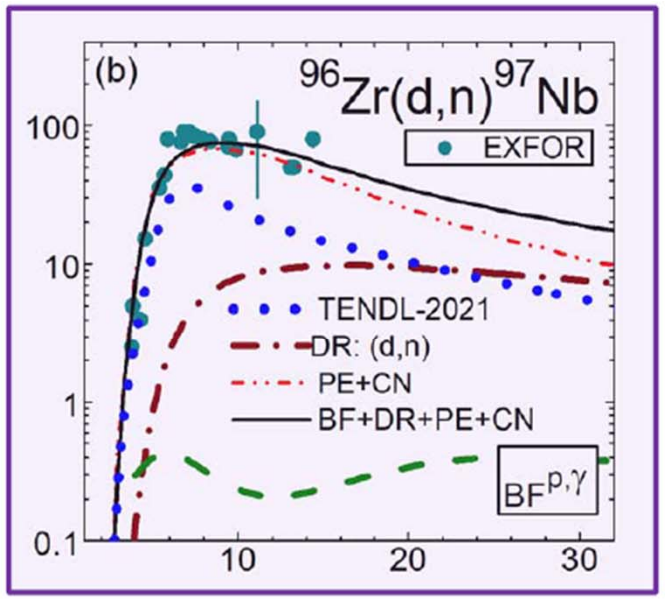
Reaction Mechanisms involved in (d,p) , (d,n) processes (2)

PHYSICAL REVIEW C 104, 044615 (2021)



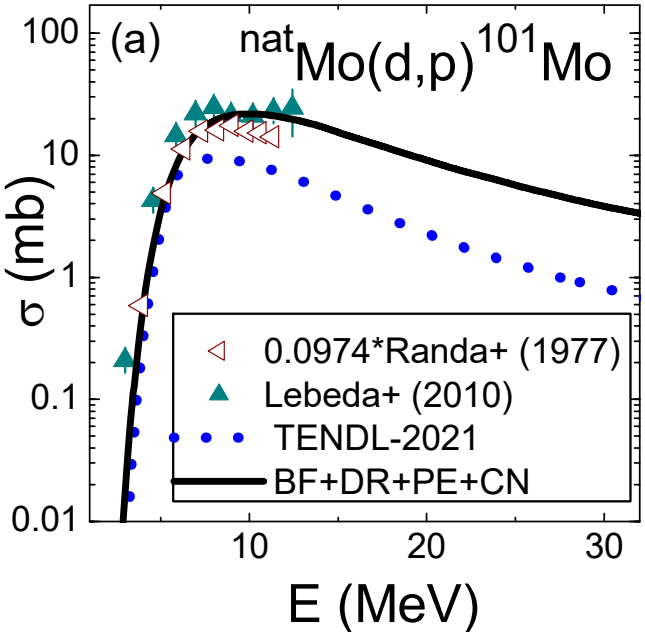


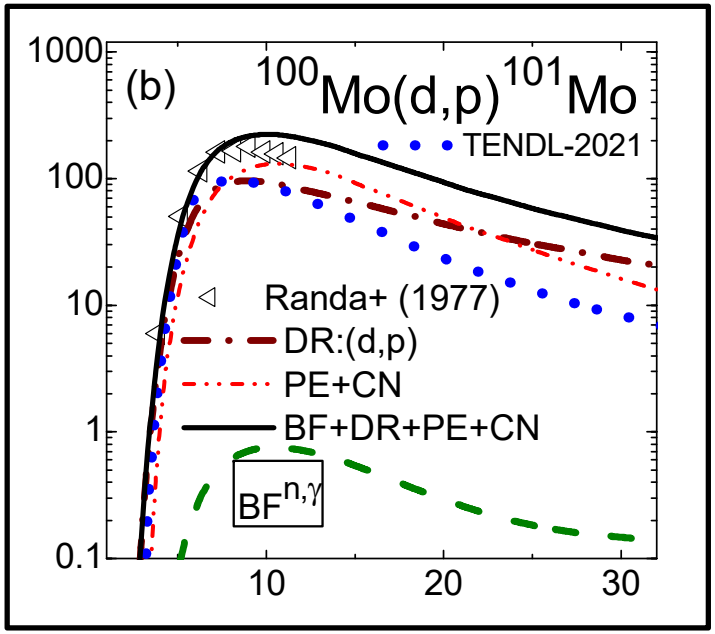


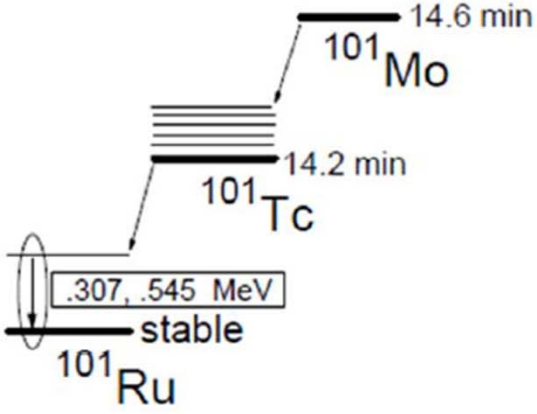


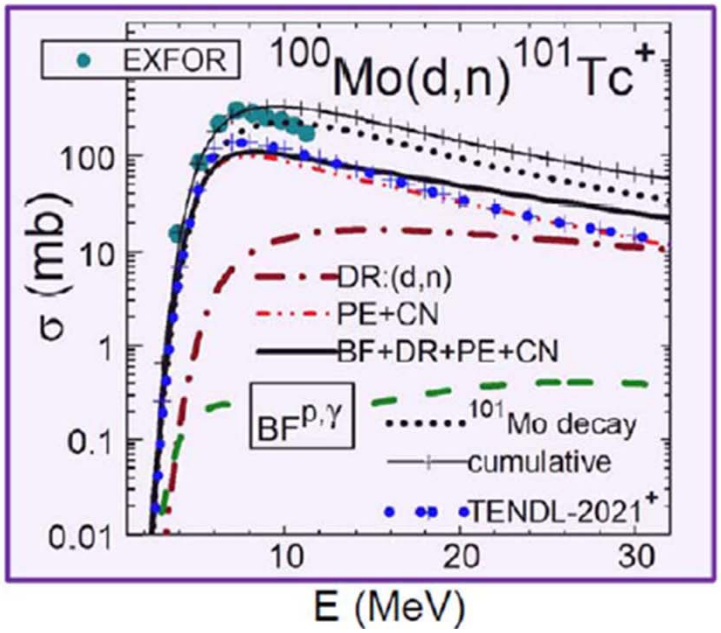
E (MeV)

Reaction Mechanisms involved in (d,p) , (d,n) processes (3)

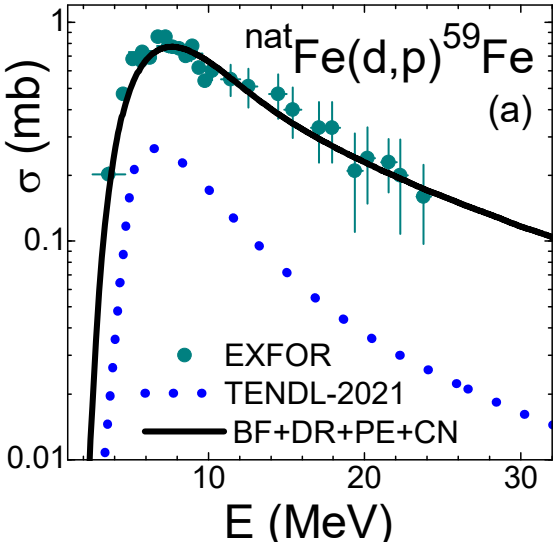


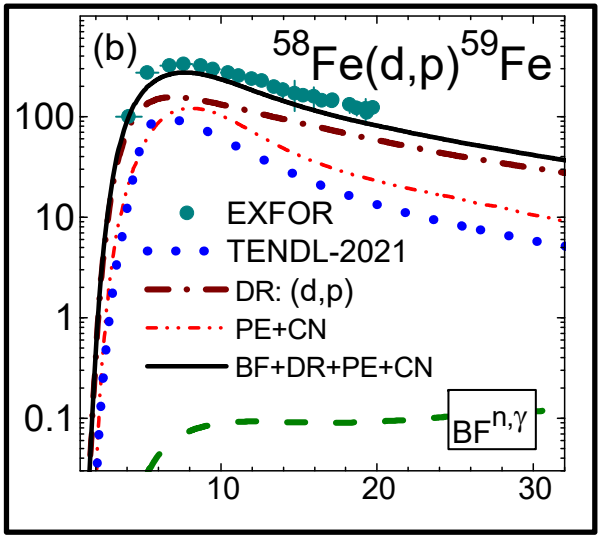




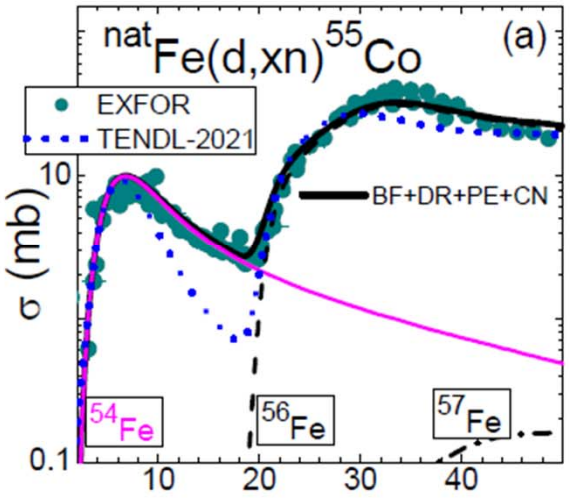


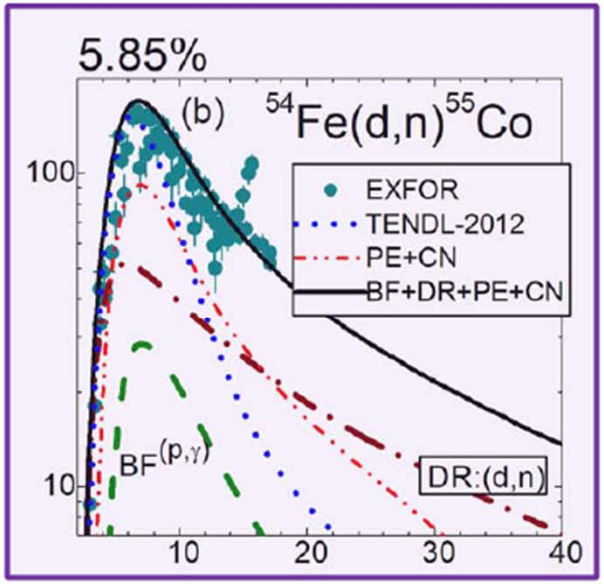
Reaction Mechanisms involved in (d,p) , (d,xn) processes

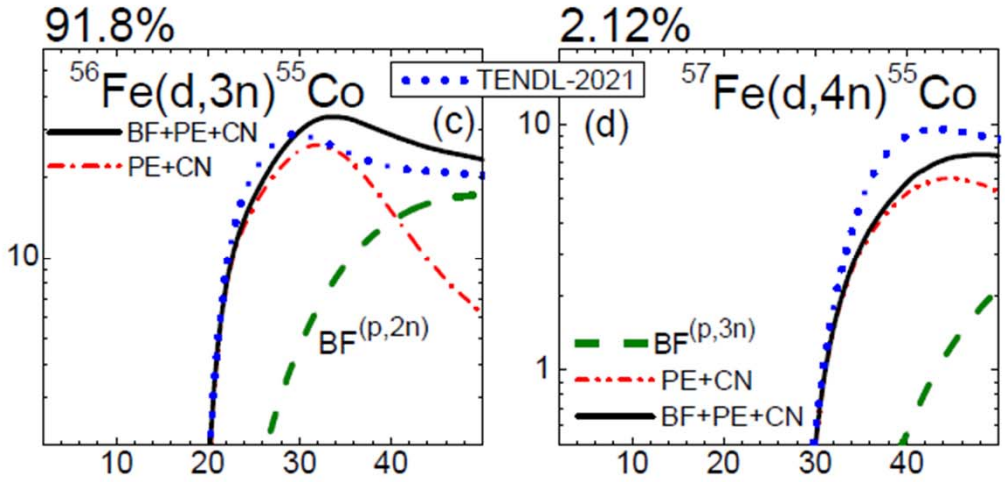




PHYSICAL REVIEW C 89, 044613 (2014)

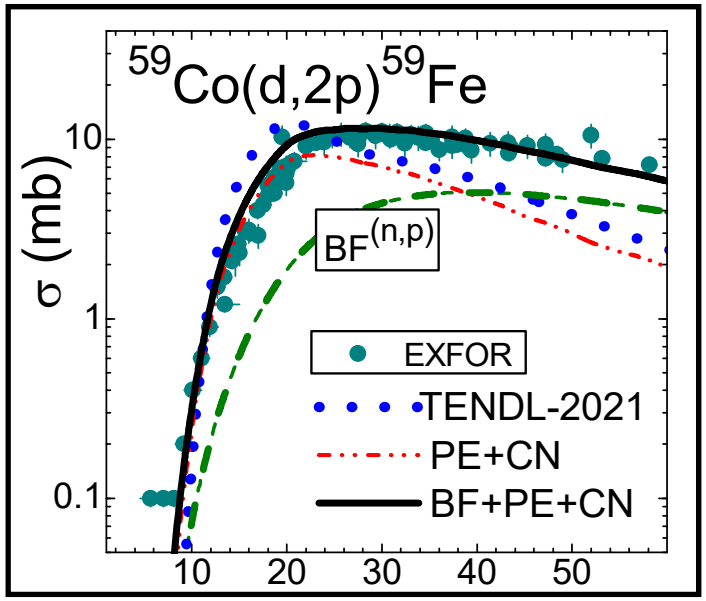




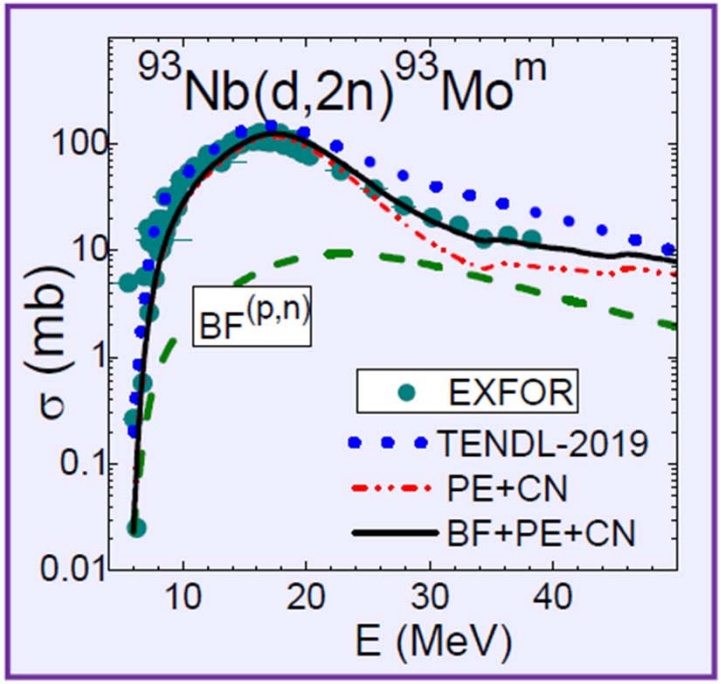


E (MeV)

Reaction Mechanisms involved in (d,2p) , (d,2n) processes

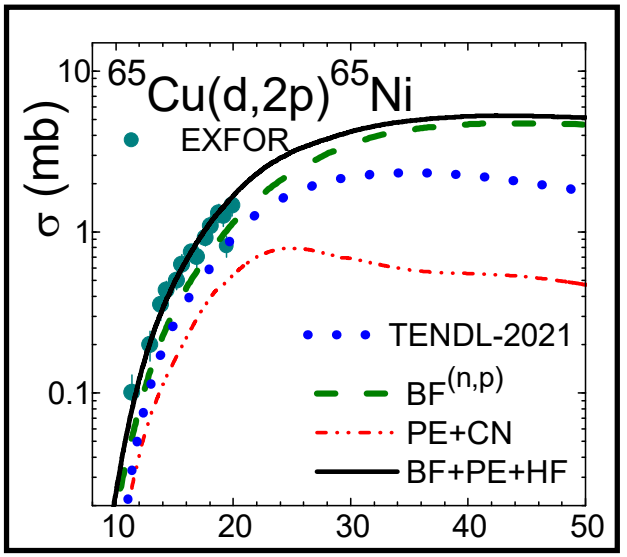


PHYSICAL REVIEW C **99**, 034611 (2019)

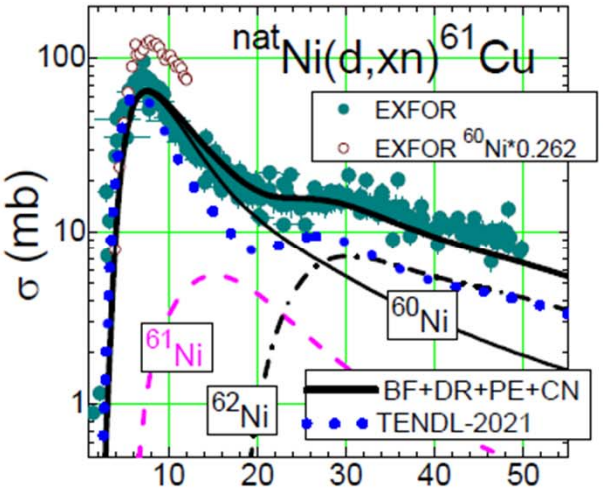


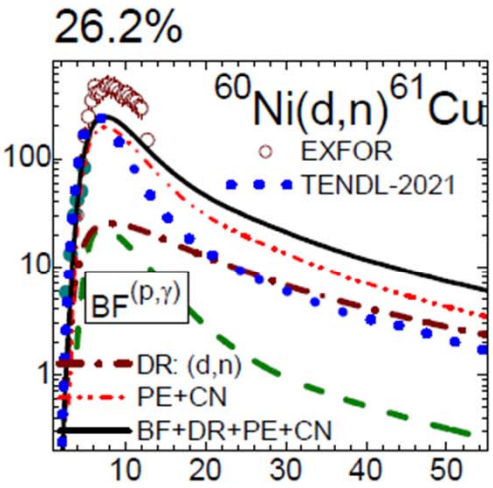
PHYSICAL REVIEW C **88**, 014612 (2013)

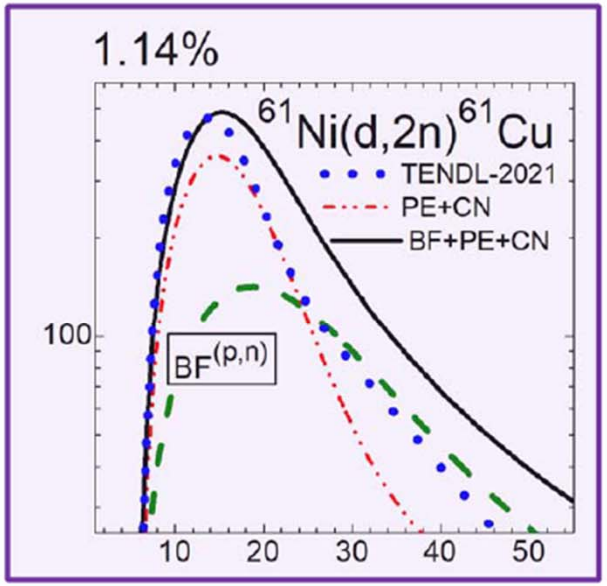
Reaction Mechanisms involved in (d,2p) , (d,xn) processes



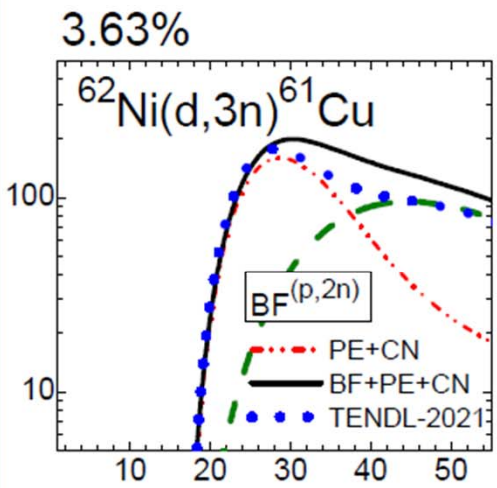
PHYSICAL REVIEW C **84**, 014605 (2011)





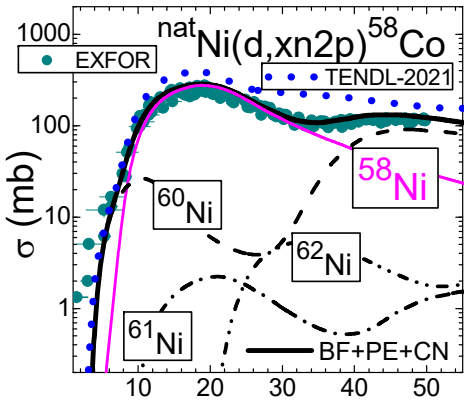


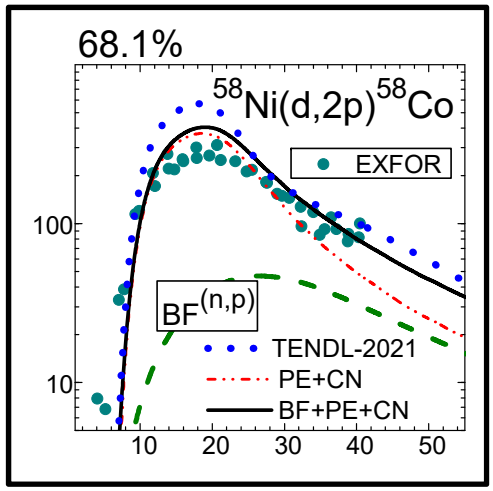
PHYSICAL REVIEW C **94**, 014606 (2016)

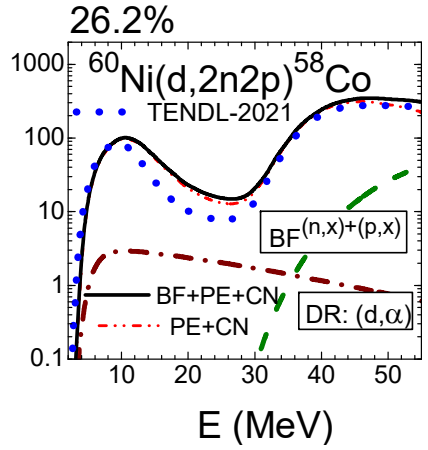


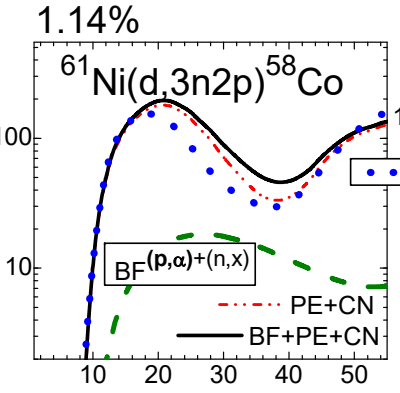
E (MeV)

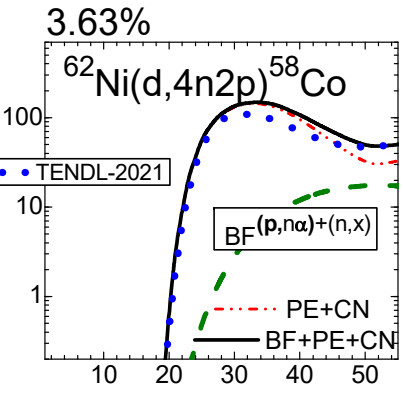
Reaction Mechanisms involved in (d,xn2p), (d,xn) processes

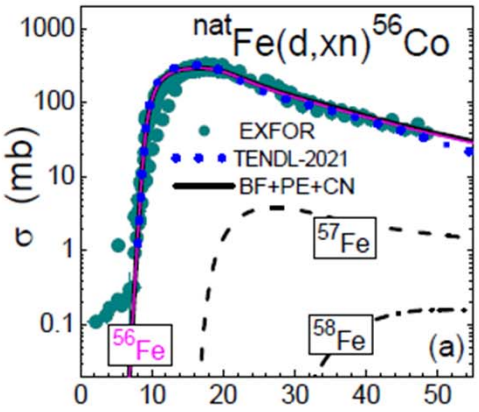


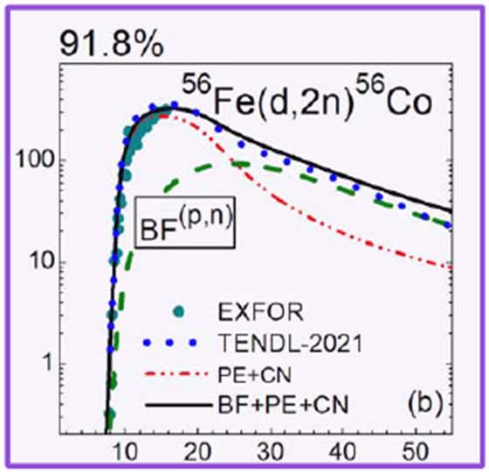


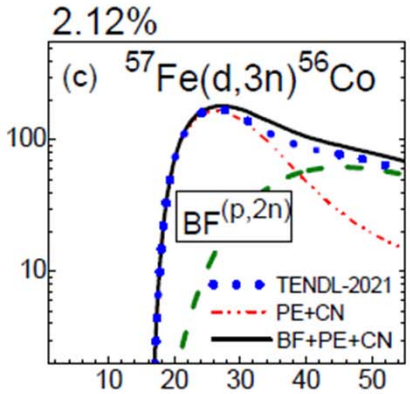


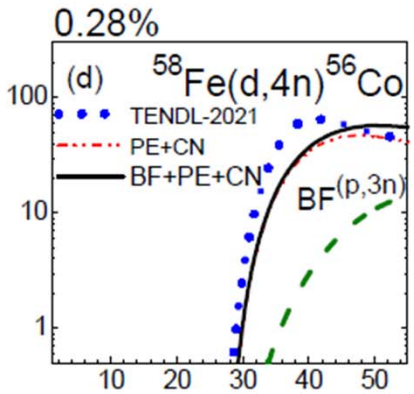












CONCLUSIONS

Thank you!

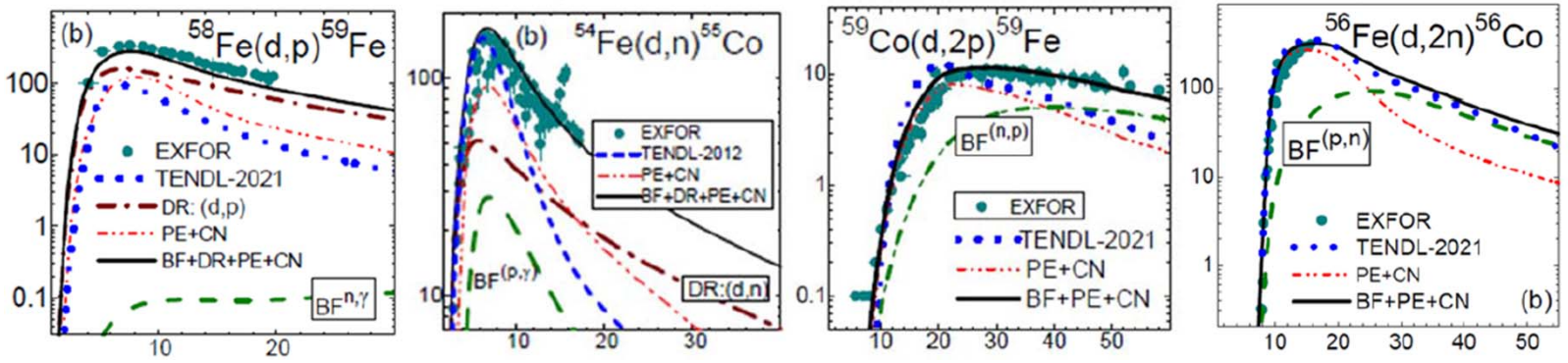
IFIN-HH

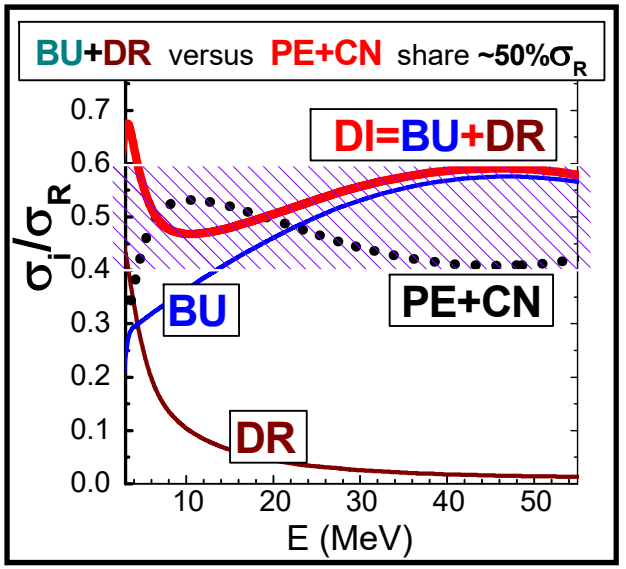
Comparative analysis DATA – Nuclear Reaction Models predictions

of (d,p), (d,n), (d,2p), and (d,xn) processes

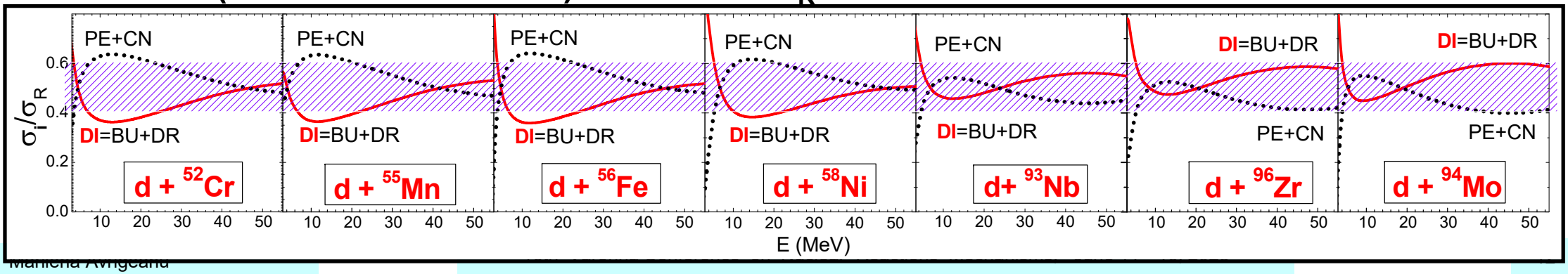
validated Nuclear Reaction Mechanisms: BU, DR, PE, CN involvement

first chance emitted particle **second chance emitted particle**



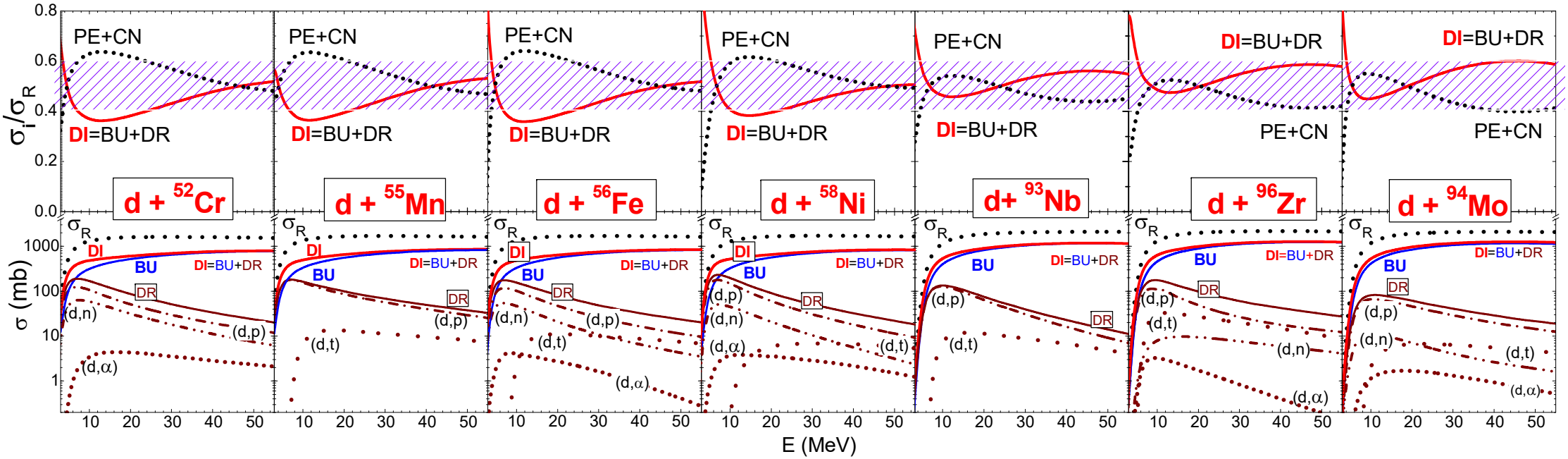


- **DR-STRIPPING (FRESCO)**
  - (d,p) DR stripping dominance for the first chance emission
  - important (d,n) DR stripping for the first chance emission
- **BREAKUP (BF: breakupmodel 2, TALYS-1.96)**
  - BU fast increase with E_{inc}
  - BF Important contribution for the second and third chance emitted particle
- **PE+CN (STAPRE-H / TALYS) ~ 50% of σ_R**



DI versus PE+CN

balance around half of deuteron reaction cross section, σ_R



Empirical parametrization versus microscopic predictions

PHYSICAL REVIEW C 94, 044619 (2016)

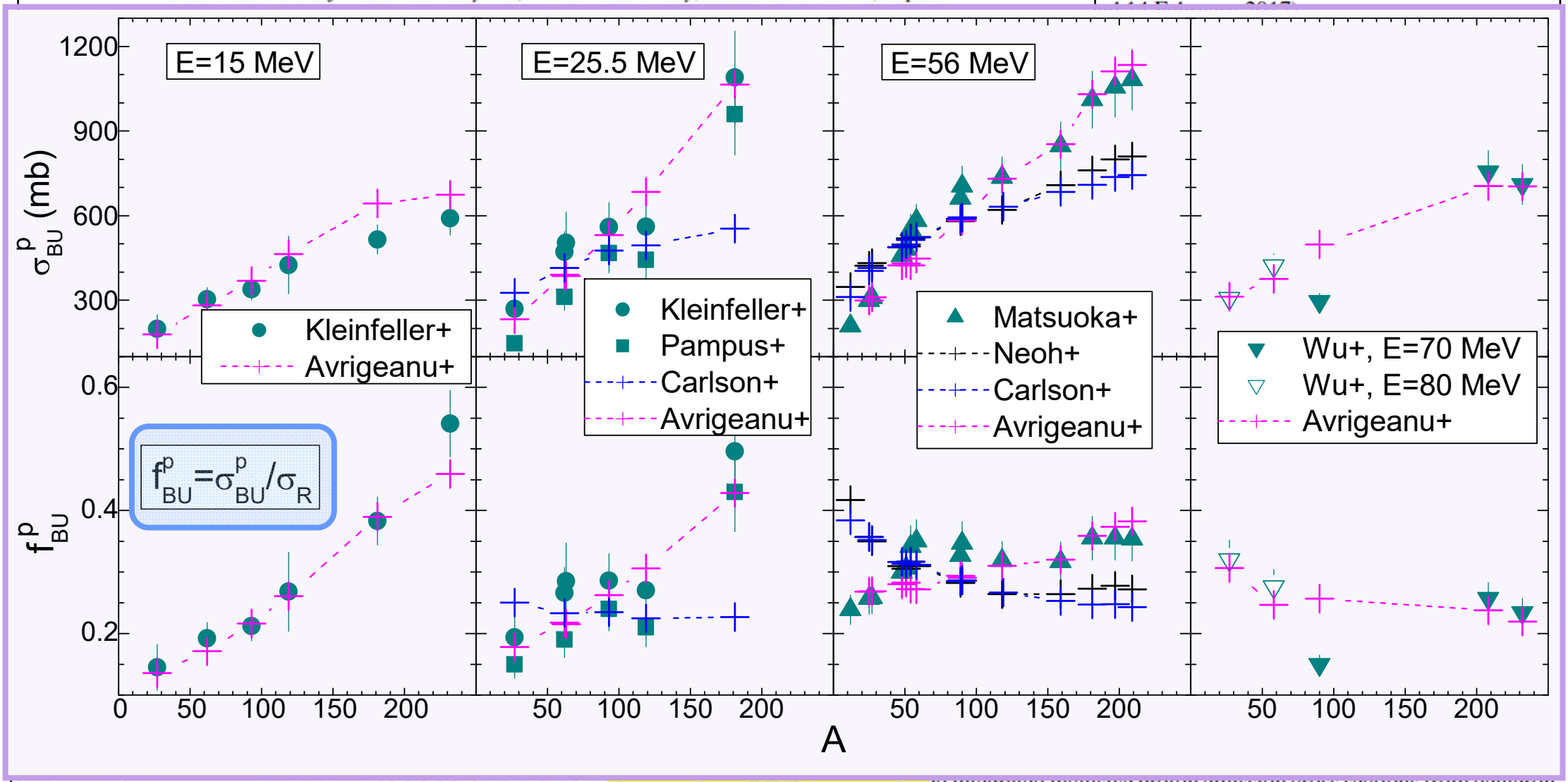
Microscopic effective reaction theory for deuteron-induced reactions

Yuen Sim Neoh,* Kazuki Yoshida, Kosho Minomo, and Kazuyuki Ogata
Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan

024607 (2017)

roscopic study of deuteron breakup

Avrigeanu
P.O. Box MG-6, R-077125 Bucharest-Magurele, I



butions at deuteron energies below 100 MeV obtained using the post-form DWBA approxima[illegible] integrated inclusive proton emission cross sections from deuteron

Deuteron OMP analysis

PHYSICAL REVIEW C **98**, 034606 (2018)

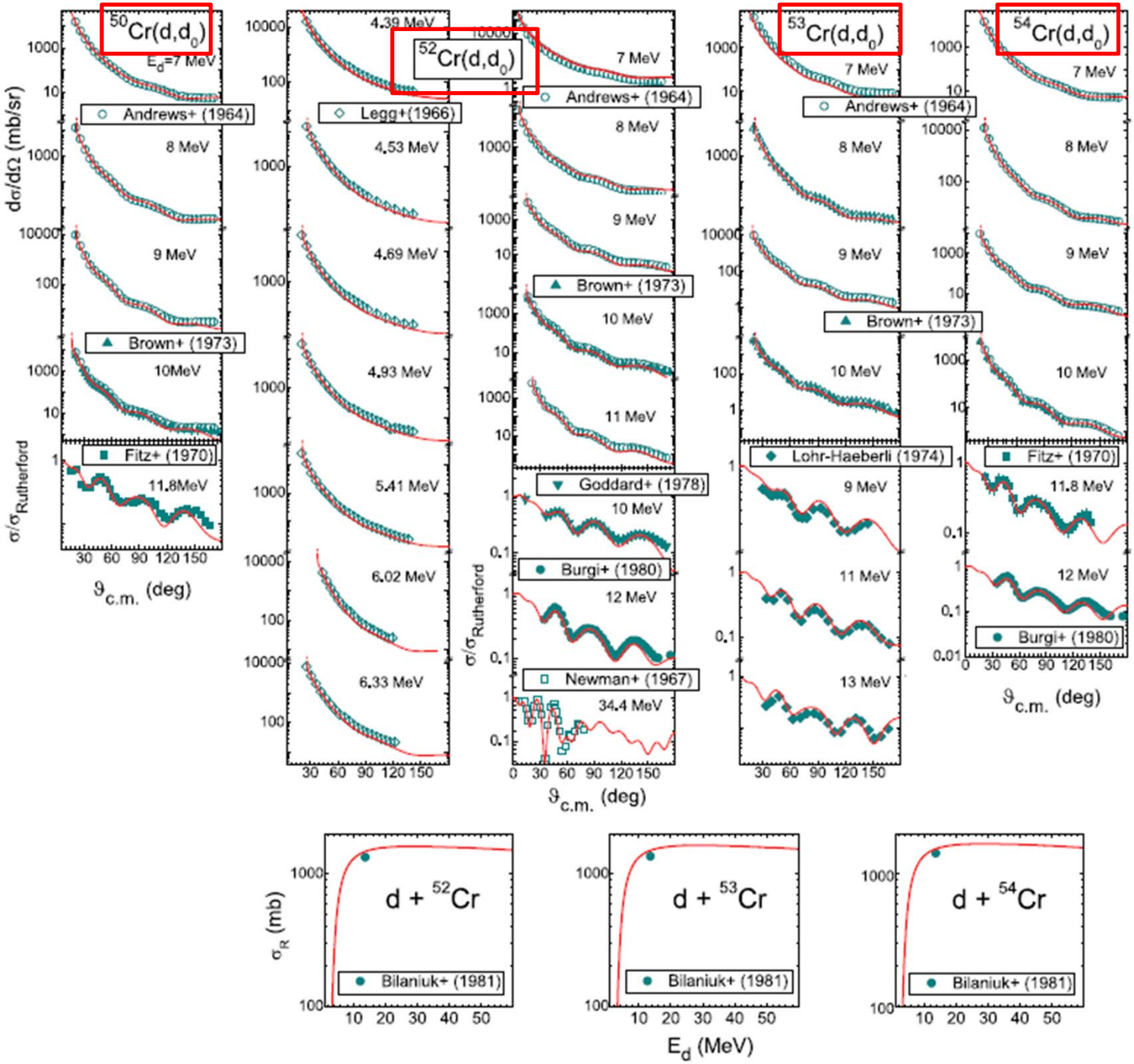


FIG. 2. Comparison of (top) measured [26–34] and calculated elastic-scattering angular distributions of deuterons on ^{50,52,53,54}Cr at energies from ~5 to ~34 MeV, using the global OMP of Daehnick *et al.* [35], and (bottom) measured [34,36] and similarly calculated total-reaction cross sections for deuterons on ^{52,53,54}Cr from 3 to 60 MeV.

Spectroscopic factors analysis for (d,p) stripping c.s. calculation

Comparison of measured and calculated proton angular distributions of stripping transitions to states with excitation energies in MeV, at various incident energies.