PNIII-P4-PCE-2021-0642

WPBB-S.05.02-T007-D005

Checking predictive power for ^{93}Zr(d,x) from ^{nat}Zr(d,x) analysis

Marilena Avrigeanu and Vlad Avrigeanu

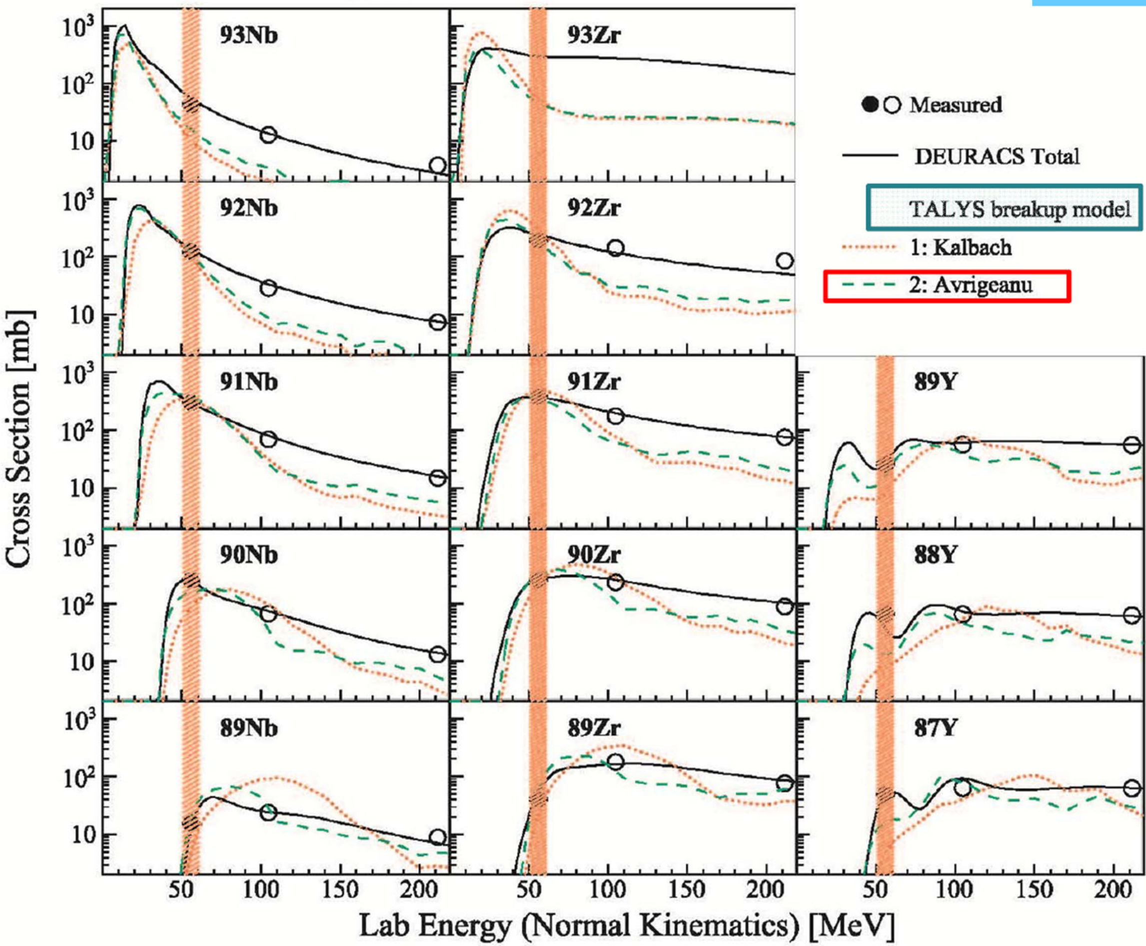
Horia Hulubei National Institute for Physics & Nuclear Engineering, (IFIN-HH), Bucharest, Romania

PTEP

Prog. Theor. Exp. Phys. 2023 121D01(11 pages)
DOI: 10.1093/ptep/ptad139

Studying the impact of deuteron non-elastic breakup on ^{93}Zr + d reaction cross sections measured at 28 MeV/nucleon

Thomas Chillery et al.



Cross sections for ^{93}Zr + d reactions as a function of laboratory energy (normal kinematics)

Content

1. Motivation
2. Nuclear Models & Codes
3. Analysis of (d,xn), (d,xnp), (d,xn2p) processes
4. Conclusions

Deuteron-nucleus interaction analysis

Motivation: **Nuclear Data Needs: ITER, IFMIF, SPIRAL2, SARAF, Medical Installations**
Transmutation facilities,…using DEUTERONS BEAM

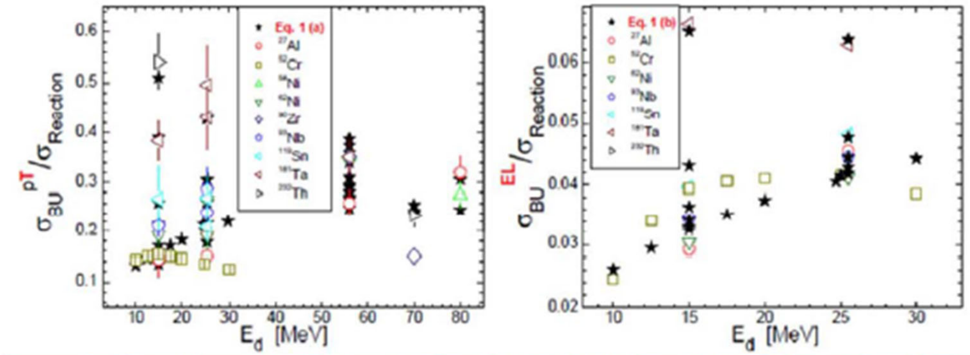
Associated Research Projects: New data & Updated theory
FENDL, EURATOM, F4E, EUROfusion

- **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

M. Avrigeanu *et al.*, **Fusion. Eng. Design 84, 418 (2009); Phys. Rev. C 95, 024607 (2017)**



- 1 (a) $f^{pT}_{BU} = 0.087 - 0.0066\,Z + 0.00163\,Z\,A^{1/3} + 0.0017\,A^{1/3}E - 2E\text{-}6\,ZE^2$
- 1 (b) $f^{EL}_{BU} = 0.031 - 0.0028\,Z + 0.00051\,Z\,A^{1/3} + 0.0005\,A^{1/3}E - 1E\text{-}6\,ZE^2$

- **Direct reactions** **(not included in $^{93}Zr(d,x)$ analysis at E_{inc} [50-200] MeV)**

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-…….1.97 [A. Koning, S. Hilaire, S. Goriely] **Eur. Phys. J. A (2023) 59:131**]
- OMP:ECIS'97; breakup, preequilibrium: **MSD / EXCITON**; evaporation: **Hauser-Feshbach**

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

IFIN-HH

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 reactions on Fe isotopes

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

Deuteron-induced reactions on Ni i… …eV

PHYSICAL RE… (2018)

Consistent acco… …ced reactions on ^{nat}Cr up to 60 MeV

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 MeV

Journal of Fusion Energy (2024) **43**:15

Modeling of Deuteron-Induced Reactions on Molybdenum at Low Energies

Priority list of IFMIF-DONES candidate materials

EURATOM

d+Al,
d+Cu,
d+Nb

GRT-1…
…or
…ergy (F4E)

d+Fe
d+Ni

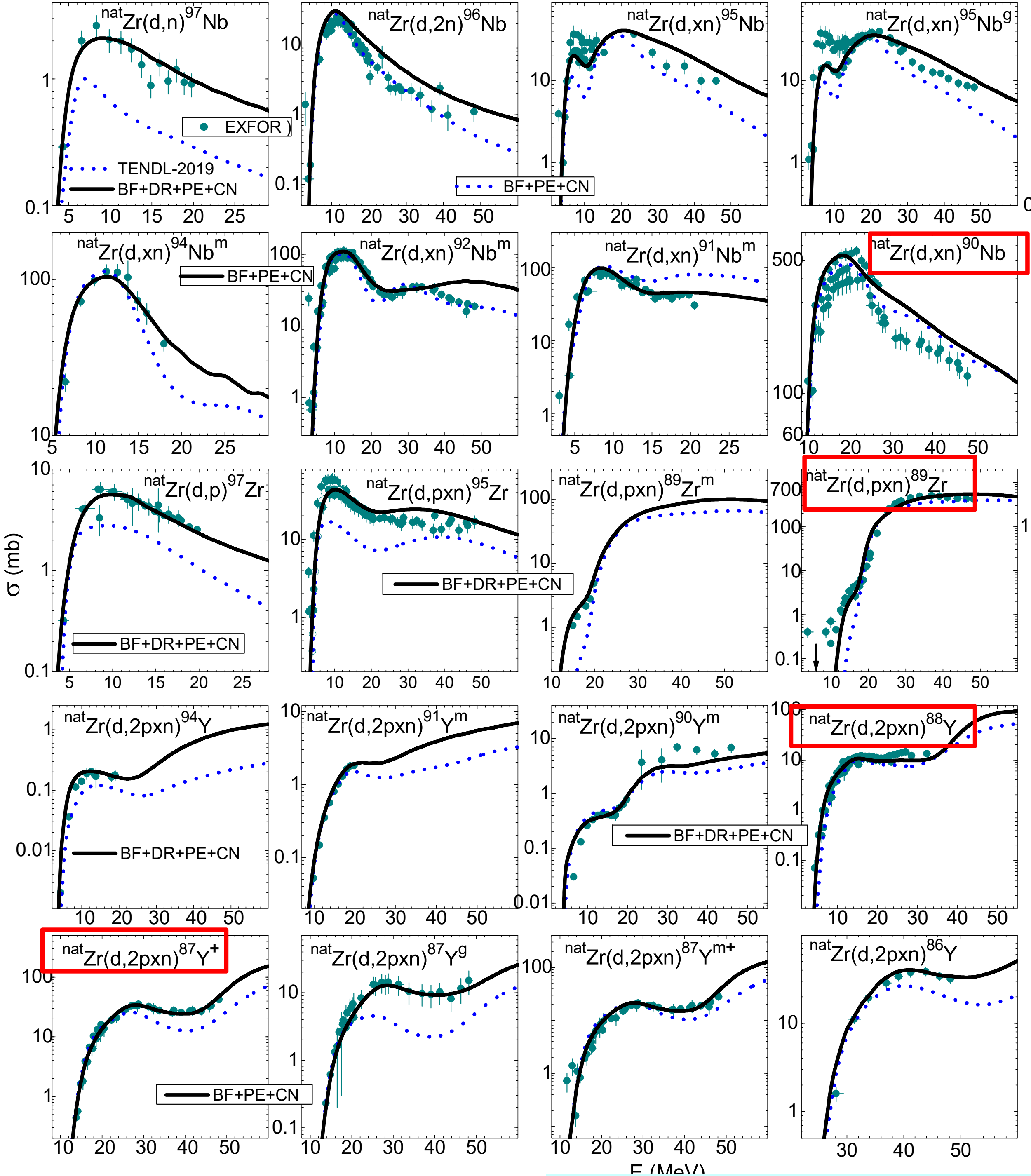
EUROfusion
d+Cr
d+Mn

SPIRAL 2
d+Zr

EUROfusion
d+Mo

$^{nat}Zr(d,x)$: Direct and Statistical Reaction Mechanisms

IFIN-HH



PHYSICAL REVIEW C 104, 044615 (2021)

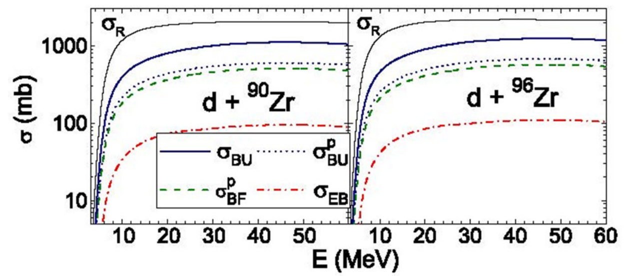
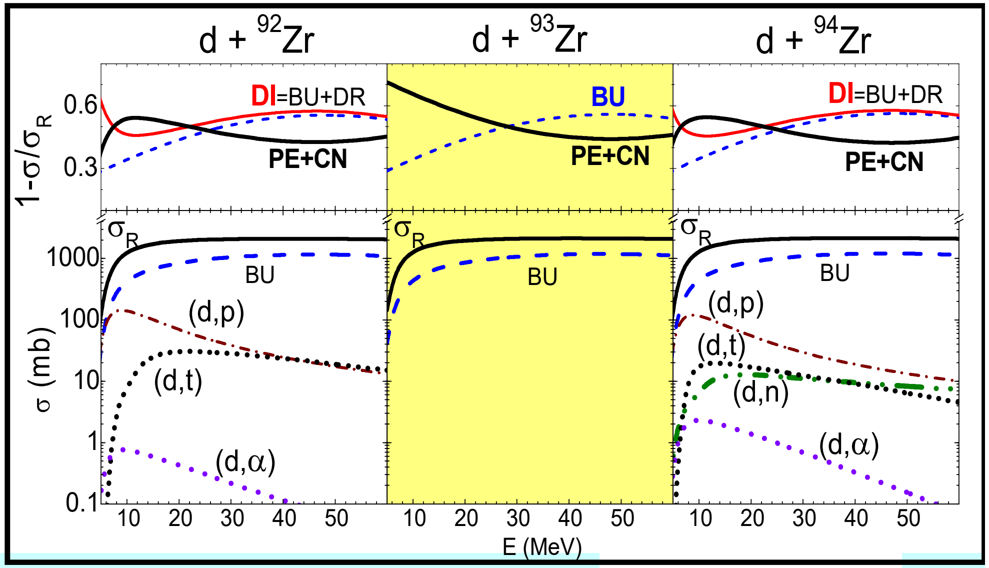


FIG. 2. The energy dependence of the deuteron total-reaction cross sections [30] (thin solid curves), total BU cross sections σ_{BU} (thick solid), and total BU proton-emission σ_{BU}^{p} (short-dashed), BF (dashed), and EB (dash-dotted) cross sections [15], for deuteron interactions with $^{90,96}Zr$ isotopes.

^{90}Zr	51.5%	stable		
^{91}Zr	11.2%	stable		
^{92}Zr	17.1%	stable		
^{93}Zr	trace	1.53×10^{6} y	β^-	^{93}Nb
^{94}Zr	17.4%	stable		
^{96}Zr	2.80%	2.0×10^{19} y[2]	$\beta^-\beta^-$	^{96}Mo



^{nat}Zr(d,x) activation analysis ⟶ predictions for ^{93}Zr(d,x)

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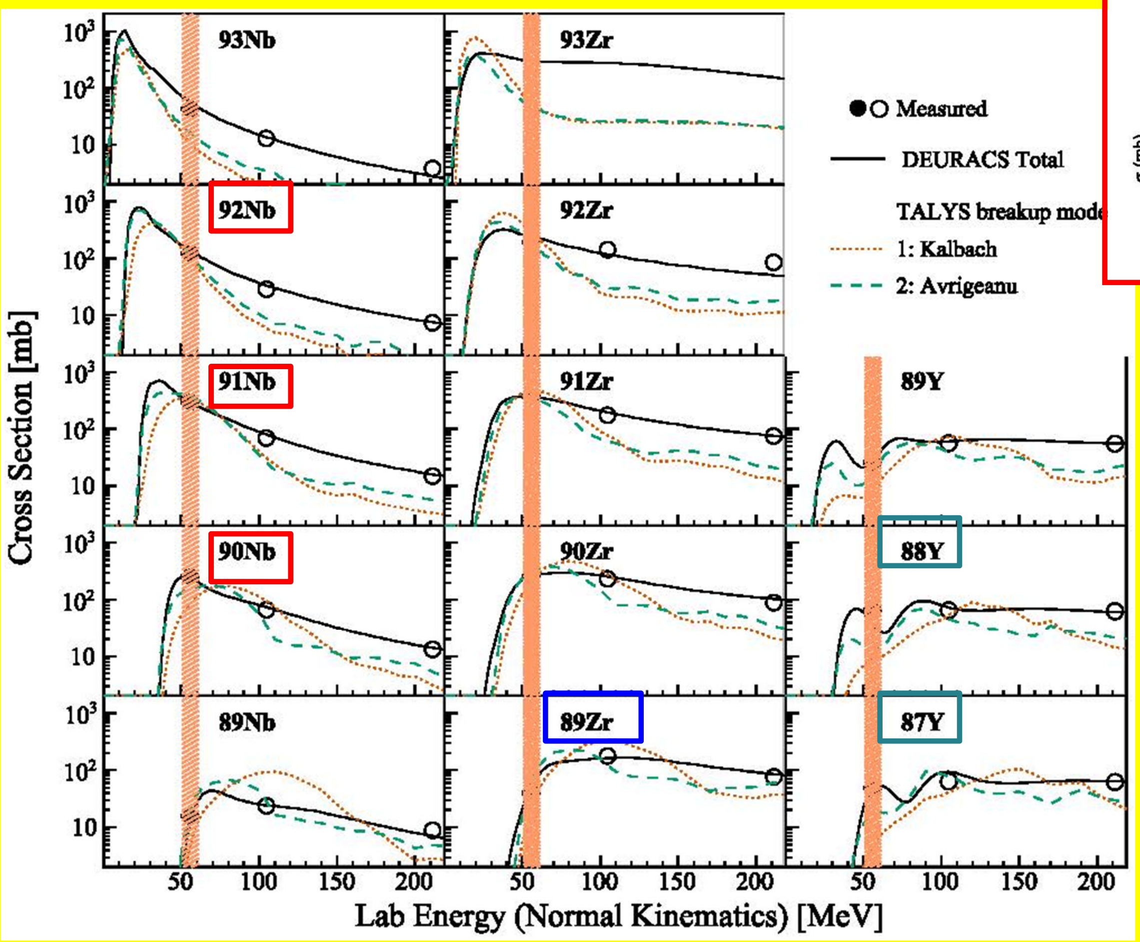
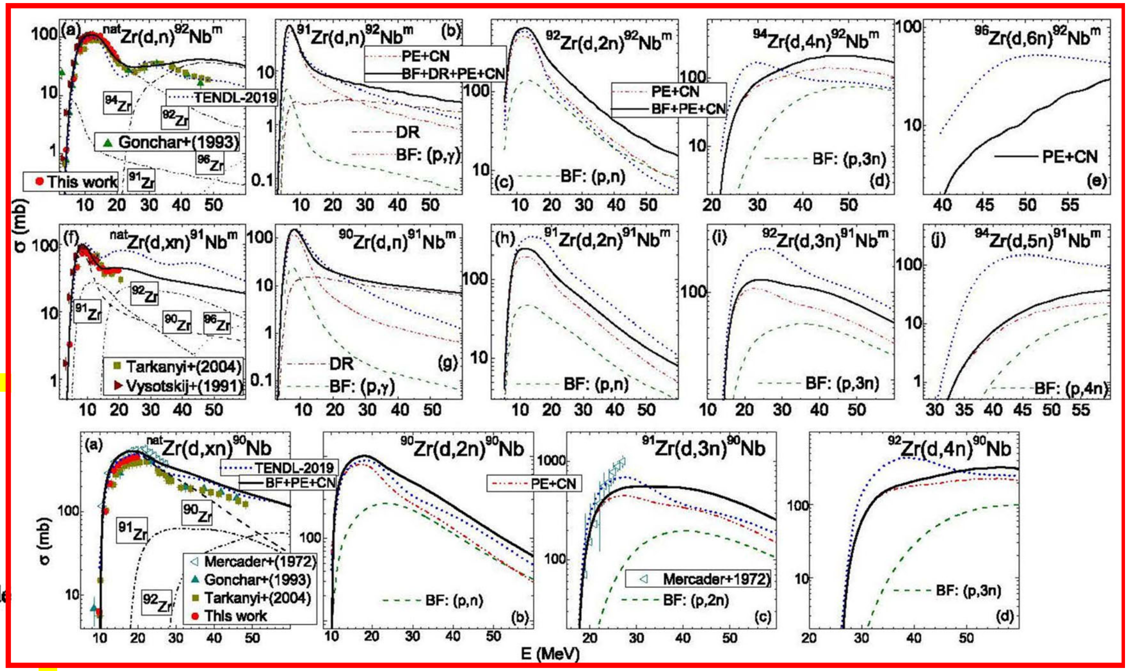
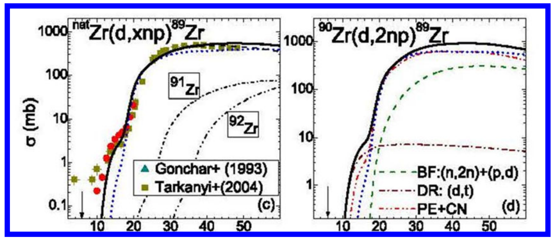
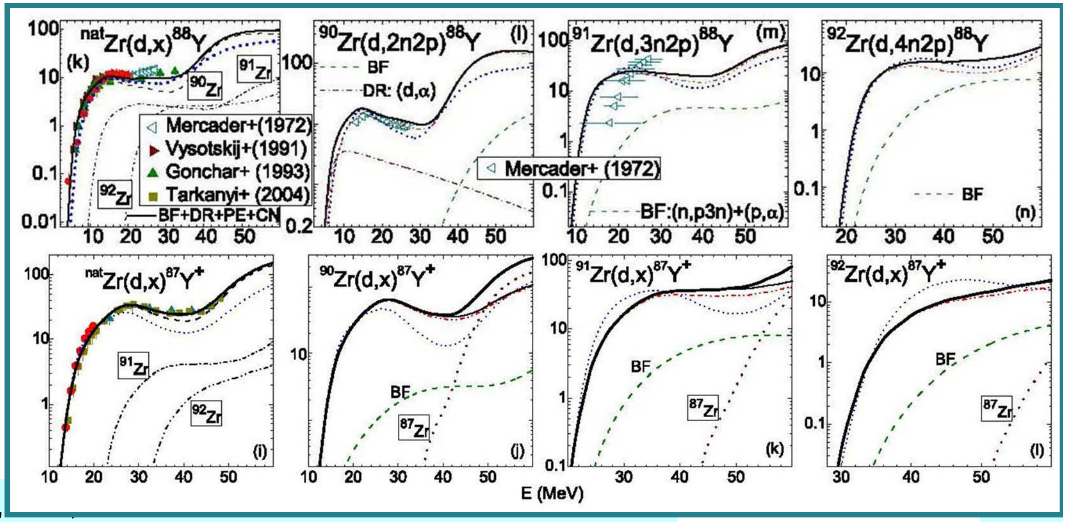


DEUTERON-INDUCED REACTIONS ON … PHYSICAL REVIEW C 104, 044615 (2021)

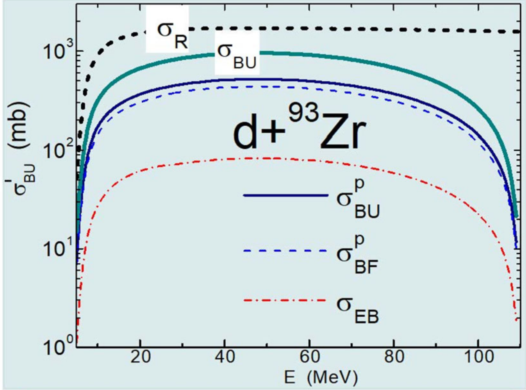




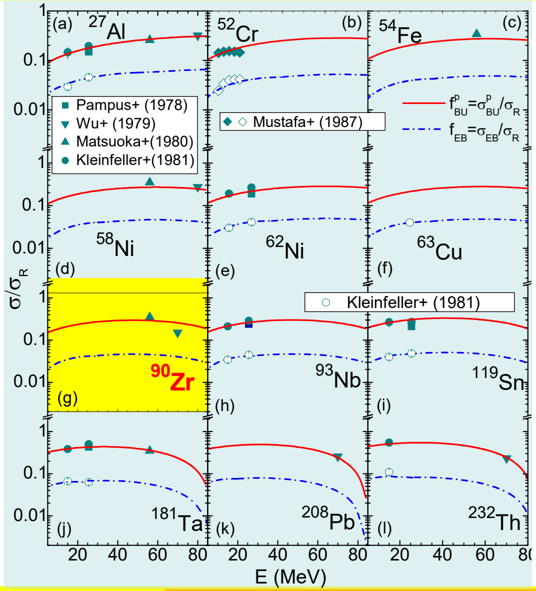


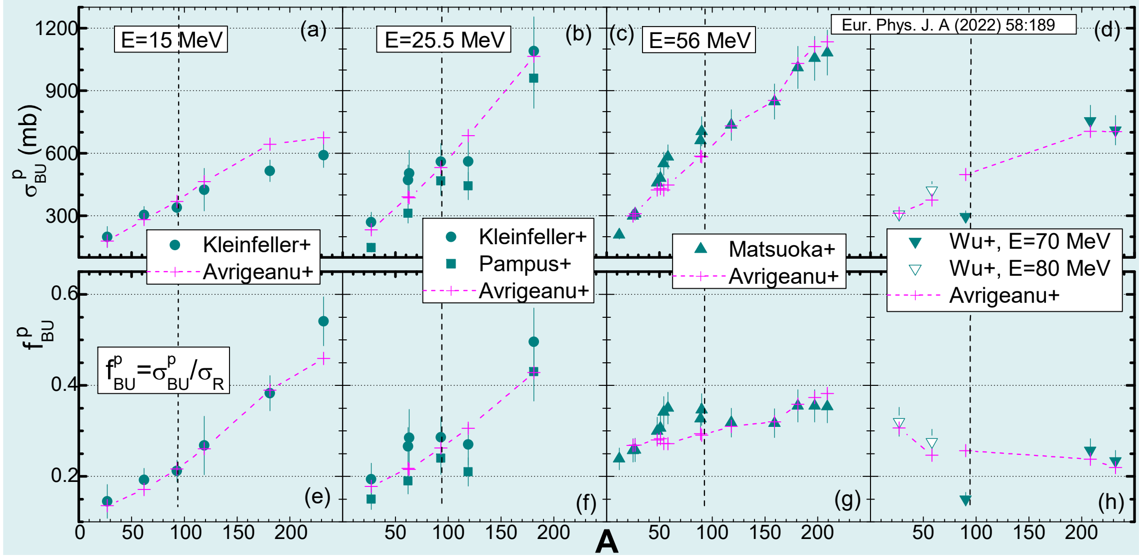
^{93}Zr(d,x): Studying impact of deuteron non-elastic breakup

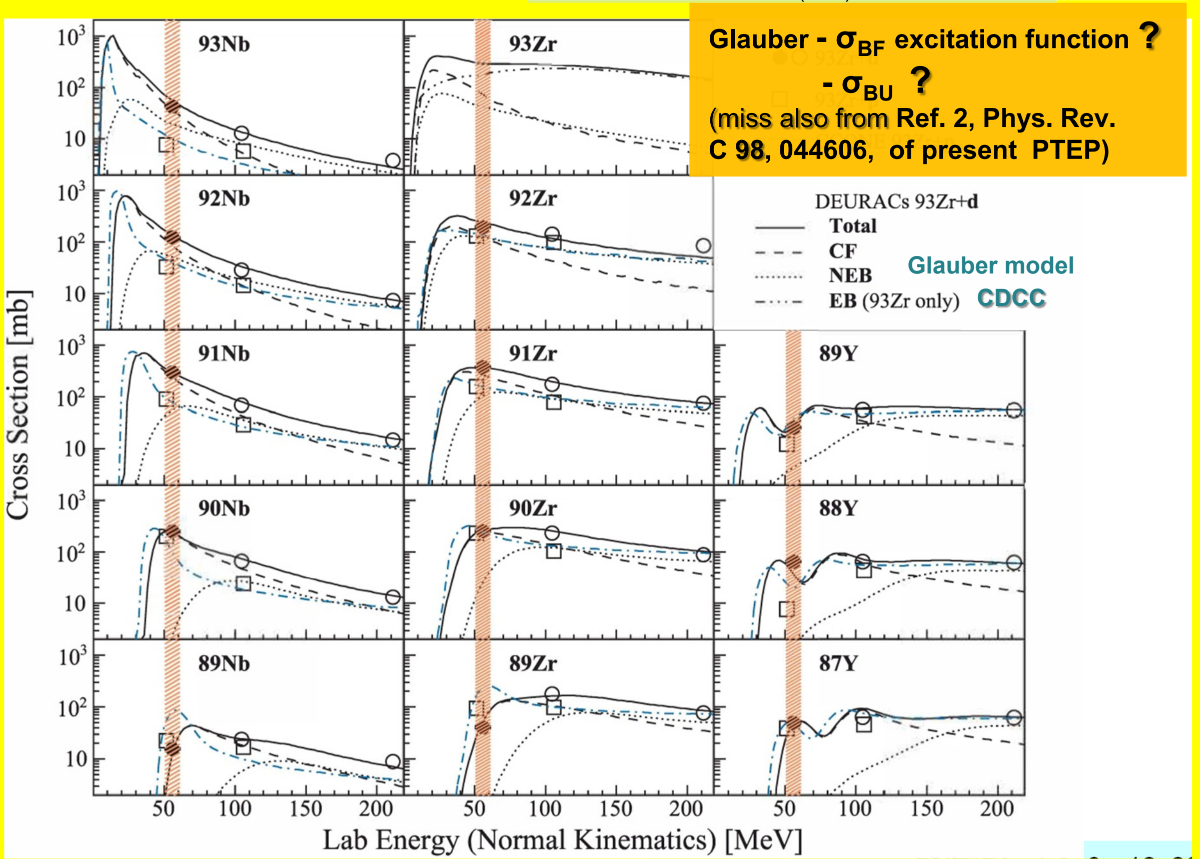
IFIN-HH



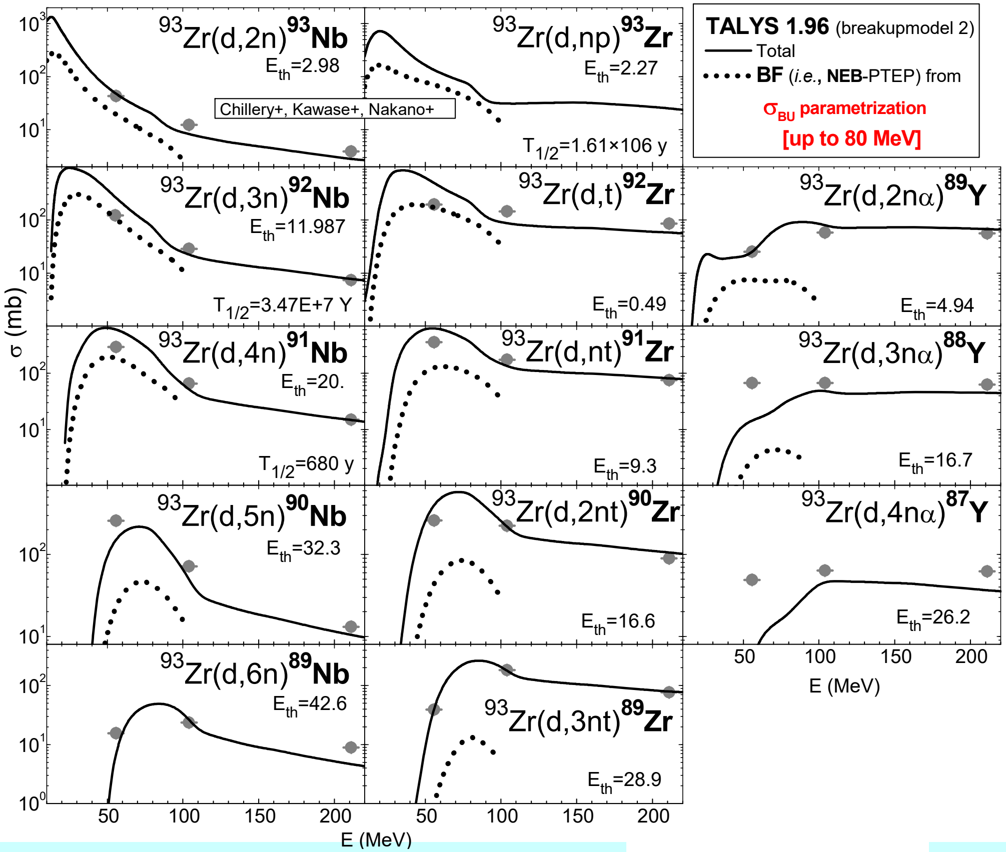
$$\sigma_{BF}^{p,x}(E) = \sigma_{BF}^{p}(E) \int dE_p \, \frac{\sigma_{(p,x)}(E_p)}{\sigma_R^p} \frac{1}{(2\pi)^{\frac{1}{2}} w} exp\left[-\frac{(E_p - E_p^0(E))^2}{2w^2}\right]$$







Glauber - σ_{BF} excitation function ?
- σ_{BU} ?
(miss also from Ref. 2, Phys. Rev. C 98, 044606, of present PTEP)



^{93}Zr(d,x) level density parameters adjustment

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TALYS 1.96 (breakupmodel 2)
— as PRC **104**, 044615 (2021)
— adjusted BSFG (a/Δ) by fit of *Nd, D0, Rho(Sn)* [Oslo CL]:
89Y: PRC **90**,044309(2014)
90Y: PRC **93**,045810(2016)
87-91Y: PRC **109**,054305(2024)

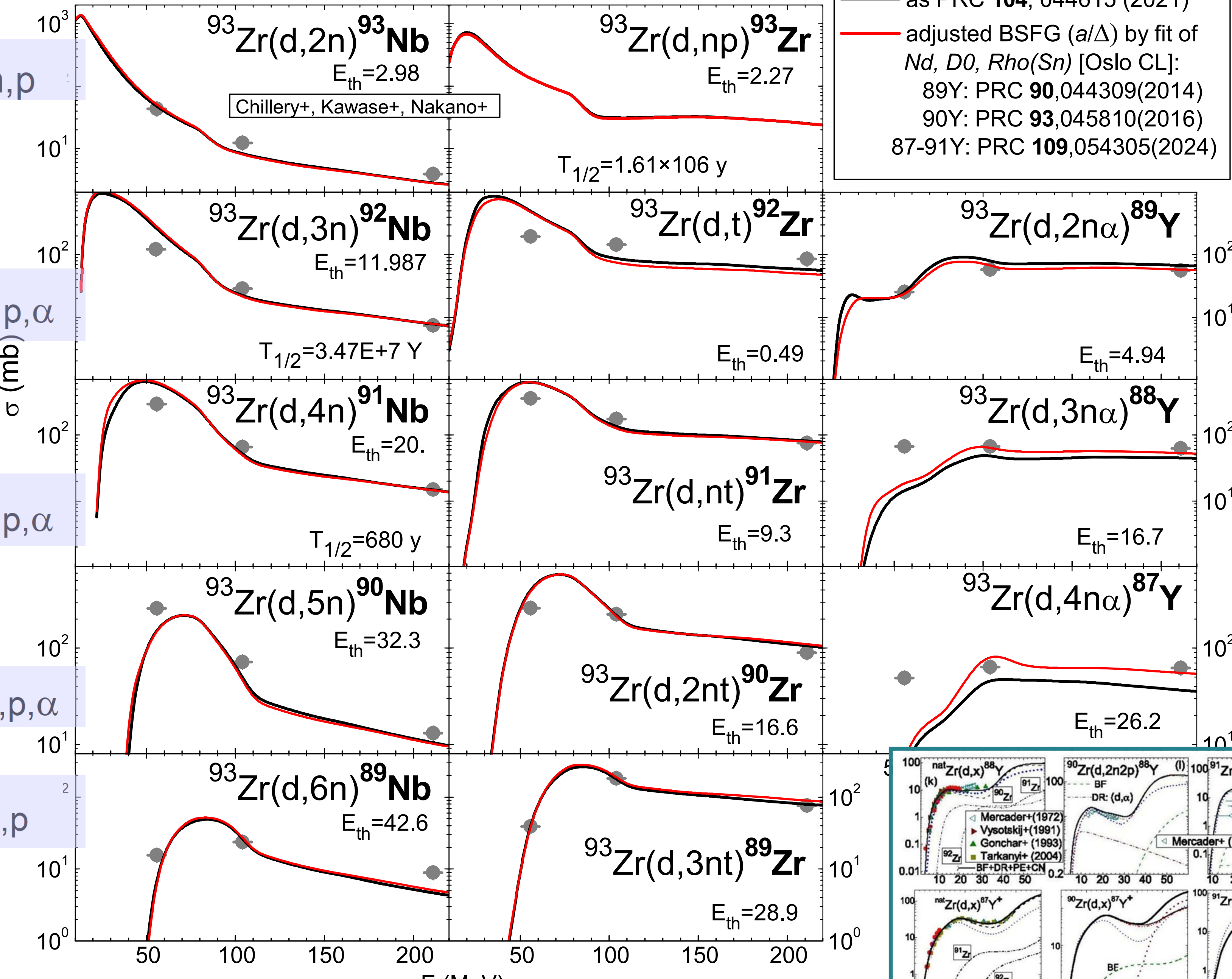
^{94}Nb* → n,p

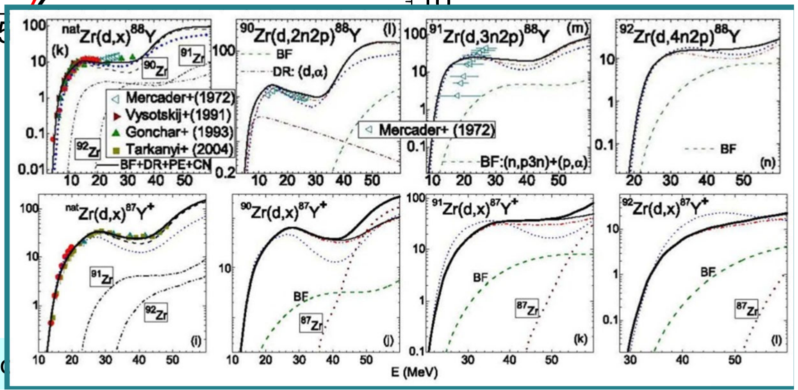
^{93}Nb* → n,p,α

^{92}Nb* → n,p,α

^{91}Nb* → n,p,α

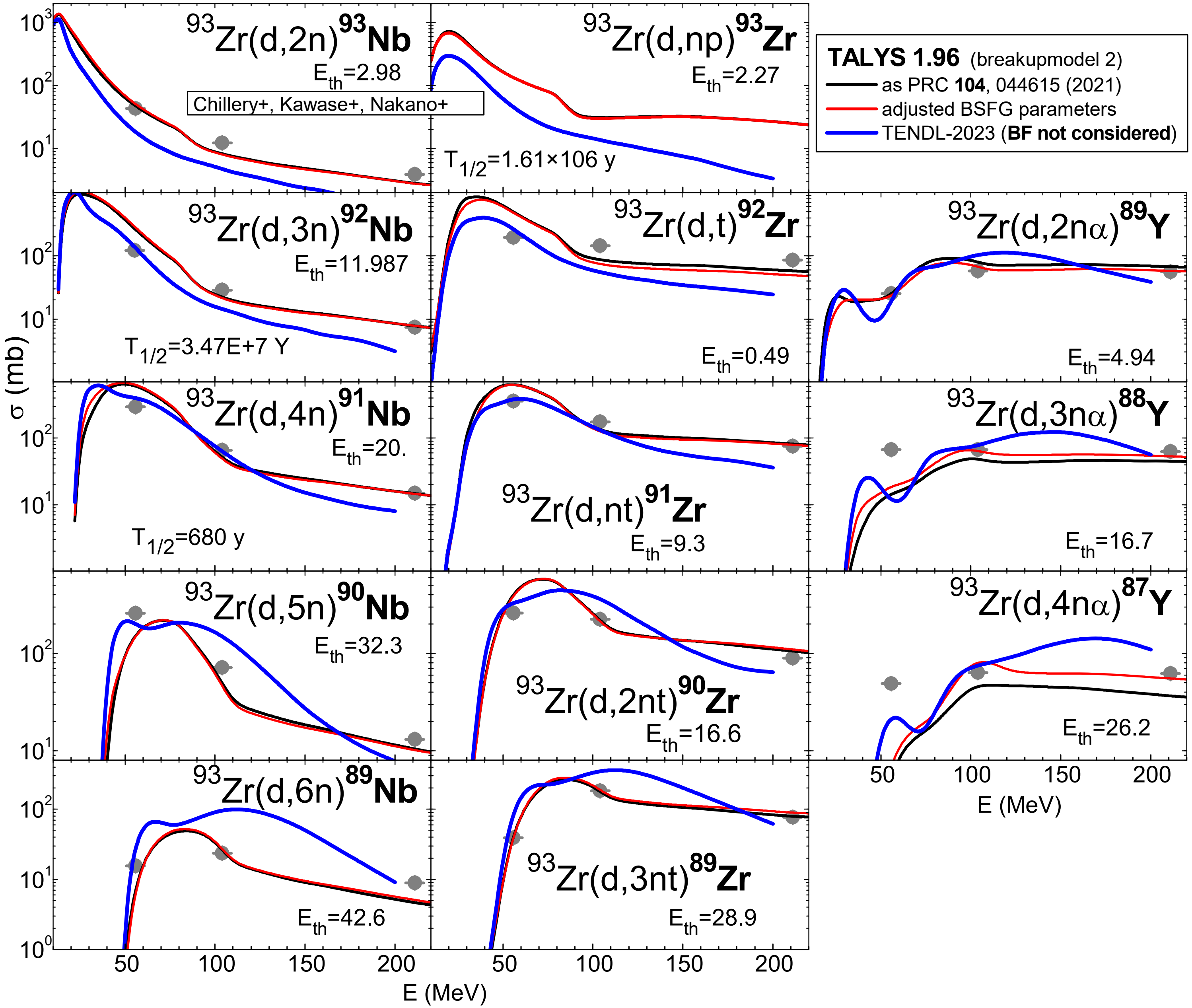
^{90}Nb* → n,p





CONCLUSIONS

Thank you!



Checked theoretical predictions for ^{93}Zr(d,xn), (d,xnp), (d,xn2p) activation involving:

- **BREAKUP (decreasing initial deuteron flux)**
- **BREAKUP ENHANCEMENT (increasing primary deuteron activation c.s.)**
- **PE, exciton, and CN, Hauser-Feshbach, mechanisms**

- **Neither model predictions nor TENDL-2023 ones describe measured $\sigma_{d,3n\alpha}$, $\sigma_{d,4n\alpha}$ at ~50 MeV**

- **Further deuteron activation measurements should be most useful**

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
(Received 1 July 2016; revised manuscript received 16 September 2016; published 27 Octob

The microscopic effective reaction theory is applied to deuteron-induced reactions. A reactio
characterized by a $p + n + A$ three-body model is adopted, where A is the target nucleus, and the

PHYSICAL REVIEW C 95, 024607 (2017)

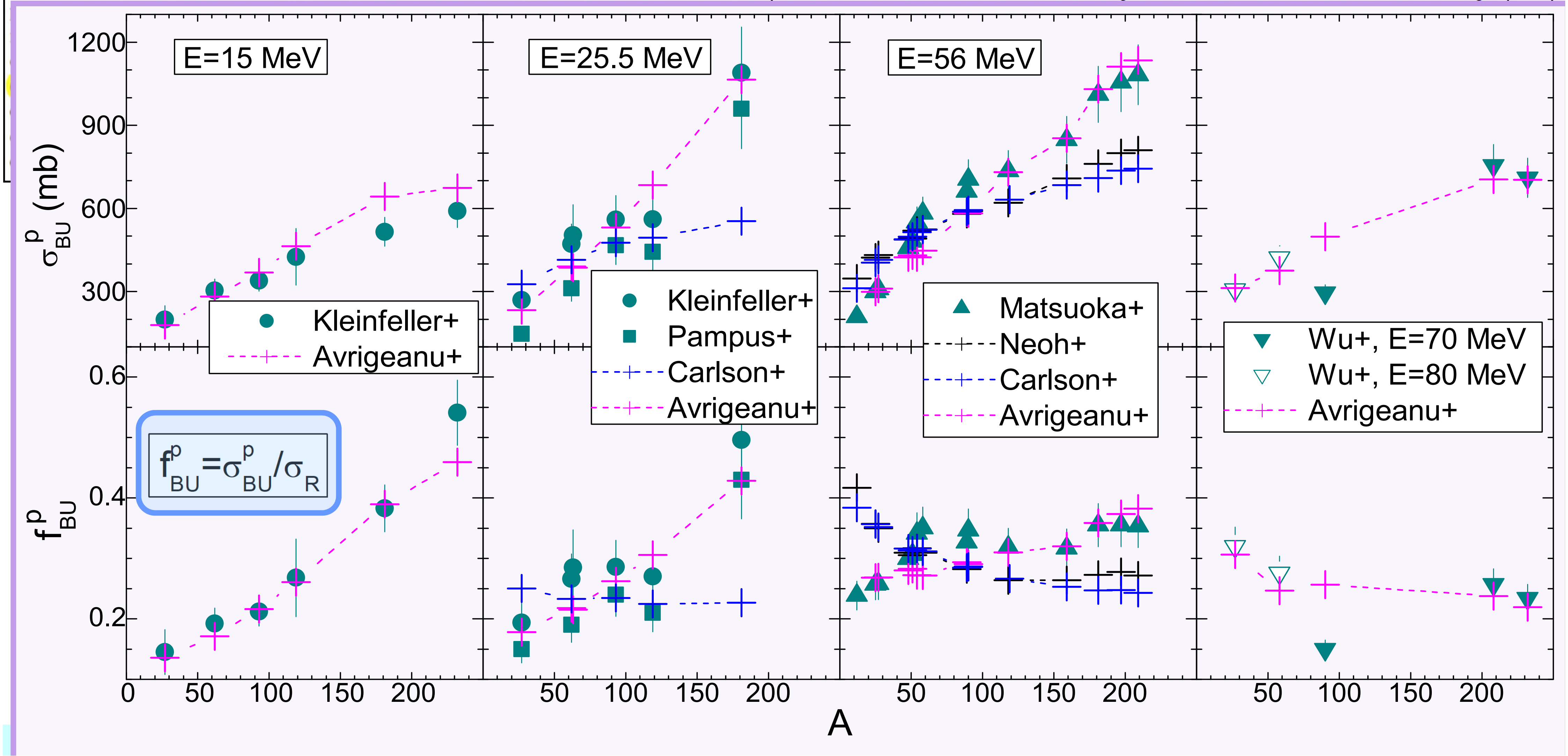
npirical parametrization and microscopic study of deuteron breakup

M. Avrigeanu* and V. Avrigeanu

Few-Body Syst (2016) 57:307–314
DOI 10.1007/s00601-016-1054-8

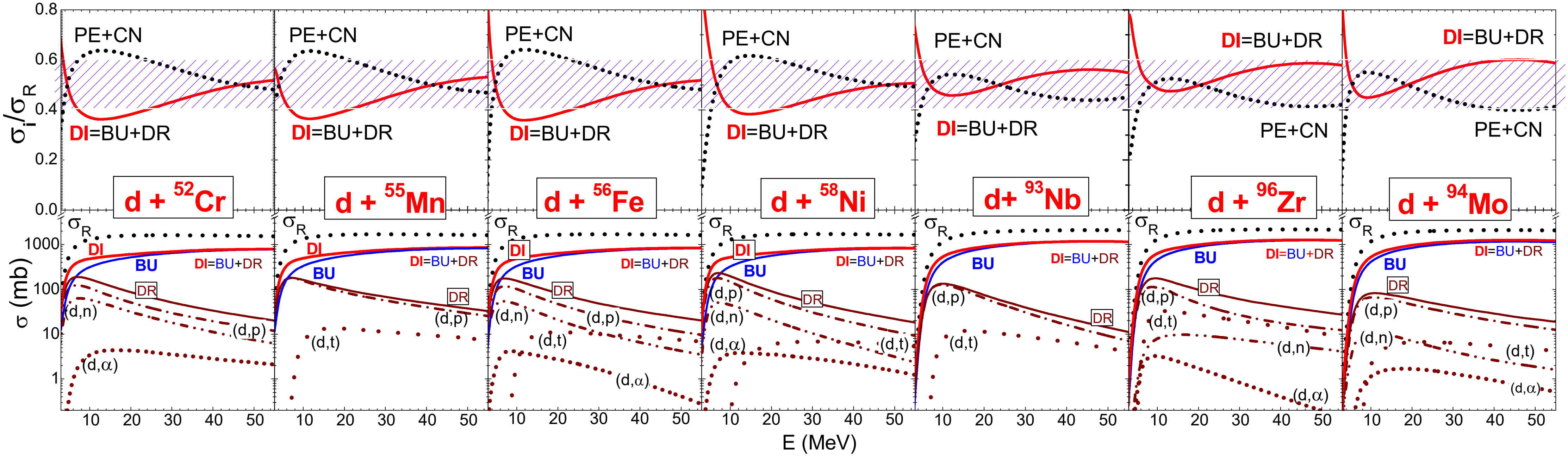
B. V. Carlson · R. Capote · M. Sin

Inclusive Proton Emission Spectra from Deuteron Breakup

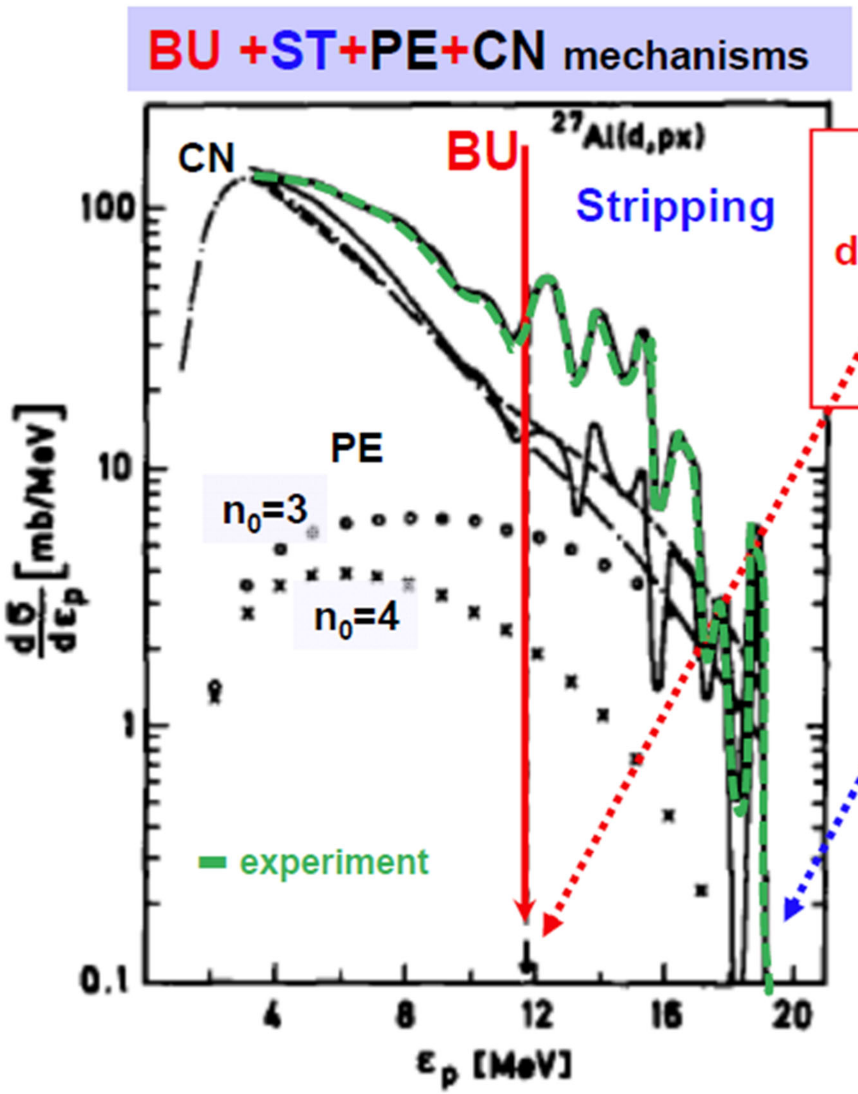


DI versus PE+CN

balance around half of deuteron reaction cross section, σ_R



Reactions Mechanisms in (d,p) Process



Nuclear Physics A370 (1981) 205–230

J. Kleinfeller et al. / Inclusive proton spectra

E_d =15 MeV (C.M. ~ 14 MeV)

BU: deuteron breakup

deuteron binding energy: B_d=2.225 MeV

$\varepsilon_p^{max} = E_d - B_d \sim 11.8$ MeV

$BU_{threshold} \sim 11.8$ MeV

ST: deuteron stripping

(d,p)

$Q_{Al(d,p)} = 5.5$ MeV

$\varepsilon_p^{max} \sim E_d + Q_{Al(d,p)}$ =19.5 MeV