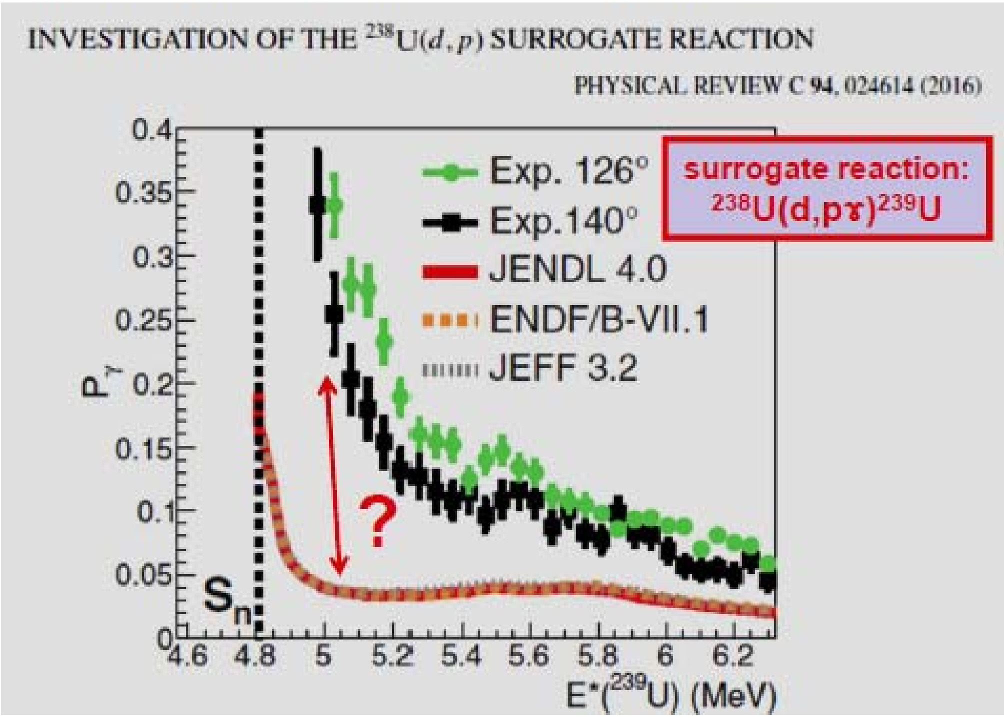
On deuteron interactions in surrogate (d,pɣ) reactions

Marilena Avrigeanu and Vlad Avrigeanu

r Physics & Nuclear Engineering (IFIN-HH),

arest, Romania



ms in deuteron interactions

Nuclear Models & CODES

: breakup, stripping & pick-up

3. Effects of DI on Deuteron Surrogate Reactions

4. Conclusions

Deuteron interaction analysis: Nuclear Models & CODES

Motivation: Nuclear Data Needs (FENDL, EURATOM, F4E, EUROfusion)

❖ITER, IFMIF, SPIRAL2, Breeder Reactors

❑REQUIRED deuteron reaction cross sections measurements & calculations

(E ~ 50 MeV): Al, Cu, Nb, Co, Mn, Fe, Cr, Ni, C…Th, U,

Reliable gas production cross-section data (H, He)

Dosimetry data file for E > 20 MeV (IRDF)

Surrogate reactions (d,pγ), (d,pf) on Th, U,…

❑ **Deuteron breakup**

BREAKUP [M. Avrigeanu, V. Avrigeanu]

- total, elastic and inelastic breakup c.s.: M. Avrigeanu *et al*., **Fusion. Eng. Design, 84, 418 (2009);**
  M. Avrigeanu and V. Avrigeanu, **Phys. Rev. C 95, 024607 (2017).**
- inelastic breakup enhancements : P. Bém *et al*., **Phys. Rev. C 79, 044610 (2009);**
  E. Šimečková *et al*., **Phys. Rev. C 84, 014605 (2011);**
  M. Avrigeanu *et al*., **Phys. Rev. C 85, 034603 (2012); 88, 014612 (2013);**
  89, 044613 (2014); **92**, 02160(R) (2015), **94**, 0146-6 (2016).

❑ **Direct reactions**

FRESCO (Version FRES 2.9, September 2011) [I.J. Thompson]

- **breakup:** elastic component (CDCC): M. Avrigeanu, A.M. Moro, **Phys. Rev. C 82, 037610 (2010).**
- **elastic transfer:** weakly bound systems: M. Avrigeanu *et al*., **Nucl. Phys. A 759, 327 (2005).**
- **stripping & pick-up:** (d,p), (d,n), (d,t), (d,α)

❑ **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**

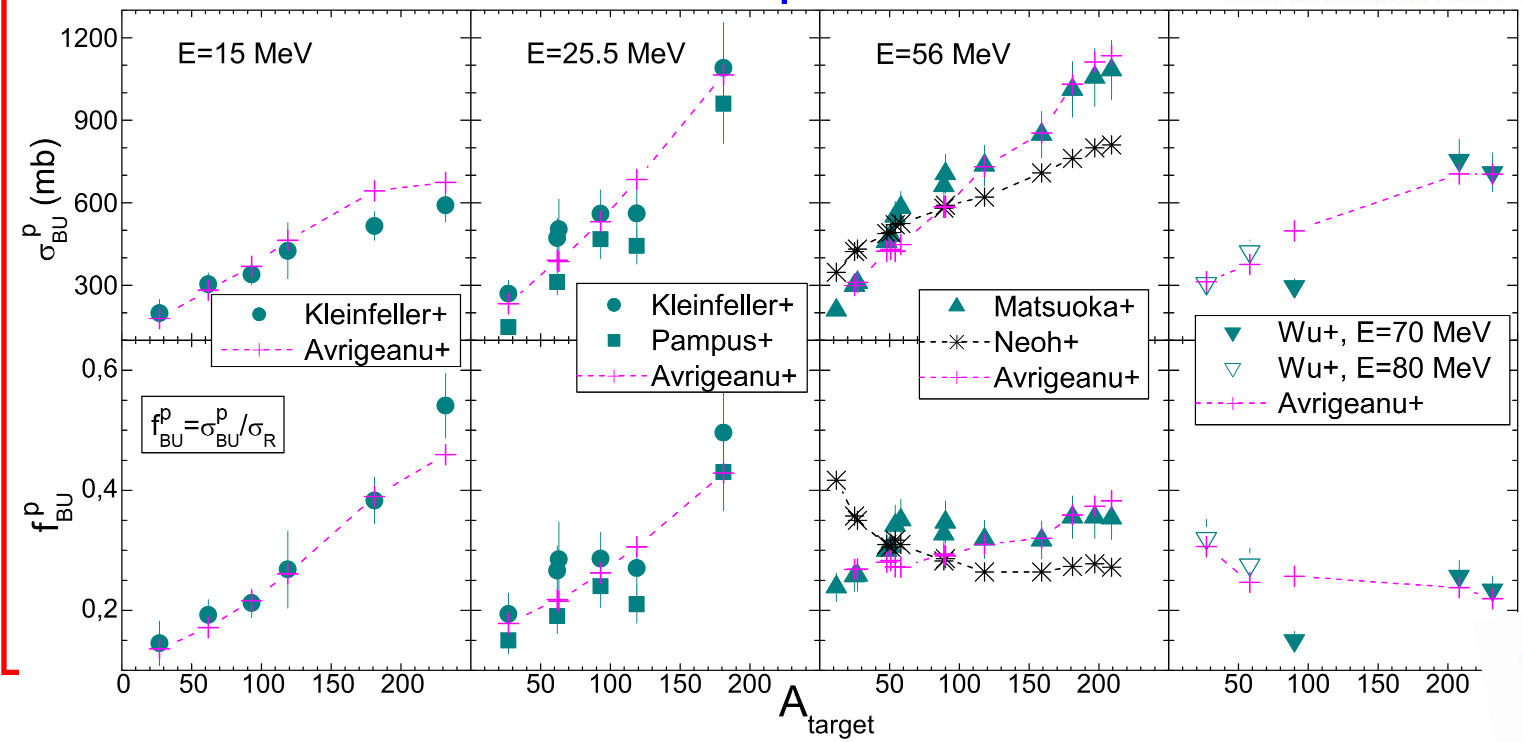
TALYS - 1.4 - 1.8 [A. Koning, S. Hilaire, M. Duijvestijn]

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

Empirical parametrization versus microscopic predictions

PHYSICAL REVIEW C **95**, 024607 (2017)

PHYSICAL REVIEW C **94**, 044619 (2016)



…y for deuteron-induced reactions

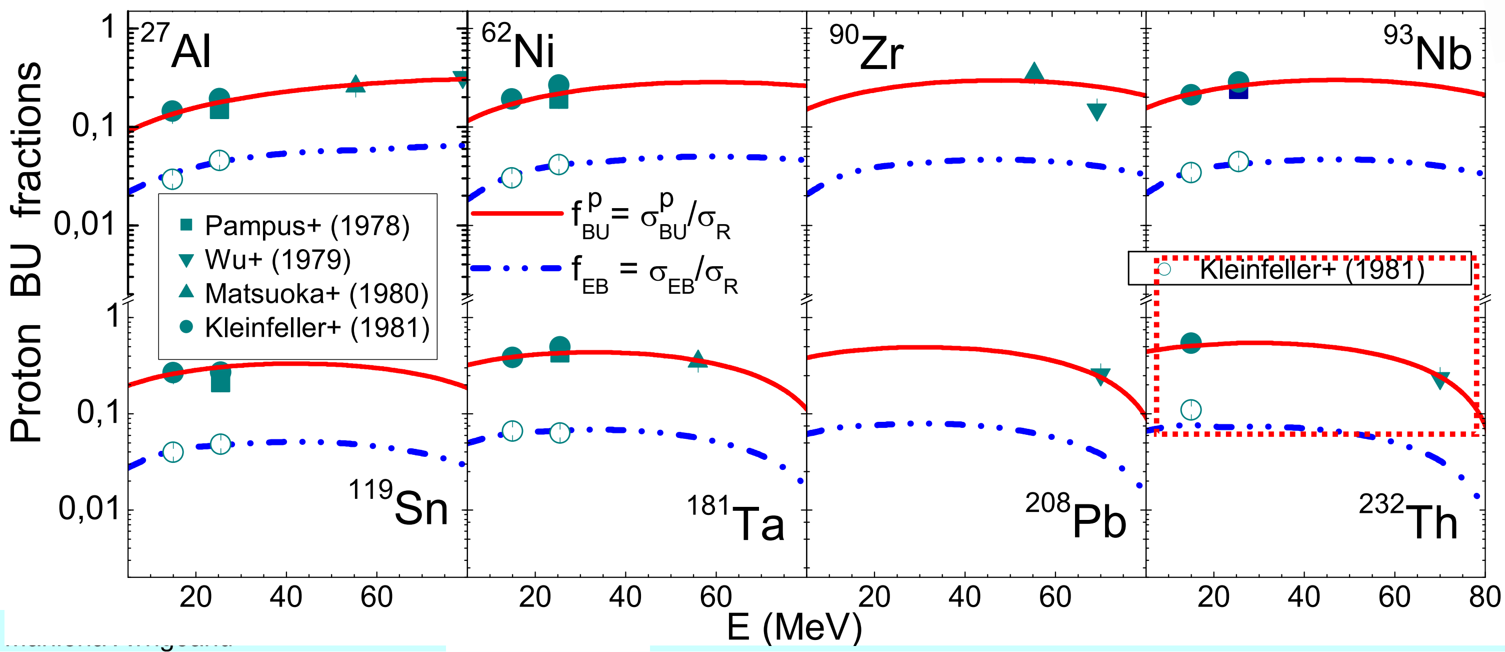
…ho Minomo, and Kazuyuki Ogata

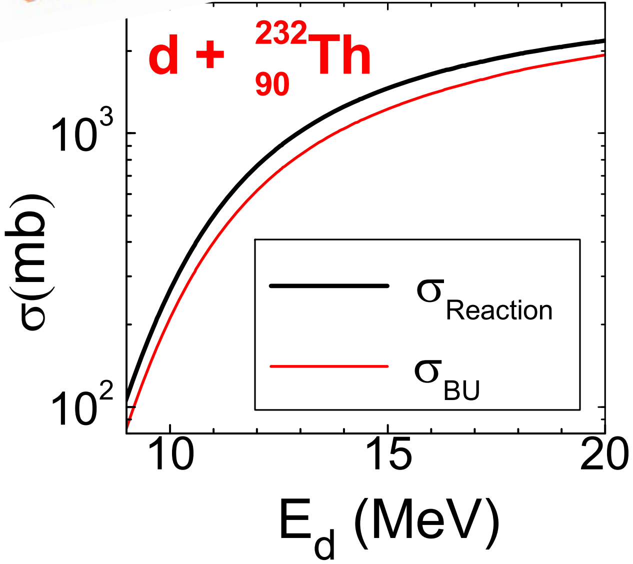
…a University, Ibaraki 567-0047, Japan

…6 September 2016; published 27 October 2016)

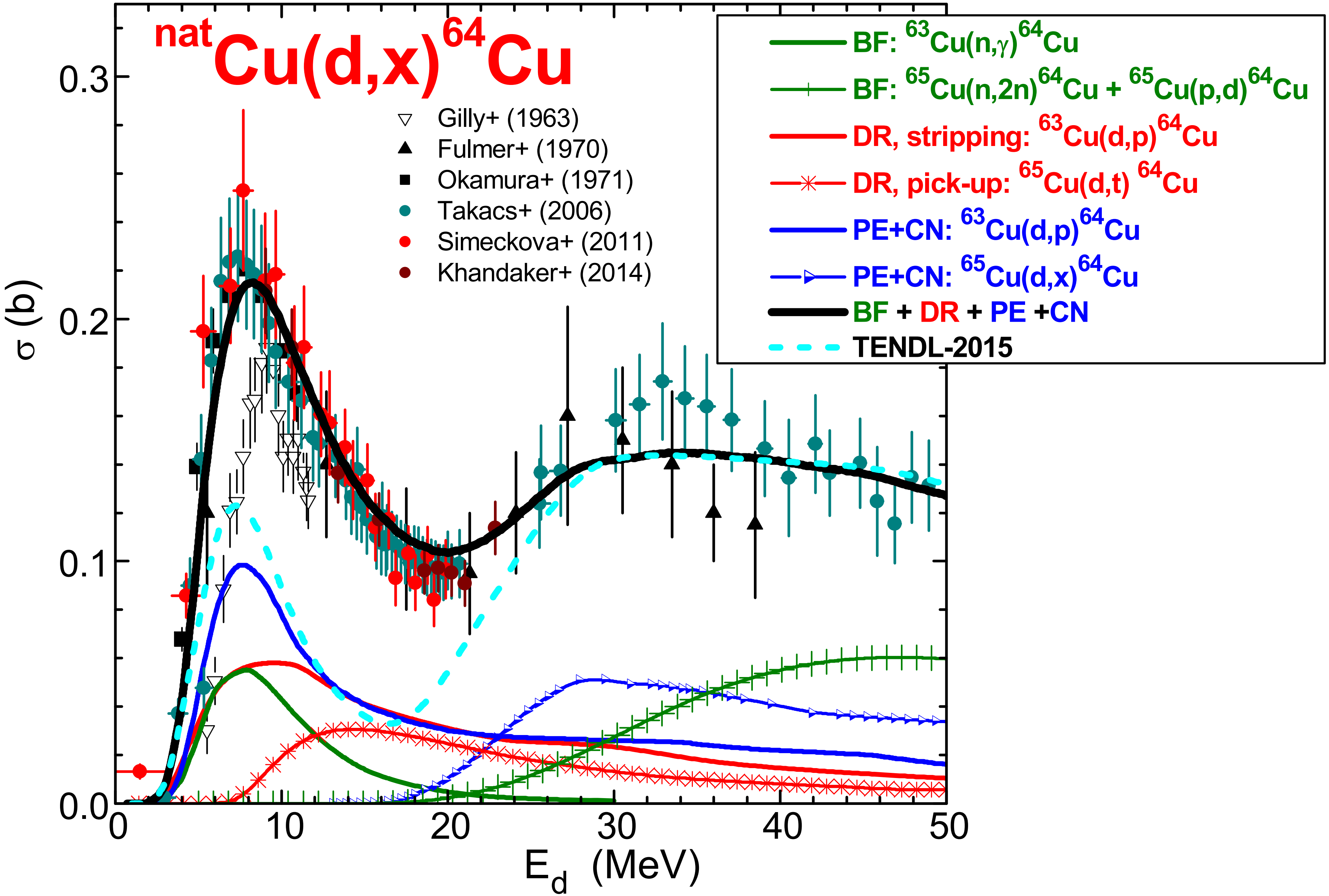
…deuteron-induced reactions. A reaction model space …, where *A* is the target nucleus, and the nucleon-target …on an effective nucleon-nucleon interaction in nuclear …body scattering wave function in the model space is …s (CDCC) method, and the eikonal reaction … of neutron removal cross secti… at several en…

breakup dominance for heavy nuclei and E_d~V_c



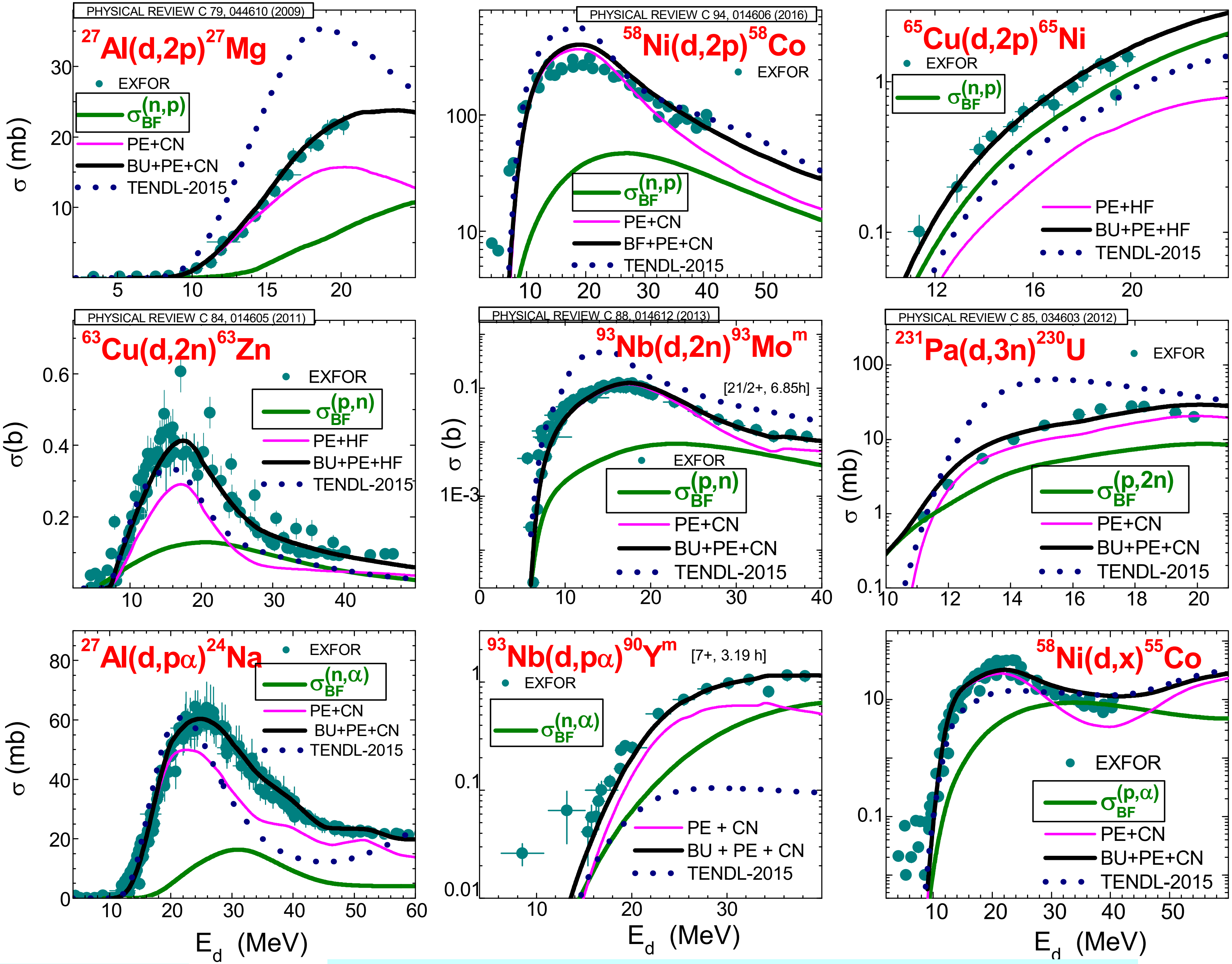


REACTION MECHANISMS INVOLVED in $^{nat}Cu(d,x)^{64}Cu$ PROCESS



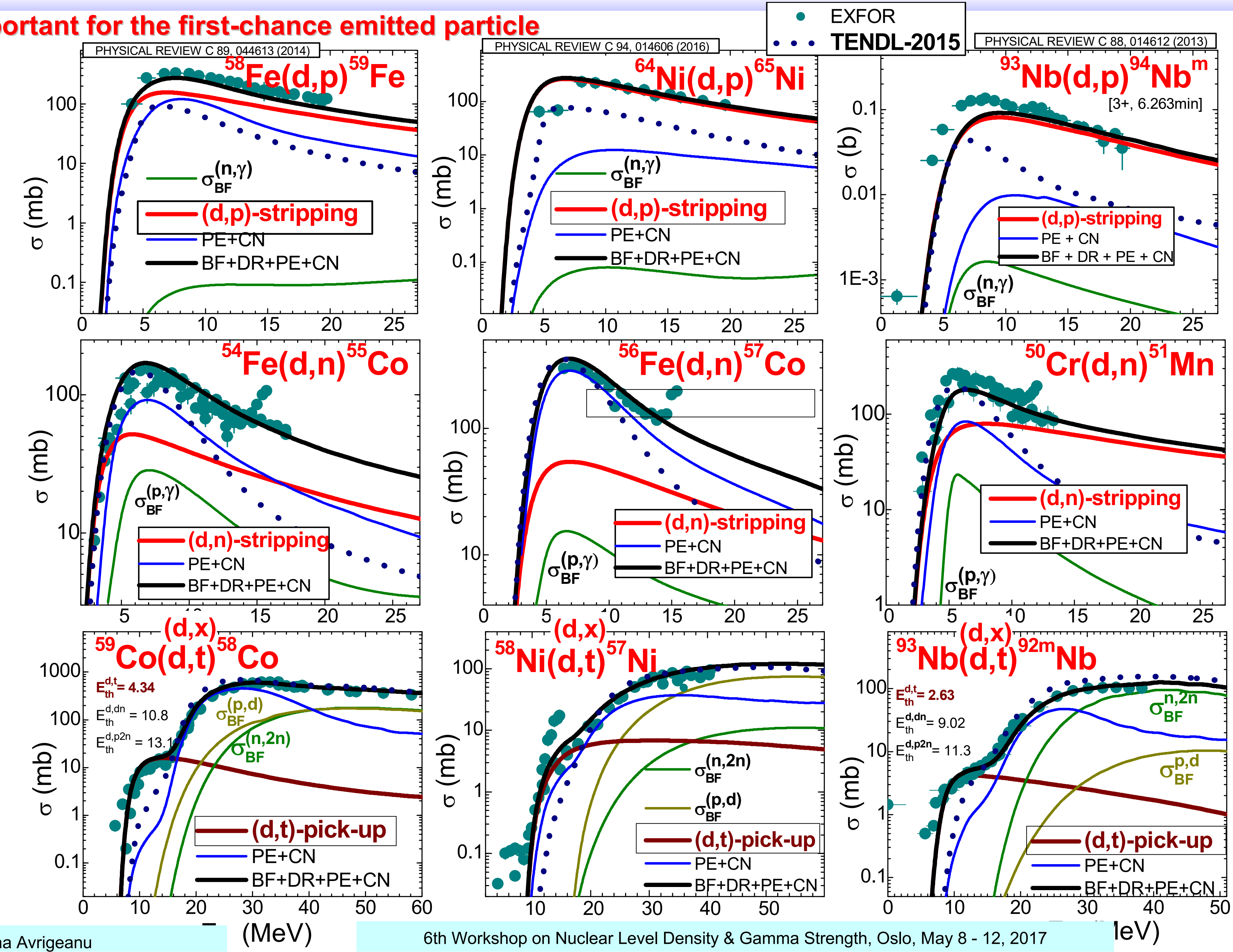
BREAKUP ENHANCEMENT:

$$\sigma^{p,x}_{BF}(E_d) = \sigma^{p}_{BF}(E_d)\int dE_p \; \frac{\sigma_{(p,x)}(E_p)}{\sigma^{p}_{R}} \frac{1}{(2\pi)^{\frac{1}{2}}w} exp[-\frac{(E_p - E^0_p(E_d))^2}{2w^2}]$$



ROLE OF DIRECT REACTIONS: STRIPPING & PICK-UP

Important for the first-chance emitted particle



SURROGATE REACTIONS: STRONG EFFECTS OF THE DEUTERON BREAKUP (1) $d+^{238}U$ INTERACTION

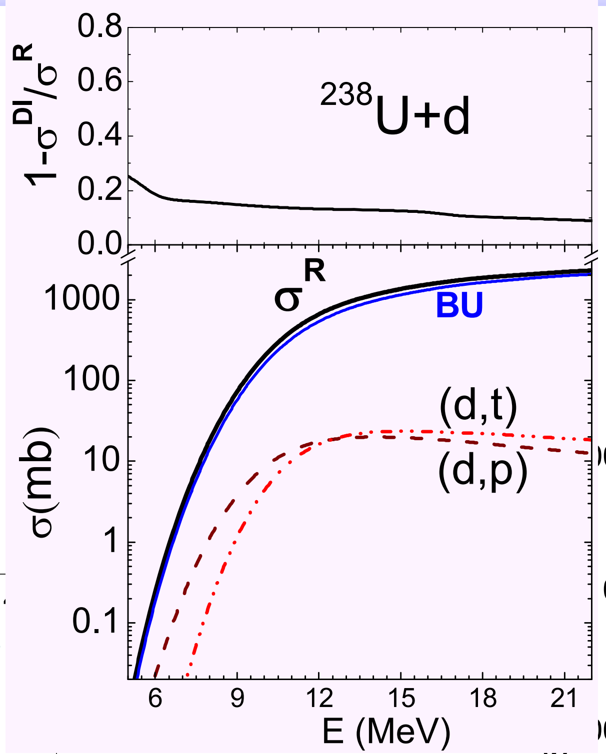
d-OMP: Haixia-Cai,
Phys. Rev. C73, 054605 (2006)

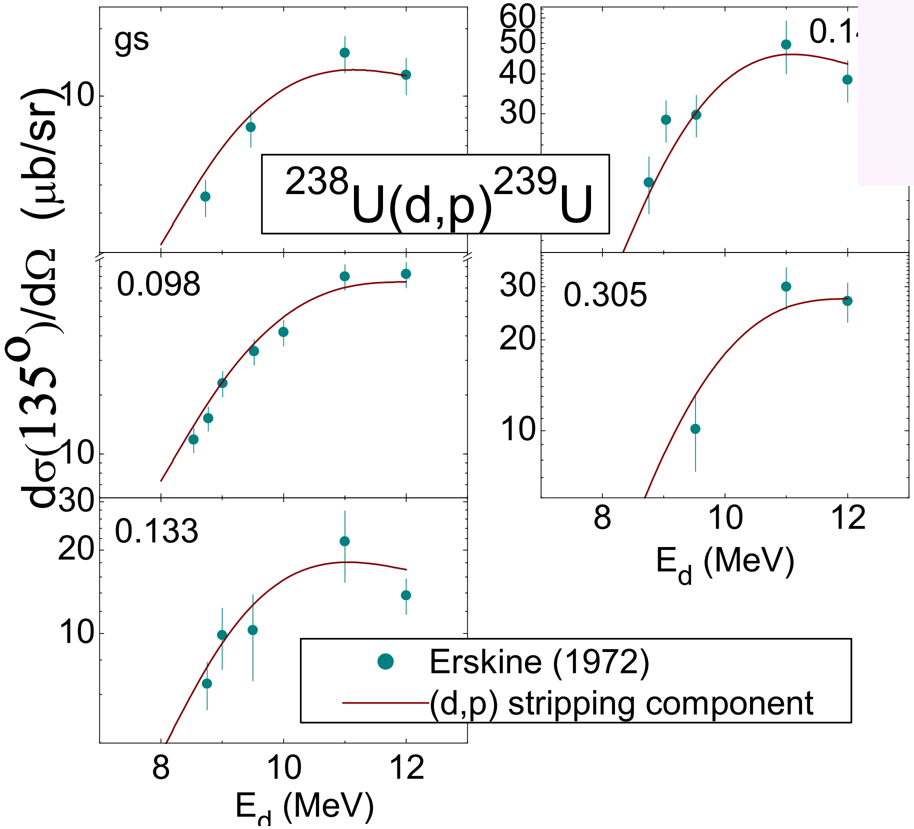
E_d=15 MeV: $1-\sigma^{DI}/\sigma^R$ =0.124

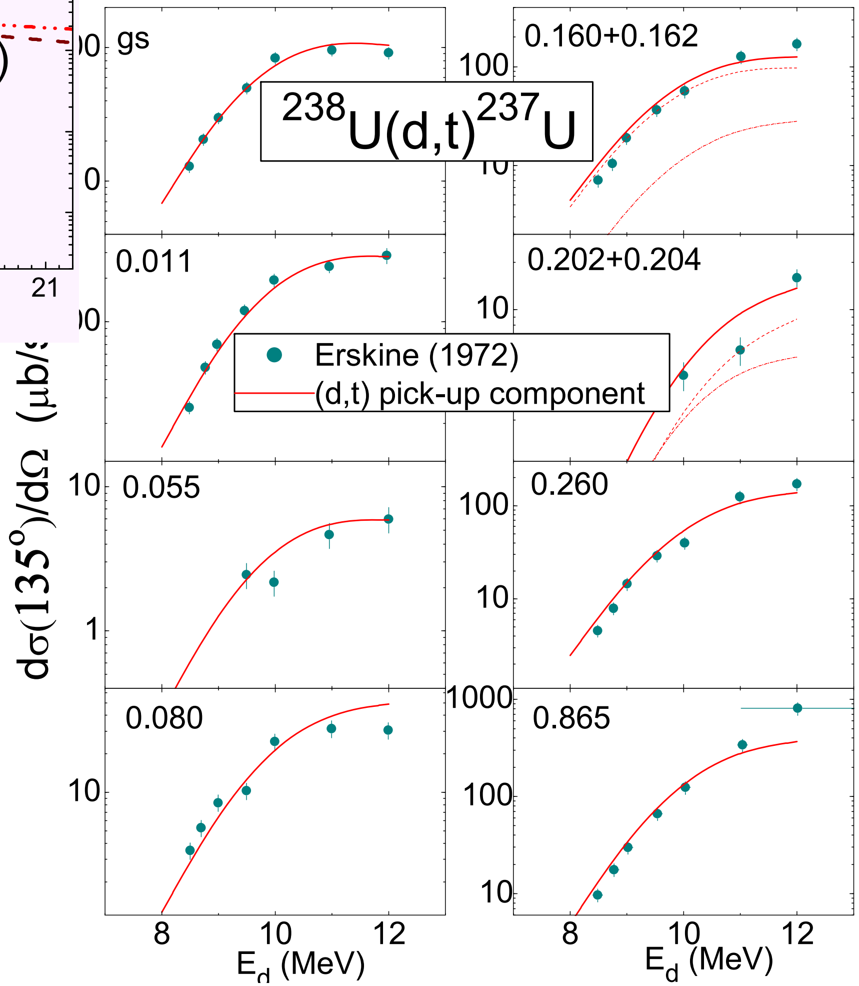
BU dominance
Warning for d-surrogates analyzed in CN frame

...ys. A789, 103 (2007)

p-OMP: Capote-Soukhovitski,
J. Nucl. Sc.&Tech 45, 333 (2008)







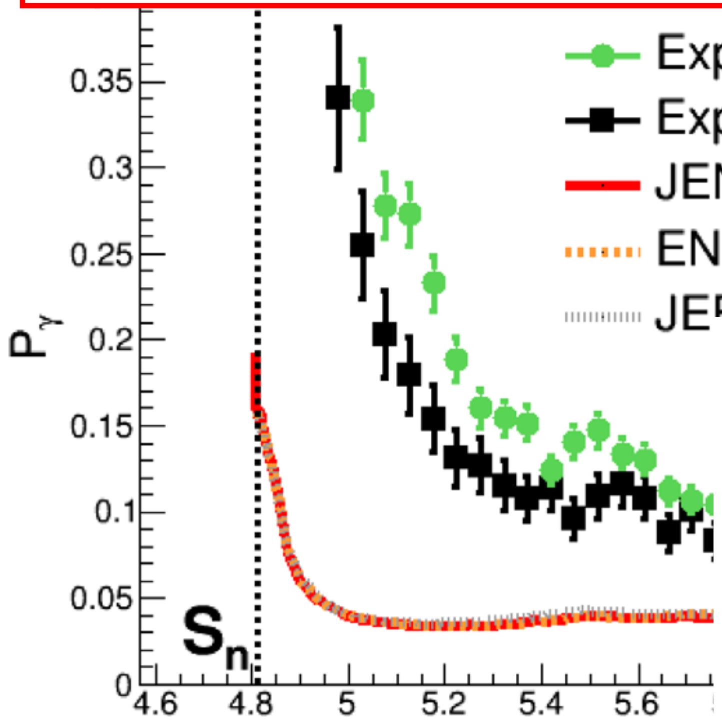
SURROGATE REACTIONS: STRONG EFFECTS OF THE DEUTERON BREAKUP (2)

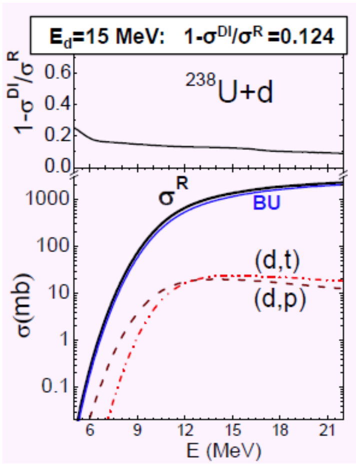
Investigation of the $^{238}U(d,p)$ surrogate reaction via the simultaneous measurement of γ-decay and fission probabilities

PHYSICAL REVIEW C **94**, 024614 (2016)

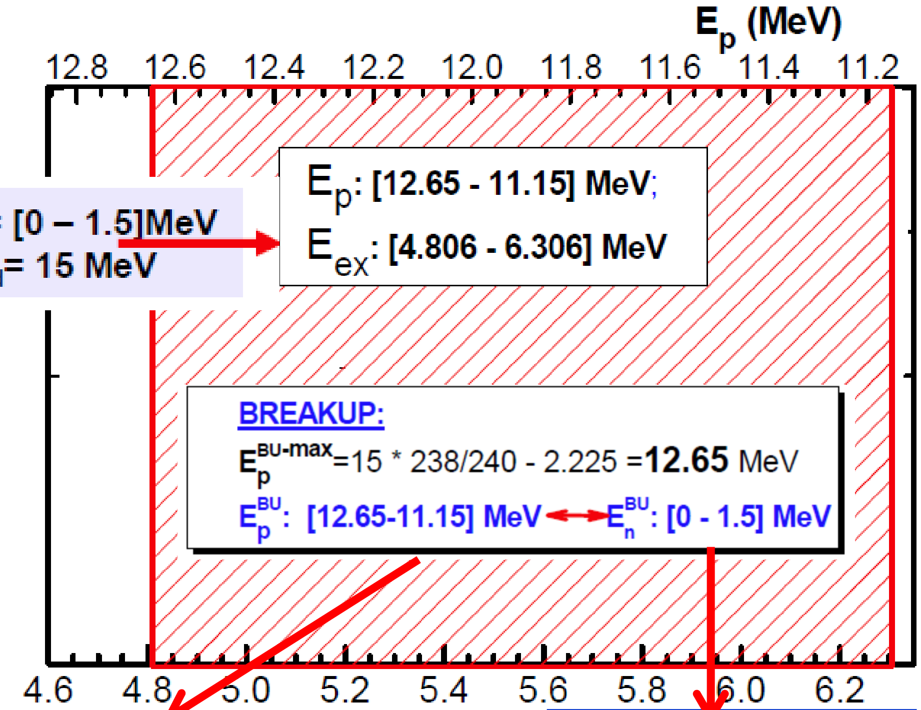
Q. Ducasse,[1,2] B. Jurado,[1,*] M. Aïche,[1] P. Marini,[1] L. Mathieu,[1] A. Görgen,[3] M. Guttormsen,[3] A. C. Larsen,[3] T. Tornyi,[3] J. N. Wilson,[4] G. Barreau,[1] G. Boutoux,[5] S. Czajkowski,[1] F. Giacoppo,[3] F. Gunsing,[6] T. W. Hagen,[3] M. Lebois,[4] J. Lei,[7] V. Méot,[5] B. Morillon,[5] A. M. Moro,[7] T. Renstrøm,[3] O. Roig,[5] S. J. Rose,[3] O. Sérot,[2] S. Siem,[3] I. Tsekhanovich,[1] G. M. Tveten,[3] and M. Wiedeking[8]

$$\sigma^{WE}_{n,\gamma}(E_n) = \sigma^{CN}_{n}(E_n) P^{exp}_{d,p\gamma}(E_{ex}) = \sigma^{CN}_{n}(E_n) \frac{N^{coincidences}_{p,\gamma}(E_{ex})}{N^{surrogateevents}_{d,p}(E_{ex})}$$





$(n,\gamma)^{239}U$; E_n= [0 – 1.5]MeV
$(d,p\gamma)^{239}U$; E_d= 15 MeV



E_p: [12.65 - 11.15] MeV;
E_{ex}: [4.806 - 6.306] MeV

BREAKUP:
E_p^{BU-max}=15 * 238/240 - 2.225 =**12.65** MeV
E_p^{BU}: [12.65-11.15] MeV ⟷ E_n^{BU}: [0 - 1.5] MeV

$$P^{exp}_{d,p\gamma}(E_{ex}) = \frac{N^{coincidences}_{p,\gamma}(E_{ex})}{N^{surrogateevents}_{d,p}(E_{ex})}$$

inelastic breakup enhancement
$^{238}U(n^{BF},\gamma)^{239}U$

$$P_{d,p\gamma}(E_{ex}) = \Sigma_{J,\pi} F^{CN}_{d,p}(E_{ex},J,\pi) G^{CN}_{\gamma}(E_{ex},J,\pi) \approx P^{exp}_{d,p\gamma}(E_{ex})$$

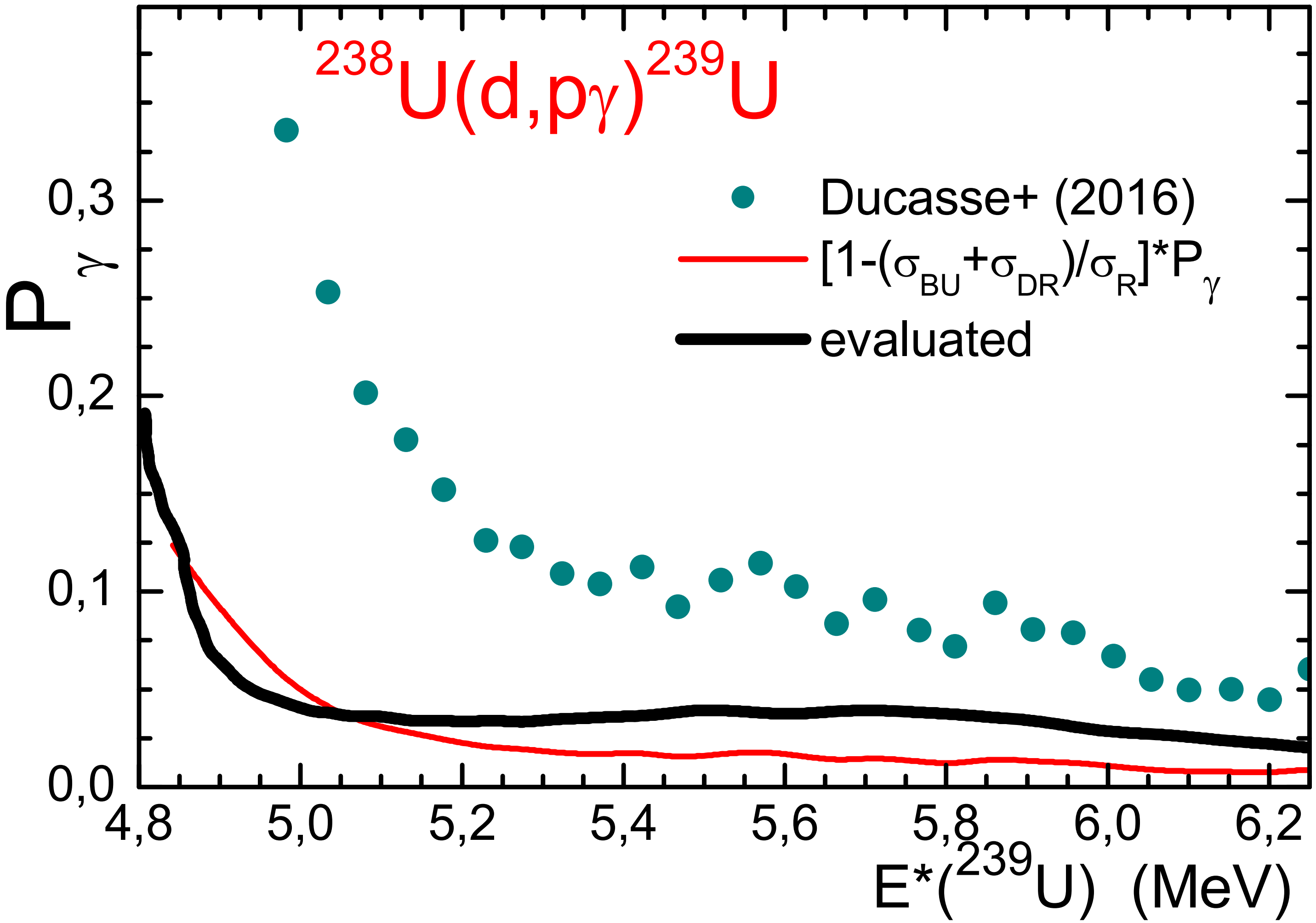
mechanism			model
$^{239}U^*$: BF	$n^{BF}+^{238}U \rightarrow$	$^{239}U^*$	phenomenologic
DR	$d+^{238}U \rightarrow$	$p+^{239}U^*$	DWBA
	$^{238}U \rightarrow$	$^{240}Np^* \rightarrow p+^{239}U^*$	H-F

CN mechanism, too restrictive frame for d-surrogate

LARGE leakage of d flux through BU + DR before CN formation

Corrected P_γ by d-flux leakage through DI (frac=0.124)

$$P_{d,p\gamma}(E_{ex}) = \Sigma_{J,\pi} \mathbf{F^{CN}_{d,p}(E_{ex}, J, \pi)} G^{CN}_{\gamma}(E_{ex}, J, \pi) \approx P^{exp}_{d,p\gamma}(E_{ex})$$



CONCLUSIONS

Thank you!

Nuclear Reactions Analysis of

deuteron induced reactions

should consider

BREAKUP & STRIPPING / PICK-UP EFFECTS

- DIRECT INTERACTIONS (DI) effects to d interactions
  - BREAKUP: DOMINANT for heavy targets at E_d~V_C surrogate
  - BREAKUP ENHANCEMENT of activation C.S. surrogate
  - (d,t) pick-up exclusive contribution at low-energy EF part

- **PE & EVAPORATION** cross sections **corrected** for initial flux leakage towards **DIRECT INTERACTIONS**

- **UPDATE FOR DEUTERON SURROGATE MODEL**

Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production (1)

Table 3: Cross-section studies of monitor reactions. January 2017

Cross sections	Agreed responsibilities, status and actions
$^{27}Al(d,x)^{22,24}Na$	Accept Pade 21 fit for ^{22}Na up to 100 MeV. For ^{24}Na, some points were excluded. Accept Pade 12 fit up to 100 MeV.

NO accompanying figure

vs.

See FENDL-report: INDC(NDS)-0645, pp. 51, November 2013

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

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

P. Bém,* E. Šimečková, and M. Honusek
Euratom/IPP.CR Fusion Association, Nuclear Physics Institute, 25068 Řež, Czech Republic

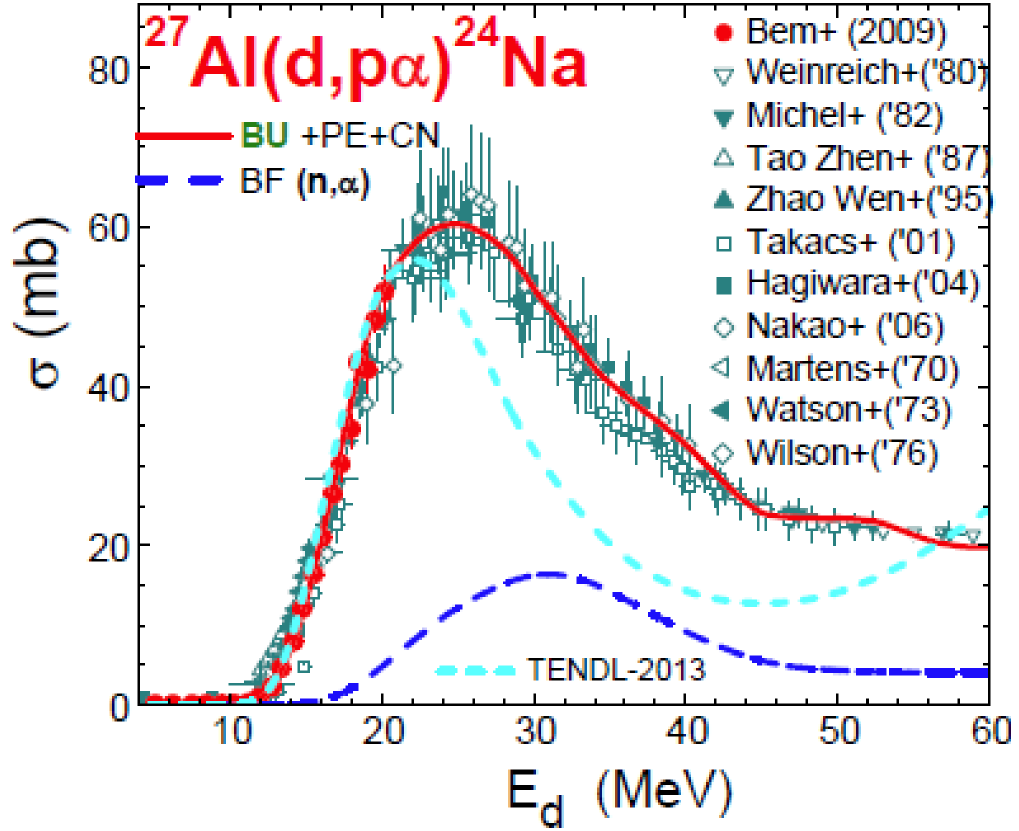
U. Fischer and S. P. Simakov
Euratom/FZK Fusion Association, Forschungszentrum Karlsruhe, Hermann-von-Helmholtz-Platz, 1, 76344 Eggenstein-Leopoldshafen, Germany

R. A. Forrest
Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, United Kingdom

M. Avrigeanu,† A. C. Obreja, F. L. Roman, and V. Avrigeanu
'Horia Hulubei' National Institute for Physics and Nuclear Engineering, P. O. Box MG-6, Bucharest-Magurele, Roma

(Received 30 January 2009; published 30 April 2009)

The activation cross sections of (d,p), $(d,2p)$, and $(d,p\alpha)$ reactions on ^{27}Al were measured in the energy range from 4 to 20 MeV using the stacked-foils technique. Following a previous extended analysis of elastic scattering, breakup, and direct reaction of deuterons on ^{27}Al, for energies from 3 to 60 MeV, the preequilibrium and statistical emissions are considered in the same energy range. Finally, all deuteron-induced reactions on ^{27}Al including the present data measured up to 20 MeV deuteron energy are properly described due to a simultaneous analysis of the elastic scattering and reaction data.



Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production (2)

Table 3: Cross-section studies of monitor reactions.

January 2017

Cross sections	Agreed responsibilities, status and actions
$^{nat}Cu(d,x)^{62}Zn$	Accept Pade 9.
$^{nat}Cu(d,x)^{63}Zn$	CRP will not recommend due to deviation at 20 MeV and at 45 MeV. However, accept Pade 12.
$^{nat}Cu(d,x)^{65}Zn$	Accept Pade 13C, uncertainties to be increased to 6%.

NO accompanying figure in the Report or in presentations

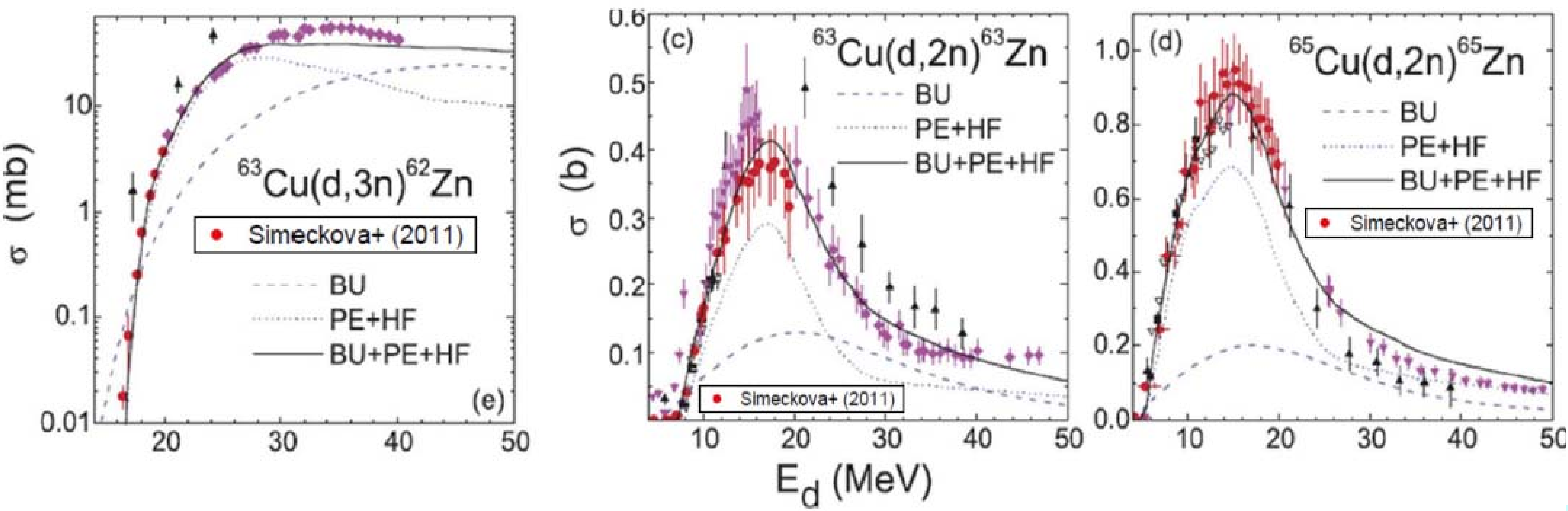
vs.

PHYSICAL REVIEW C 84, 014605 (2011)

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

E. Šimečková,* P. Bém, M. Honus

See FENDL-report: INDC(NDS)-0645, pp. 48, November 2013



Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production (3)

Table 3: Cross-section studies of monitor reactions.

January 2017

Cross sections	Agreed responsibilities, status and actions
$^{nat}Fe(d,x)^{56}Co$	Hermanne to de-select Nakua 2006 data, and re-send to Ignatyuk for re-fitting by July 1, 2016.

NO accompanying figure

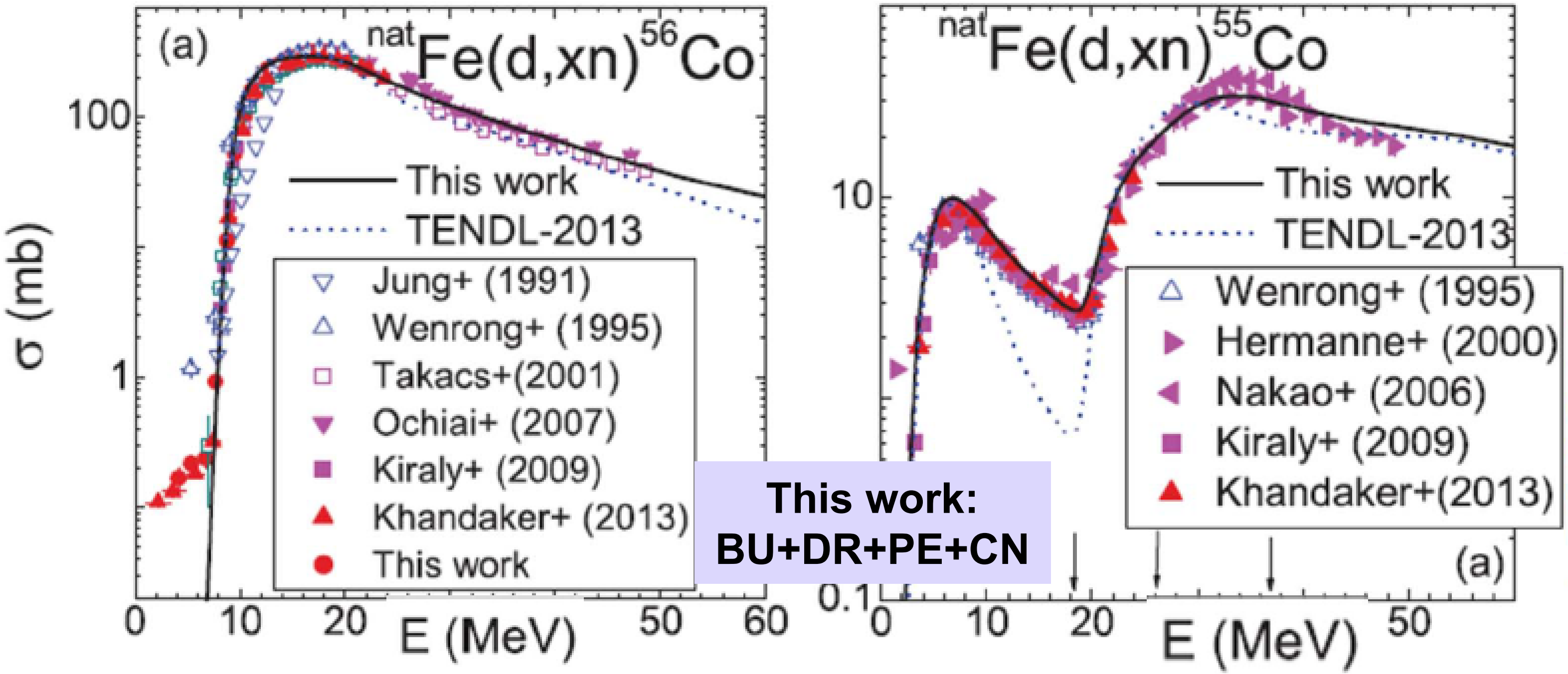
vs.

PHYSICAL REVIEW C 89, 044613 (2014)

Low energy deuteron-induced reactions on Fe isotopes

M. Avrigeanu,[1,*] V. Avrigeanu,[1] P. Bém,[2] U. Fischer,[3] M. Honusek,[2] K. Katovsky,[4] C. Mănăilescu,[1] J. Mrázek,[2] E. Šimečková,[2,†] and L. Závorka[2]

[1]Horia Hulubei National Institute for Physics and Nuclear Engineering, P.O. Box MG-6, 077125 Bucharest-Magurele, Romania



This work: BU+DR+PE+CN

Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production (4)

January 2017

Table 3: Cross-section studies of monitor reactions.

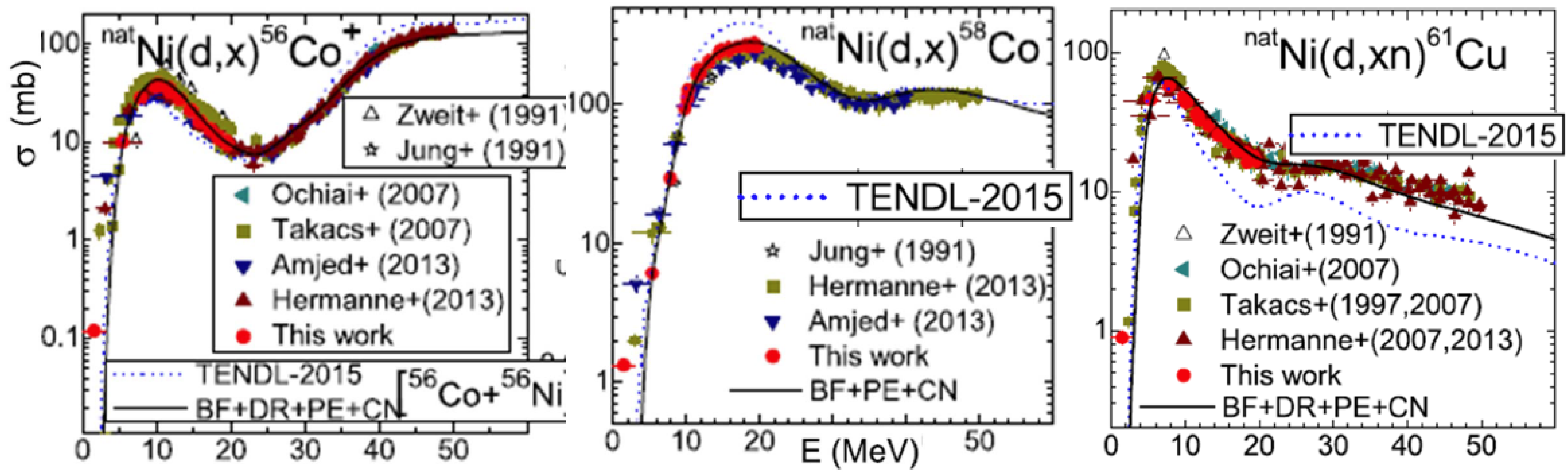
Cross sections	Agreed responsibilities, status and actions
$^{nat}Ni(d,x)^{56}Co$	CRP will recommend data up to 50 MeV. Accept Pade 11; fit uncertainties to be increased by Ignatyuk to at least 5%.
$^{nat}Ni(d,x)^{58}Co$	Accept Pade 12.
$^{nat}Ni(d,x)^{61}Cu$	Potential systematic shifts due to use of different gamma lines were considered. Accept Pade 10.

NO accompanying figure

vs.

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

Deuteron-induced reactions on Ni isotopes up to 60 MeV



Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production (5)

January 2017

Table 7: Cross-section studies for the production of therapeutic α emitters.

Cross sections	Agreed responsibilities, status and actions
$^{231}Pa(d,3n)^{230}U$	Ignatyuk to refit up to 30 MeV based on additional supporting theoretical calculations.

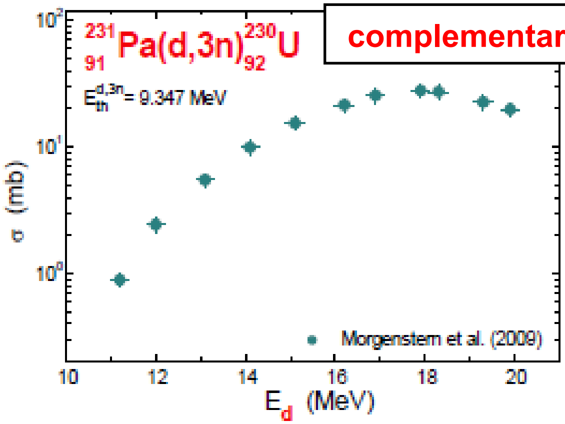
NO accompanying figure

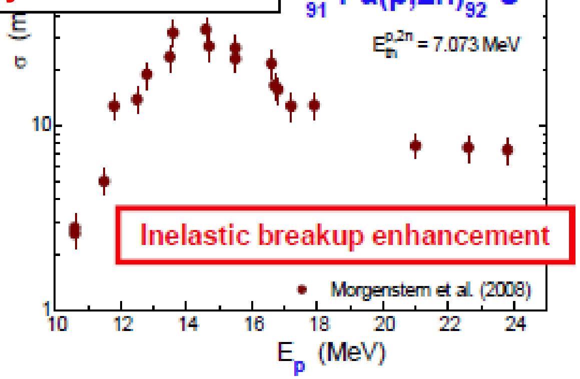
See FENDL-report: INDC(NDS)-0645, pp. 50, November 2013

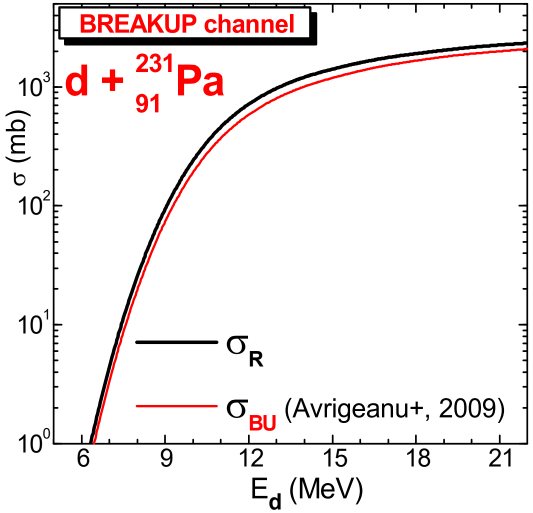
vs.

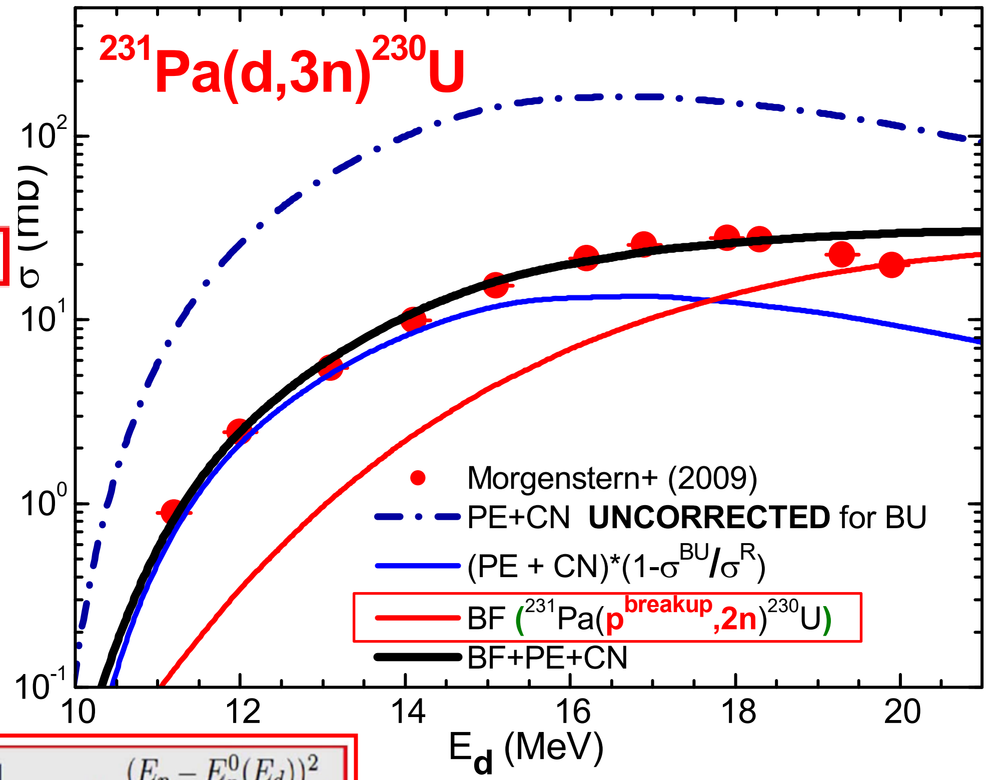
PHYSICAL REVIEW C **85**, 034603 (2012)

complementary measurements









$$\sigma^{p,x}_{BF}(E_d) = \sigma^{p}_{BF}(E_d) \int dE_p \frac{\sigma_{(p,x)}(E_p)}{\sigma^p_R} \frac{1}{(2\pi)^{\frac{1}{2}} w} exp[-\frac{(E_p - E^0_p(E_d))^2}{2w^2}]$$

EURATOM, FENDL, F4E, CHARPAR, EUROfuson

Should be correlated various international projects involving deuteron interaction process analysis, e.g.
FENDL, F4E, CHARPAR, EUROfusion

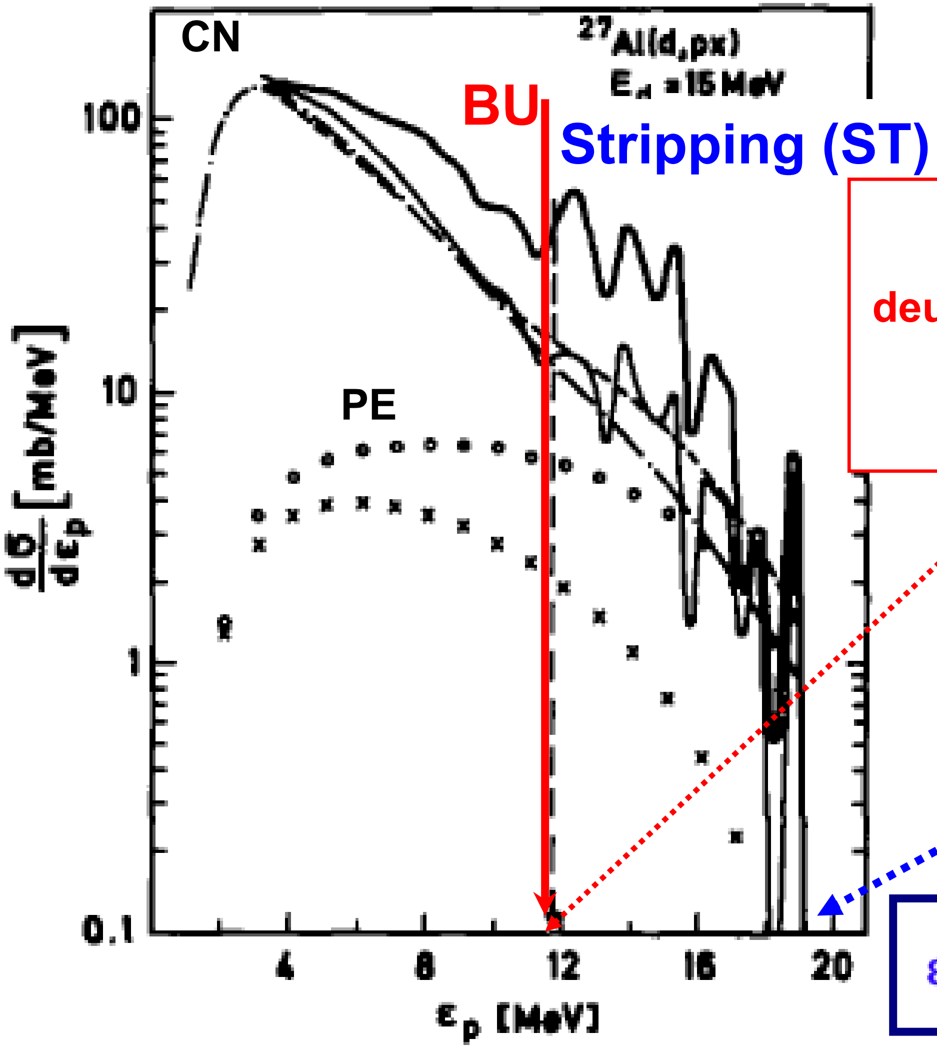
Consistent Theoretical Calculations of
deuteron induced reactions
involving
BREAKUP - STRIPPING - PICK-UP - PE - CN
should be recommended instead of
PADE APPROXIMATIONS

as long as exist
Powerful Computers and Available Dedicated Codes

Breakup versus Stripping

BU +ST+PE+CN mechanisms

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

$$\varepsilon_p^{max\text{-}strippig} - \varepsilon_p^{max\text{-}breakup} = Q_{d,p} + B_d$$

Fig. 3. Decomposition of the experimental angle-averaged proton spectrum (thick full curve) into MSC and MSD type contributions. The thin full curve is derived from the spectrum at 128° by means of eq. (11) and represents the MSC contribution. It is compared with theoretical CN+PE calculations (see text) with $n_0 = 3$ (PE part: ∘∘∘∘∘, sum CN+PE: – – –) and $n_0 = 4$ (PE part: xxxxxx, sum CN+PE: — · —).

The arrow indicates the BU threshold separating the BU and Stripping energy regions

Direct Interactions : BU + stripping + pick-up