Improvement of modeling of triton energy distributions for reaction induced by nucleons at intermediate energies

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Objectives

- to analyze available experimental energy distributions using the proposed method for the modeling of precompound triton emission

- to get effective values of model parameters for triton emission

- to consider the role of the optical potential on the calculated values of precompound triton energy distributions

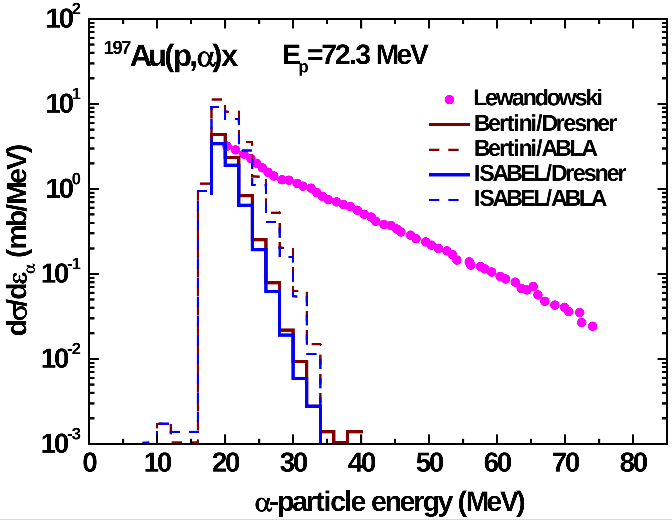
Complex particle emission in pre-compound reactions

C.Kalbach-Cline (1972) : "Extensions to the Pre-Equilibrium Statistical Model"

$$W_\beta(p, h, \varepsilon)\mathrm{d}\varepsilon = \frac{2s_\beta + 1}{\pi^2 \hbar^3} \mu_\beta \varepsilon \sigma_\beta(\varepsilon) \mathrm{d}\varepsilon \, p_\beta! R_\beta(p) \frac{\omega(p - p_\beta, h, U)}{\omega(p, h, E)}$$

criticized by Ribansky, Oblozinsky (1973), Kalbach (1977)

Used: LAHET, MCNPX (all versions)



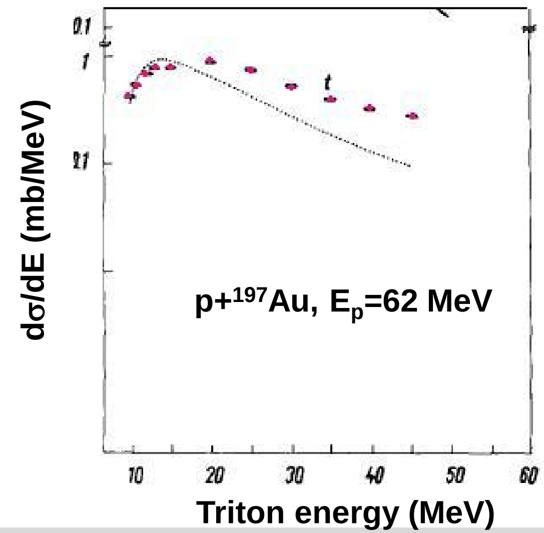
I.Ribansky, P.Oblozinsky (1973) : “Emission of Complex Particles in the Exciton Model”

coalescence model

$$W_\beta(n,\epsilon_\beta)\,d\epsilon_\beta = \gamma_\beta \frac{2s_\beta+1}{\pi^2\hbar^3}\,\mu_\beta\,\epsilon_\beta\,\sigma_{inv}(\epsilon_\beta) \times \frac{\omega(p_\beta,0,E-U)}{g}\,\frac{\omega(p-p_\beta,h,U)}{\omega(p,h,E)}\,R_\beta(p)\,d\epsilon_\beta.$$

criticized by Kalbach (1977), Iwamoto, Harada (1982)

Used: CEM (MCNPX)



G.M. Braga-Marcazzan, L.Milazzo-Colli (1972) : “The preformation of α-particles in heavy nuclei”

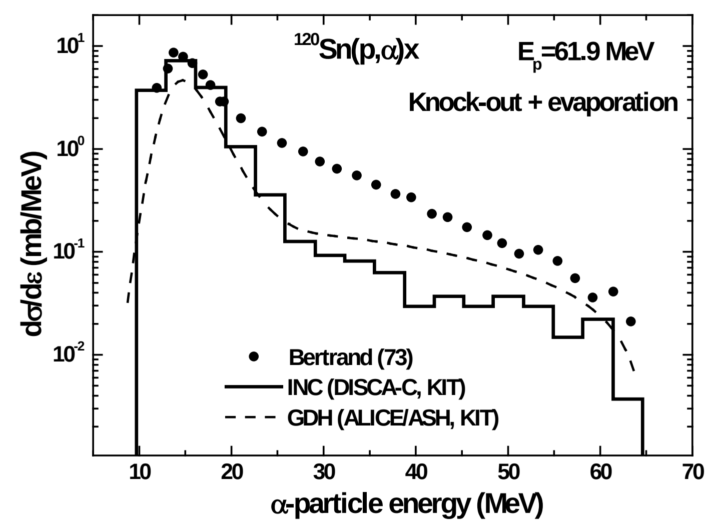
knock-out model

$$\frac{d\sigma(p,\alpha)}{d\varepsilon} = \sigma_r \frac{m\varepsilon\sigma_{inv}(\varepsilon) g_R}{4\pi^3 \hbar^2 |M|^2 g_C^5 E^3} \sum_{\substack{n=3\\(\Delta n=2)}}^{\bar{n}} \frac{\varphi K^{\alpha}_{n-1}}{(\varphi K^{\alpha}_{n} + (1-\varphi) K^{\nu}_{n})} \left(\frac{g^R U}{g_C E}\right)^{(n-2)} (n+1)(n^2-1)$$

developed by Gadioli and coauthors to the middle 80th, Avrigeanu, Avrigeanu (90th), Blann (2009)

criticized by Gadioli et al (1986)

Used: STAPRE-H, HMS, ALICE-2010



C.Kalbach (1977) : "The Griffin Model, Complex Particles and Direct Nuclear Reactions"

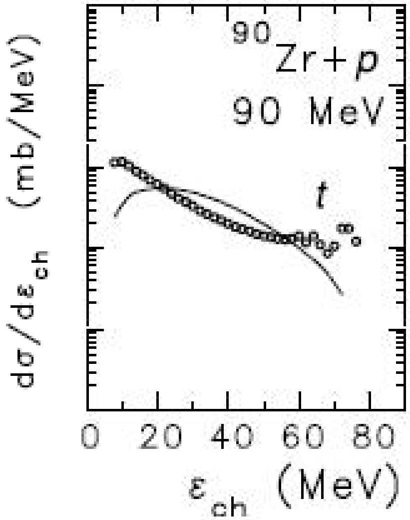
phenomenological approach

pick-up: d,t, ^{3}He, α-particles, knock-out: α-particles

$$\frac{d\sigma^{p-s}}{d\varepsilon}(a,b) = (2s_b+1)\, p_b\, \varepsilon\, \sigma_b(\varepsilon)\, \omega_P(U)(20)^{\delta_a} \cdot f\left(\frac{E_a}{p_a}\right)^{-2A} \left(\frac{780}{A}\right)^{A} 1.4 \times 10^{-4} (\mathrm{MeV})^{2A-1}$$

developed by Kalbach (2005)

Used: PRECO, GNASH, TALYS

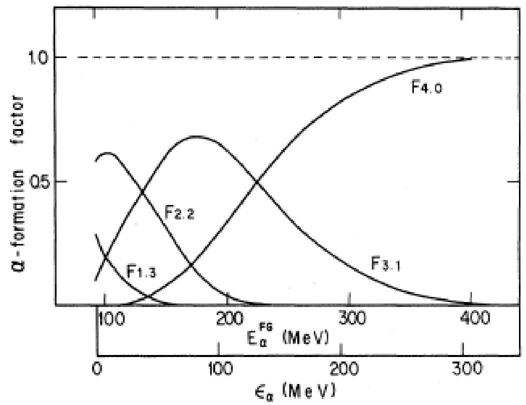


A.Iwamoto, K.Harada (1982) : "Mechanism of Cluster Emission in Nucleon-Induced Preequilibrium Reactions"

pick-up - coalescence model

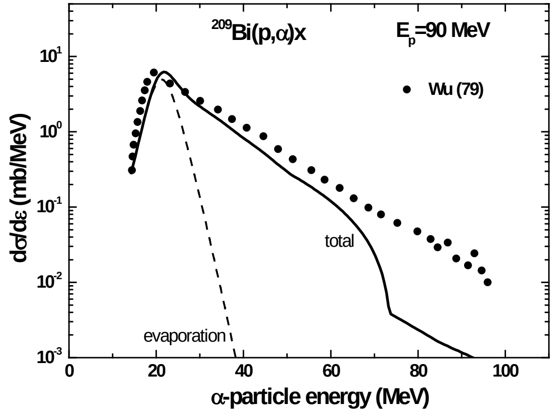
$$W^{(\alpha)}_{n(l,m)}(\epsilon_\alpha)=\frac{1}{\pi^2\hbar^3}\mu_\alpha\epsilon_\alpha\sigma^{(\alpha)}_{\rm abs}F_{l,m}(\epsilon_\alpha)\frac{\omega^*_{n(l,m)}(U)}{\omega(p,h,E)}$$

$F_{l,m}(\varepsilon_\alpha)$



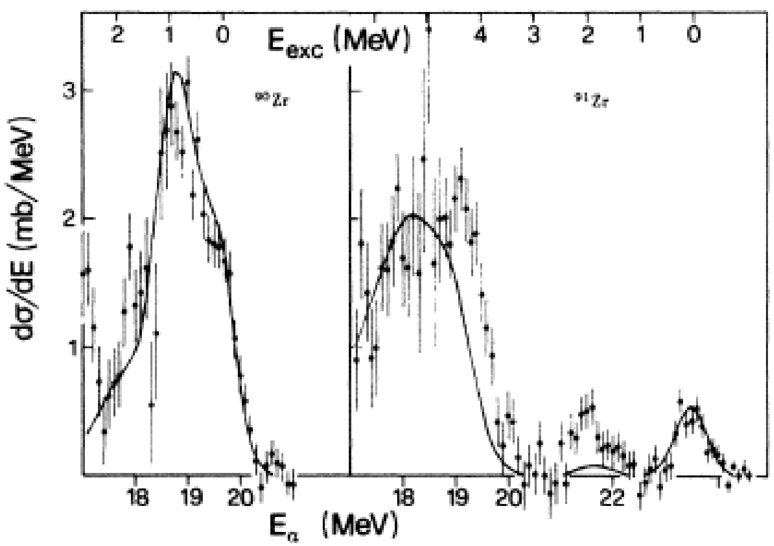
Attempt to improve: Pronyaev and coauth (1994)

Used: EMPIRE, STAPRE ("ADL" version)

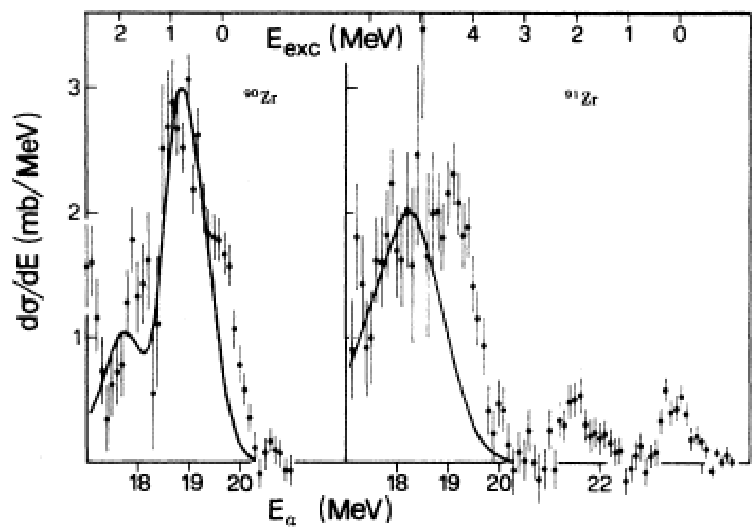


E.Gadioli and co-authors (1986) : Microscopic calculations of (n,α)x spectra using pick-up and knock-on theories

pick-up theory

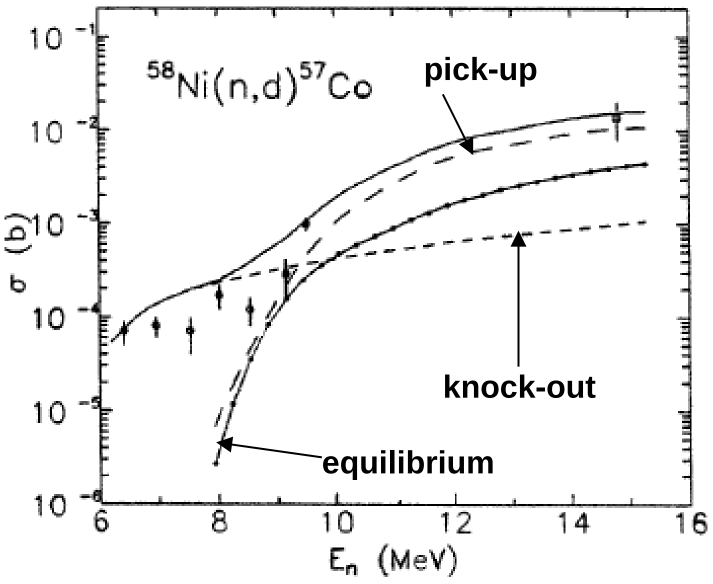


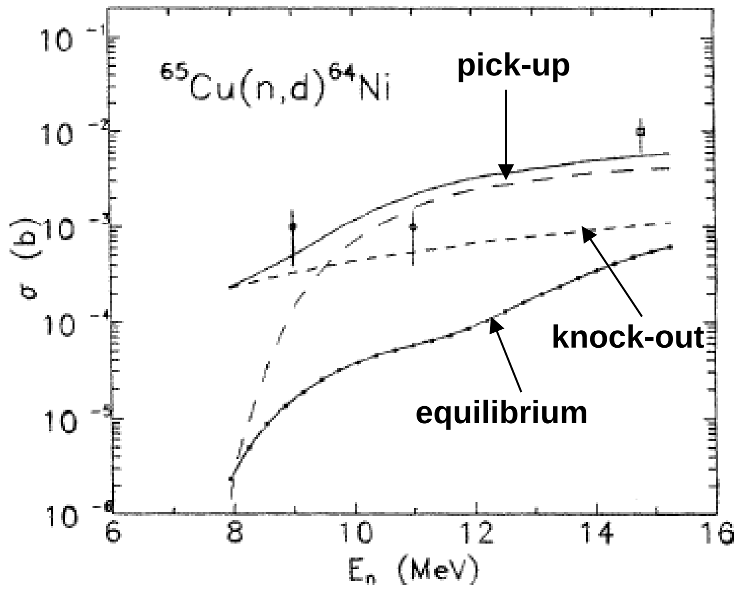
knock-on theory



Pick-up calculations provide a very satisfactory reproduction of the data. Knock-on calculations do not allow a fully satisfactory reproduction of them

S. Dimitrova, V Avrigeanu and coauthors (1997): (n,d)-Reactions on Medium Mass Nuclei“



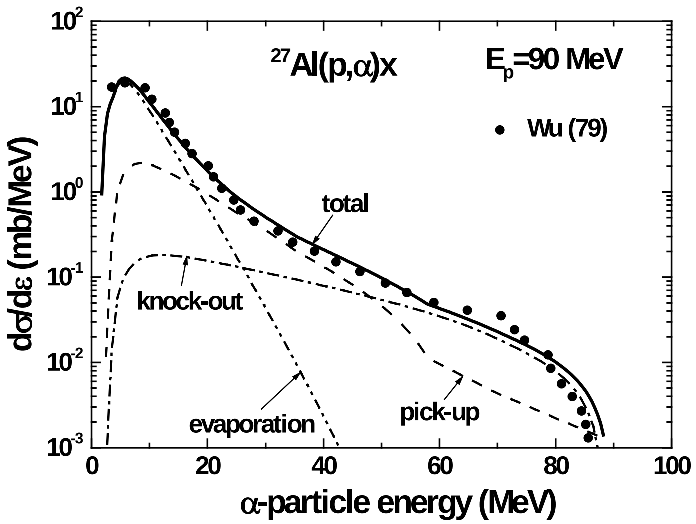


INPE, FZK (1994,1995) : Modeling of pre-compound cluster emission using GDH

First succesfull attempt to describe α-particle spectra for nucleon induced reactions in a wide energy range of projectiles

α-particles: pick-up + knock-out

d,t,3He: pick-up (IHS)



The model was used to produce evaluated data files up to 50 MeV (1995)

Development (FZK, KIT)

Karlsruhe Institute of Technology

α-particles: improvement (2004)

deuterons: essential changes and improvements (2005)

tritons: changes and improvement (2011)

Main features of cluster emission:

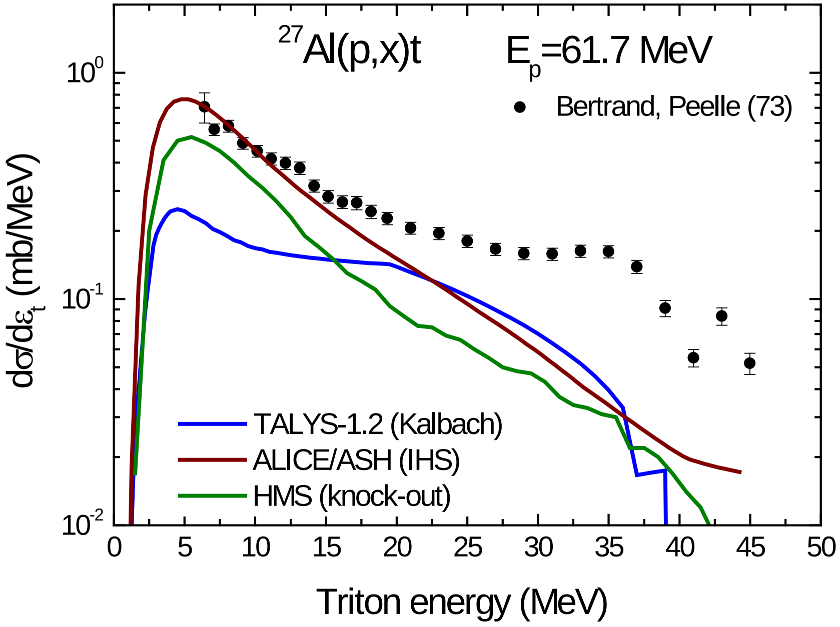
nucleon pick-up: middle part of emission spectra. Dominant at relative low projectile energies

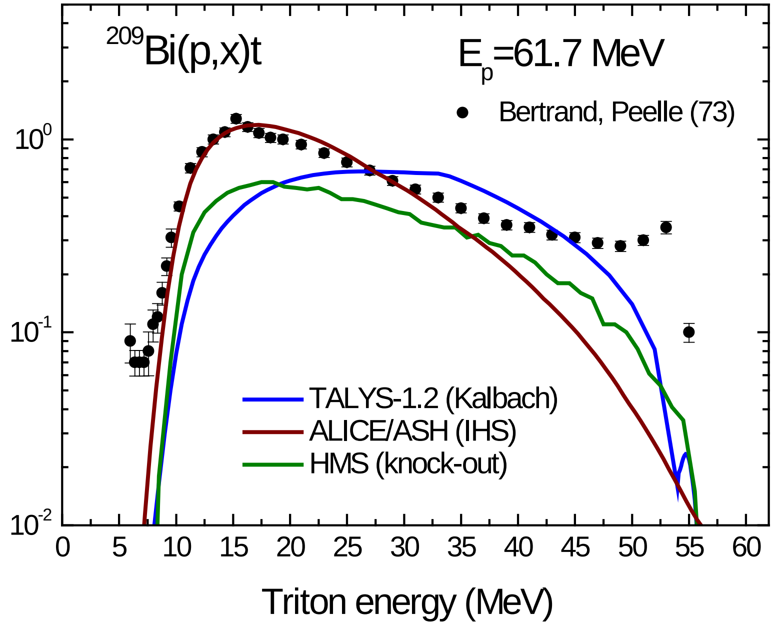
knock-out: high energy part of emission spectra. The contribution grows with the increase of projectile energy

coalescence: dominates at high energy of projectiles (INC)

direct processes: the highest part of emission spectra

Triton energy distributions calculated using modern codes





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Precompound triton emission in nucleon induced reaction

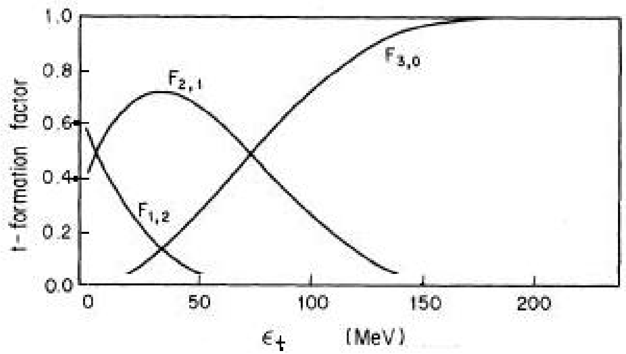
$$\frac{d\sigma}{d\varepsilon_t} = \frac{d\sigma^{P-U,C}}{d\varepsilon_t} + \frac{d\sigma^{K-O}}{d\varepsilon_t} + \frac{d\sigma^{D}}{d\varepsilon_t}$$

Pick-up and coalescence

$$\frac{d\sigma^{P-U,C}}{d\varepsilon_t} = \sigma_{non}(E_0) \sum_{n=n_0} \sum_{k+m=3} F_{k,m}(\varepsilon_t + Q_t) \frac{\omega(p-k,h,U)}{\omega(p,h,E)} \frac{\lambda_t^e(\varepsilon_t)}{\lambda_t^e(\varepsilon_t) + \lambda_t^+(\varepsilon_t)} g_t\, D(n)$$

$$\lambda_t^e = \frac{(2S_t + 1)\mu_t\, \varepsilon_t\, \sigma_t^{inv}(\varepsilon_t)}{\pi^2 \hbar^3 g_t}$$

$$\lambda_t^+ = 2 W_t^{opt} / \hbar$$

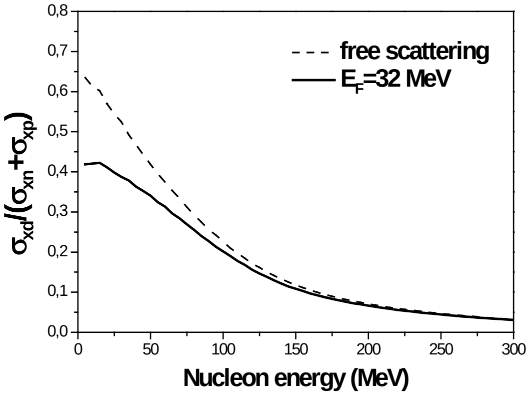


Knock-out

$$\frac{d\sigma^{K-O}}{d\varepsilon_t} = \sigma_{non}(E_0) \sum_{n=n_0} \Phi_t(E_0) \frac{g}{g_t\, p} \frac{\omega(p-1,h,U)}{\omega(p,h,E)} \frac{\lambda_t^e(\varepsilon_t)}{\lambda_t^e(\varepsilon_t) + \lambda_t^+(\varepsilon_t)} g_t\, D(n)$$

$$\Phi_t(E_0) = 2\, F_t(E_0)$$

$$F_t = \frac{\varphi_t\, \sigma_{xt}(E_0)}{\frac{Z'}{A'}\sigma_{xp}(E_0) + \frac{(A'-Z')}{A'}\sigma_{xn}(E_0) + \varphi_t\, \sigma_{xt}(E_0) + Y}$$



Direct pick-up process

$$\frac{d\sigma^D}{d\varepsilon_t}=\sigma_{non}\ \frac{\omega^*(U)}{\omega(1p,0h,E)}\ \frac{\lambda_t^e(\varepsilon_d)}{\lambda_t^e(\varepsilon_t)+\lambda_t^+(\varepsilon_t)}\ g_t$$

The old approach: $\omega^*(U)=\omega(0p,1h,U)\cdot\gamma/g$

$$\frac{d\sigma^D}{d\varepsilon_t}=\sigma_{non}\ \alpha_1\ \exp\left(-\frac{(E-\alpha_2 E_F)^2}{2(\alpha_3 E_F)^2}\right)\frac{\lambda_t^e(\varepsilon_t)}{\lambda_t^e(\varepsilon_t)+\lambda_t^+(\varepsilon_t)}\ g_t$$

Multiple pre-equilibrium emission .

$$\frac{d\sigma_2^{F-U,C}}{d\varepsilon_t}=\pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)T_l\sum_{x=\pi,\nu}^{2}\int_{E_x^{min}}^{E_x^{max}}\sum_{n=n_0}{}_nX_x\ \frac{\omega(p-1,h,E-Q_x-\varepsilon_x)}{\omega(p,h,E)}\ \frac{\lambda_x^e(\varepsilon_x)}{\lambda_x^e(\varepsilon_x)+\lambda_x^+(\varepsilon_x)}\ g\ D(n)$$

$$\times\sum_{n'=p+h-1}\ \sum_{k+m=3}F_{k,m}(\varepsilon_t+Q_t')\ \frac{\omega(p'-k,h',E-Q_x-\varepsilon_x-Q'_t-\varepsilon_t)}{\omega(p',h',E-Q_x-\varepsilon_x)}\ \frac{\lambda_t^e(\varepsilon_t)}{\lambda_t^e(\varepsilon_t)+\lambda_t^+(\varepsilon_t)}\ g_t\ D_2(n')\ d\varepsilon_x$$

Experimental data

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(p,x)t reactions:

targets: **C-12, Al-27, Si-0, Fe-54, Fe-56, Ni-58, Y-89, Zr-90, Sn-120, Au-197, Pb-208, Bi-209**
proton energy: 26.5 – 90 MeV

F.E.Bertrand, R.W.Peelle, PRC,8,1045 (1973)
P.Demetriou et al, PRC,72, 034607 (2005)
A.Guertin et al, EPJA,23,49 (2005)
J.R. Wu et al, PRC, 19, 698 (1979)

(n,x)t reactions:

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targets: C-12, O-16, Al-27, Si-00, Fe-56, Co-59, Pb-208, Bi-209
neutron energy: 31.5 – 95.6 MeV

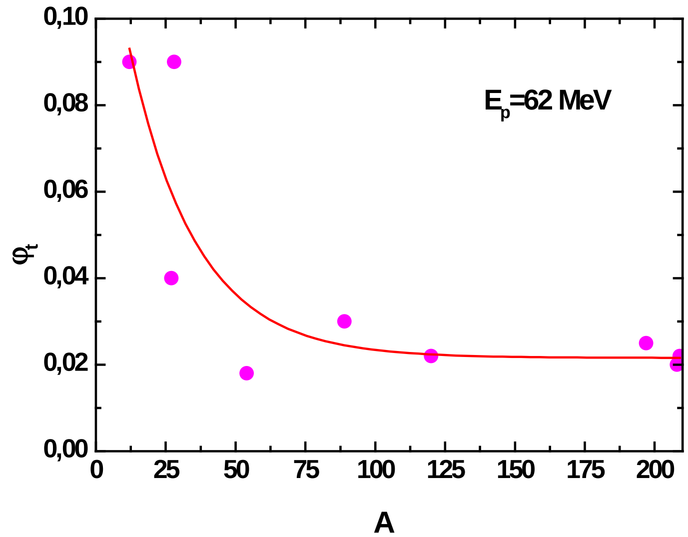
S.Benck et al, PRC,58,1558 (1998); AND,72,1 (1999); NSE,141,55 (2002)
V.Blideanu et al, PRC,70,014607 (2004)
N.Nica et al, JPG,28,2823 (2002)
E.Raeymackers et al, NPA,726,210 (2003)
I.Slypen et al, AND,76,26 (2000)
U.Tippawan et al, PRC,69,064609 (2004); PRC,79,064611 (2009)

Model parameters

nucleon pick-up

$$\sum_{k+m=3} F_{k,m}(\varepsilon_t) = 0.3$$

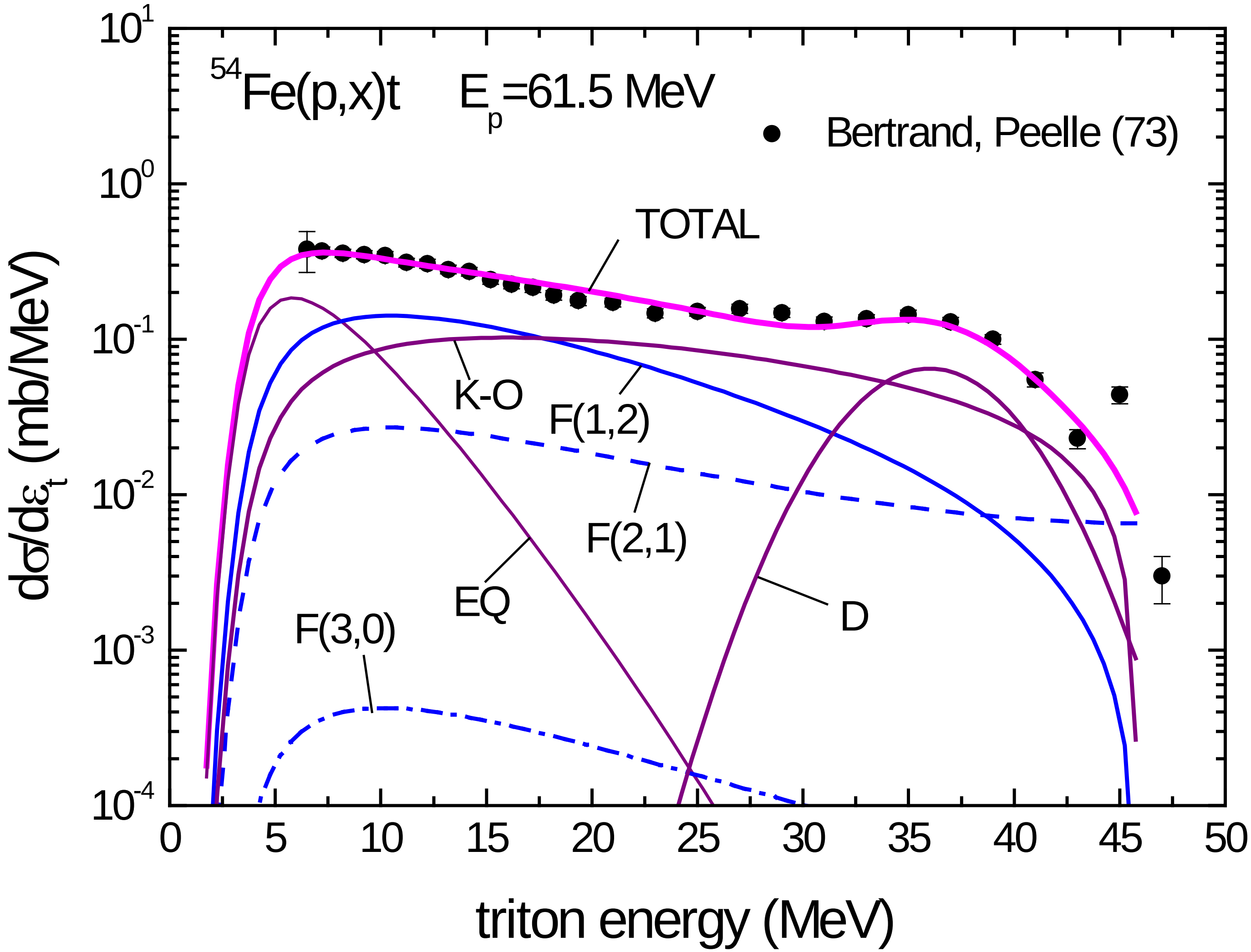
t-knock-out



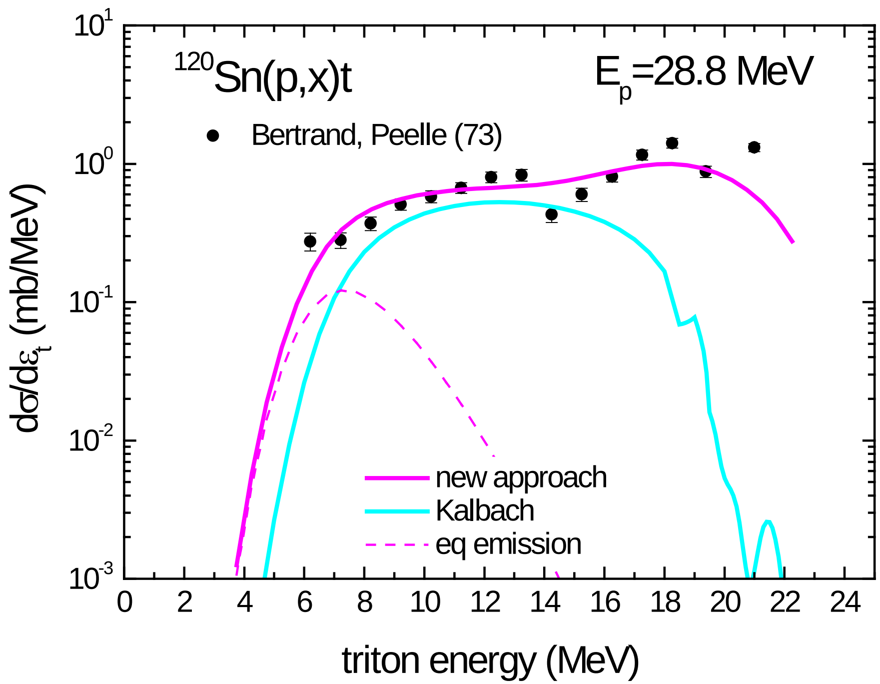
absorption

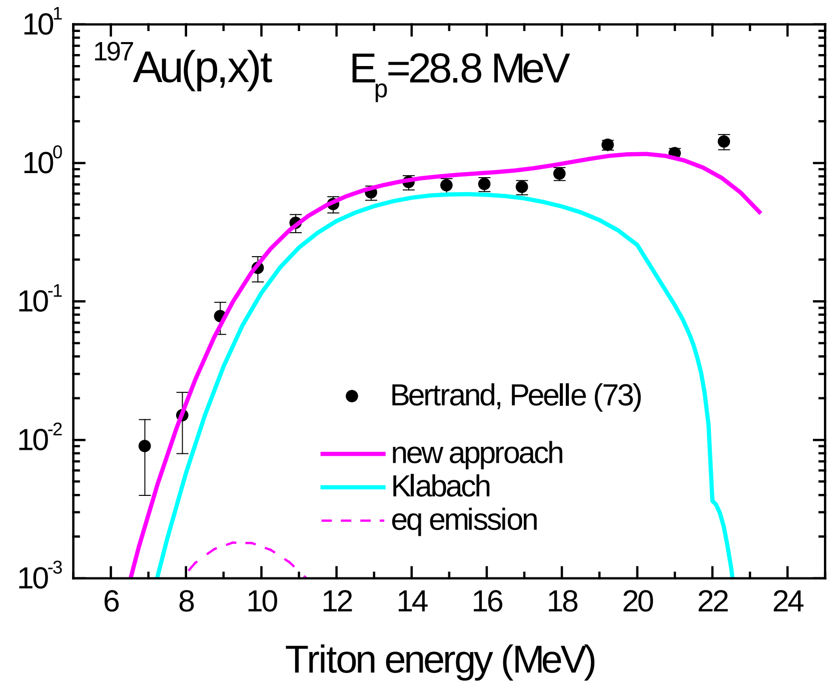
Becchetti-Greenlees: $W^t_{opt} = 46 - 0.33\,E - 110\,(N\text{-}Z)/A$

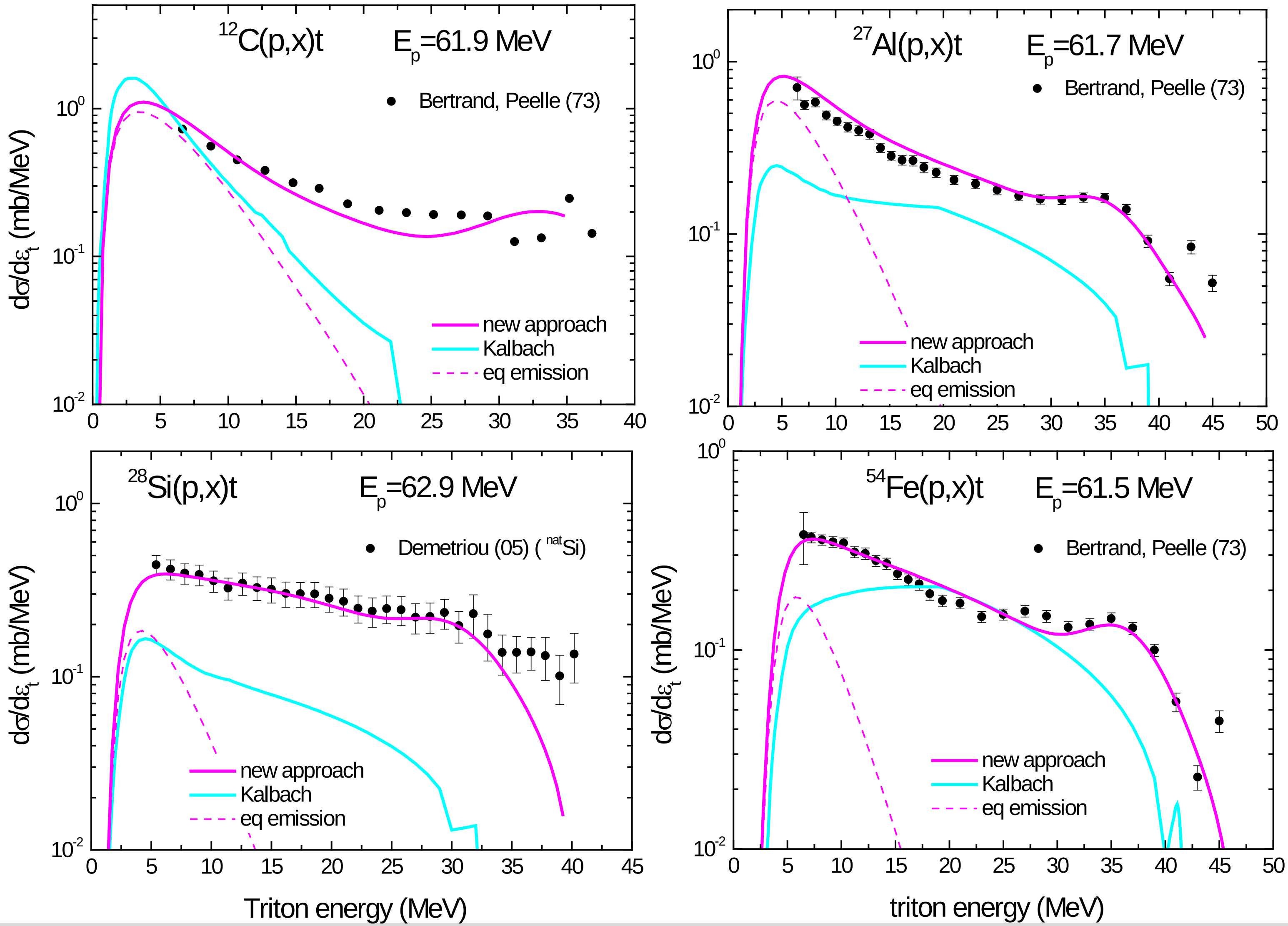
Contributions



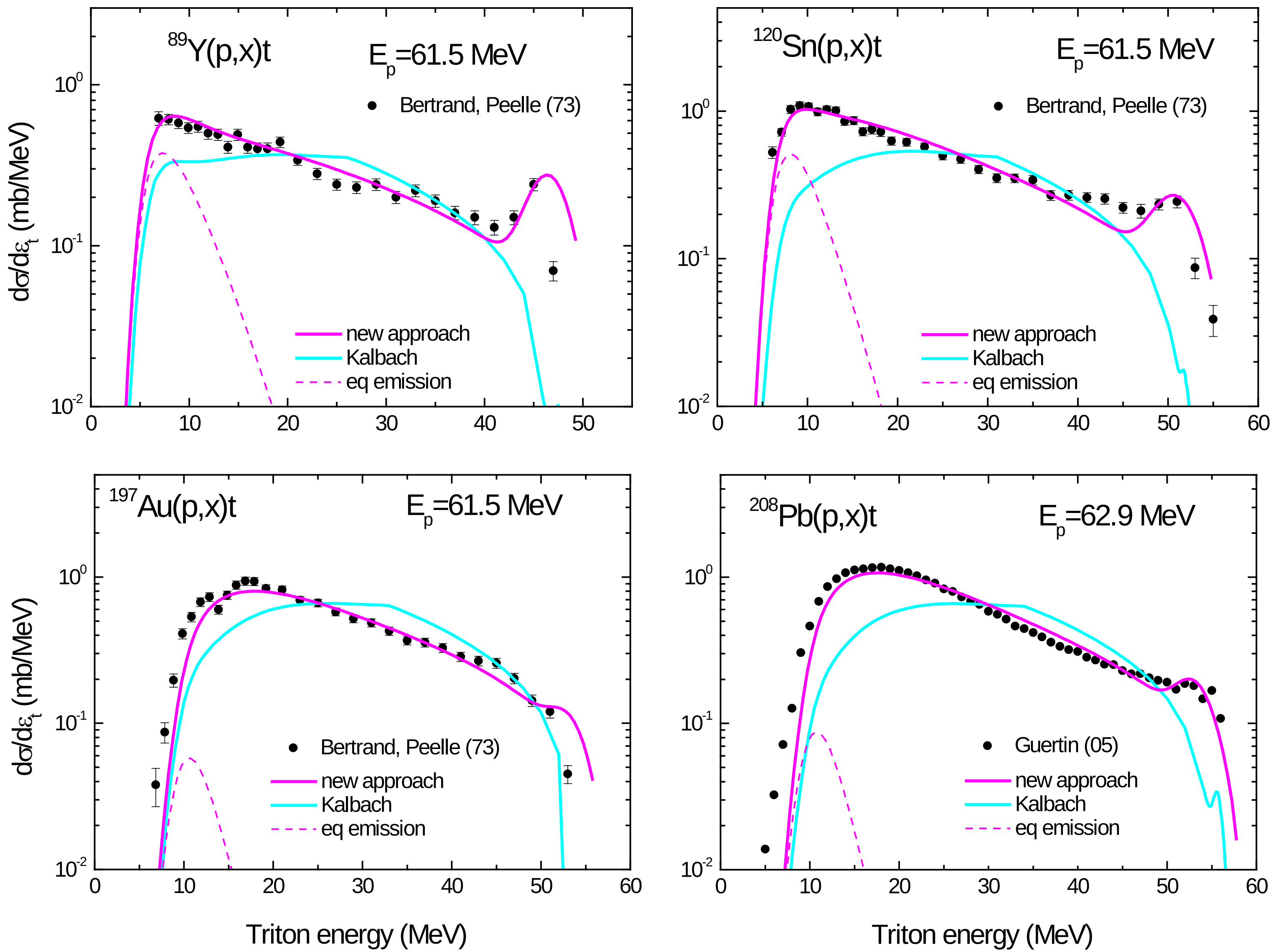
Examples. Calculations using ALICE/ASH (2011)



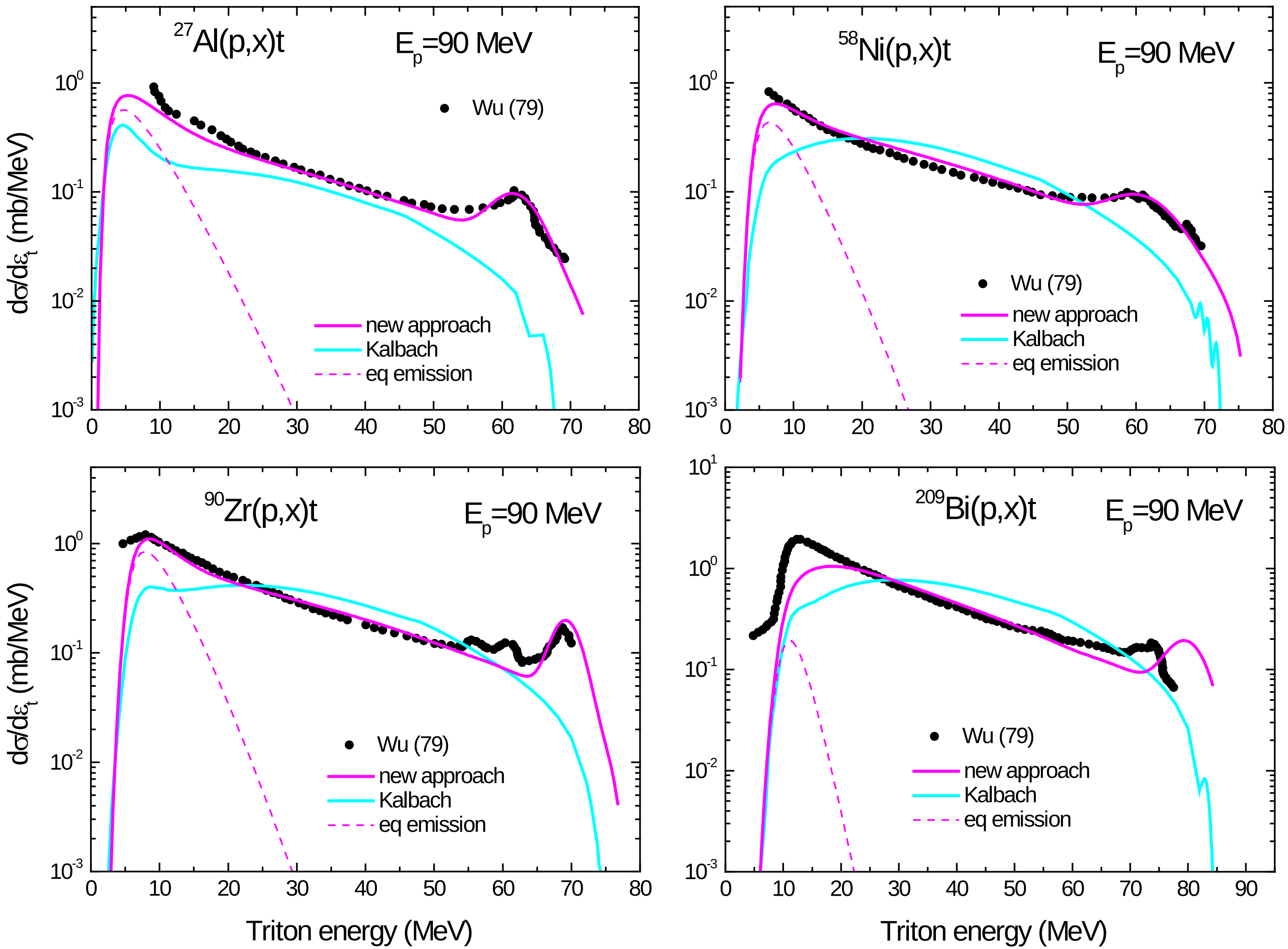


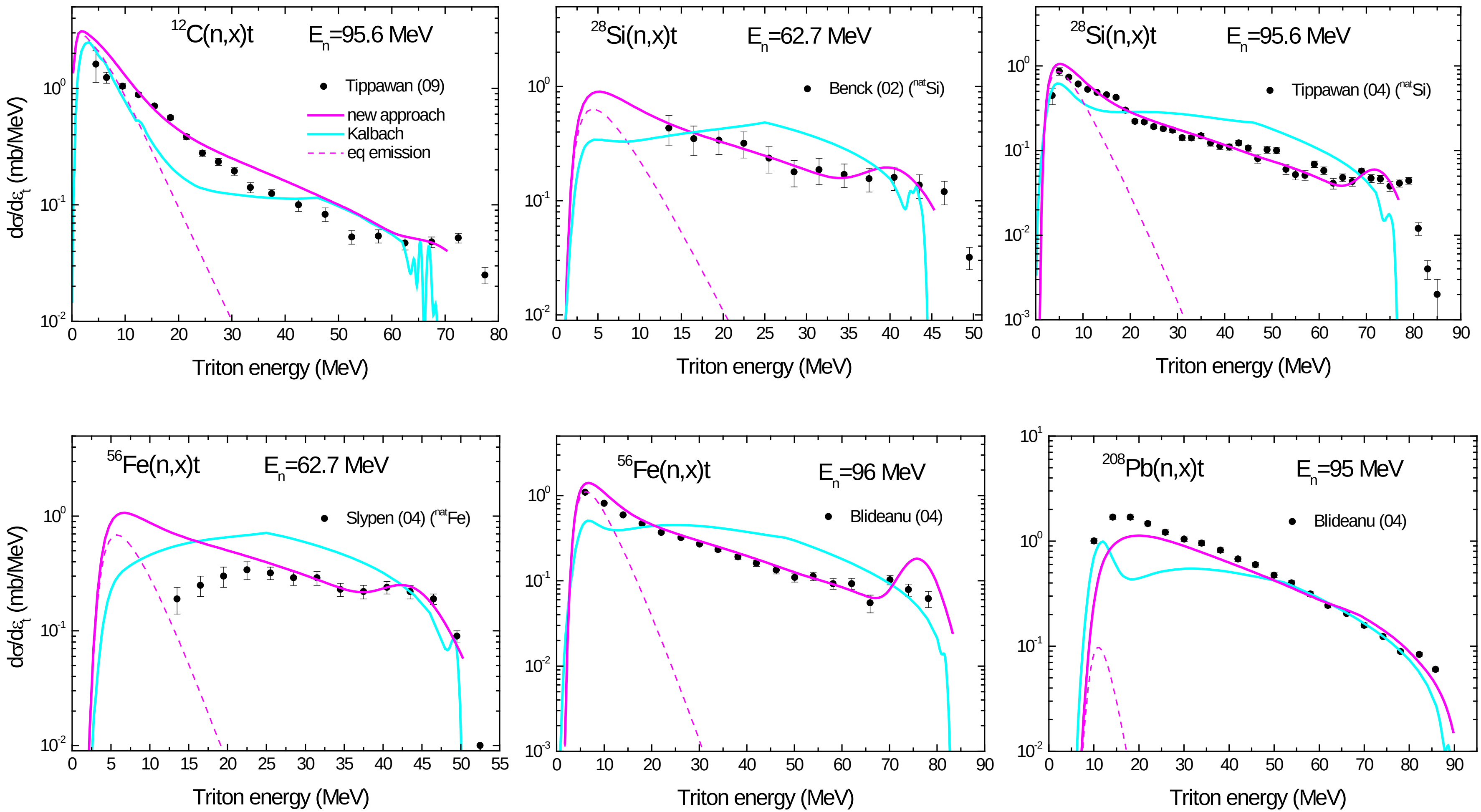


12C(p,x)t
Ep=61.9 MeV
Bertrand, Peelle (73)
new approach
Kalbach
eq emission
27Al(p,x)t
Ep=61.7 MeV
Bertrand, Peelle (73)
new approach
Kalbach
eq emission
28Si(p,x)t
Ep=62.9 MeV
Demetriou (05) (natSi)
new approach
Kalbach
eq emission
54Fe(p,x)t
Ep=61.5 MeV
Bertrand, Peelle (73)
new approach
Kalbach
eq emission
dσ/dεt (mb/MeV)
Triton energy (MeV)
triton energy (MeV)



^{89}Y(p,x)t
E_p=61.5 MeV
Bertrand, Peelle (73)
new approach
Kalbach
eq emission
^{120}Sn(p,x)t
E_p=61.5 MeV
Bertrand, Peelle (73)
new approach
Kalbach
eq emission
^{197}Au(p,x)t
E_p=61.5 MeV
Bertrand, Peelle (73)
new approach
Kalbach
eq emission
^{208}Pb(p,x)t
E_p=62.9 MeV
Guertin (05)
new approach
Kalbach
eq emission
dσ/dε$_t$ (mb/MeV)
Triton energy (MeV)


27Al(p,x)t
Ep=90 MeV
Wu (79)
new approach
Kalbach
eq emission
58Ni(p,x)t
Ep=90 MeV
Wu (79)
new approach
Kalbach
eq emission
90Zr(p,x)t
Ep=90 MeV
Wu (79)
new approach
Kalbach
eq emission
209Bi(p,x)t
Ep=90 MeV
Wu (79)
new approach
Kalbach
eq emission
dσ/dεt (mb/MeV)
Triton energy (MeV)



$^{12}C(n,x)t$ E_n=95.6 MeV
Tippawan (09)
new approach
Kalbach
eq emission
$^{28}Si(n,x)t$ E_n=62.7 MeV
Benck (02) (^{nat}Si)
$^{28}Si(n,x)t$ E_n=95.6 MeV
Tippawan (04) (^{nat}Si)
$^{56}Fe(n,x)t$ E_n=62.7 MeV
Slypen (04) (^{nat}Fe)
$^{56}Fe(n,x)t$ E_n=96 MeV
Blideanu (04)
$^{208}Pb(n,x)t$ E_n=95 MeV
Blideanu (04)
$d\sigma/d\varepsilon_t$ (mb/MeV)
Triton energy (MeV)

The role of the optical potential

F.D.Becchetti, G.W.Greenlees: $W^t_{opt} = 46 - 0.33\,E - 110\,\xi$

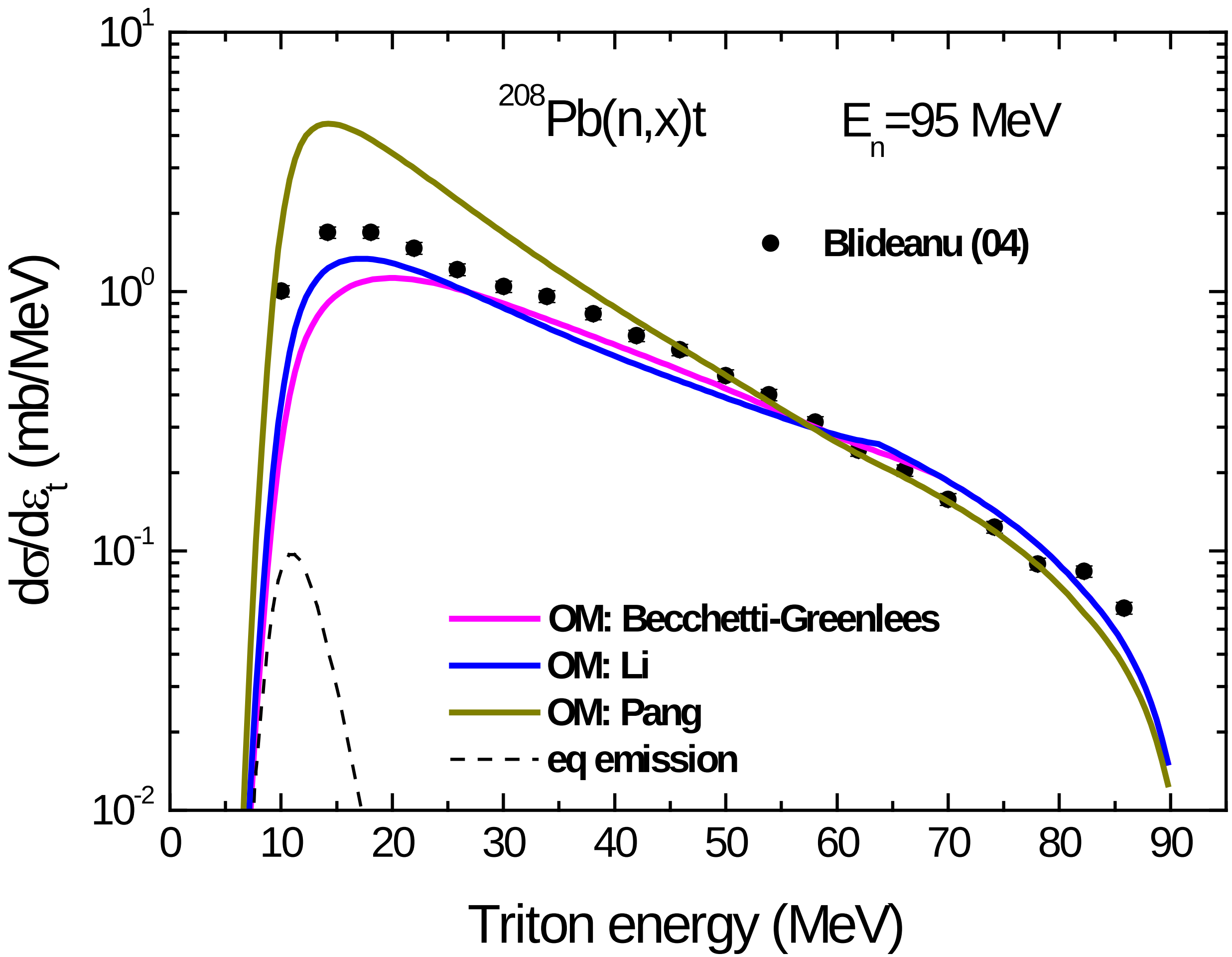
Xiaohua Li et al: $W^t_{opt} = 7.38 + 0.5\,E - 0.0097\,E^2$

D.Y. Pang et al: $W^t_{opt} = 38.5\,[1 + \exp(156-(E-E_C))/52.4)]^{-1}$

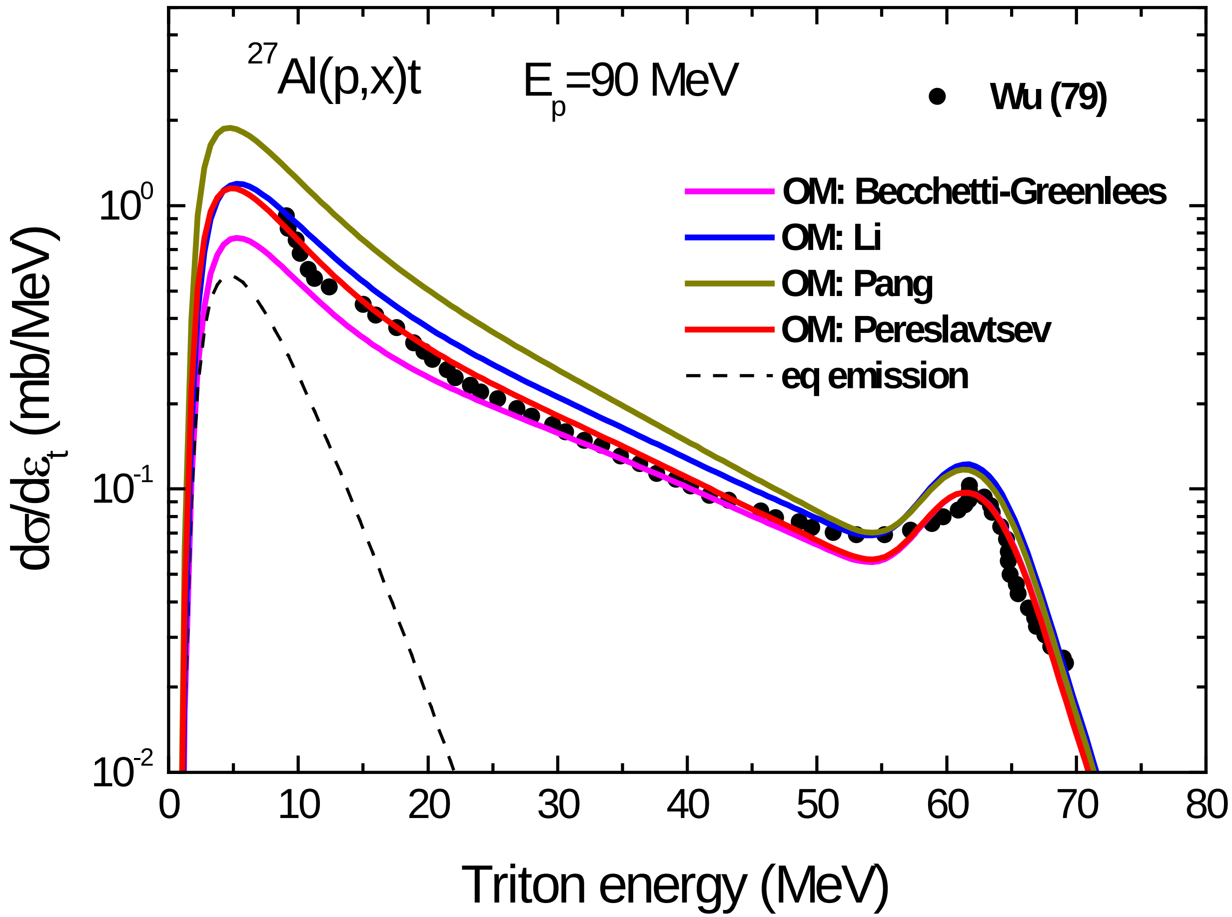
P.Pereslavtsev: $W^t_{opt} = W_0\,[1 - \exp(-\varepsilon_W E)](1+\alpha_W E)$

$W_0 = 24.5 + 5.13\,\xi, \;\; \varepsilon_W = 0.0978 + 0.425\,\xi$

$\alpha_W = -0.002 + 0.00159\,\xi, \;\; \xi = (N-Z)/A$



^{208}Pb(n,x)t
E_n=95 MeV
Blideanu (04)
OM: Becchetti-Greenlees
OM: Li
OM: Pang
eq emission
$d\sigma/d\varepsilon_t$ (mb/MeV)
Triton energy (MeV)
10^1
10^0
10^{-1}
10^{-2}
0
10
20
30
40
50
60
70
80
90



Promising: P.Pereslavtsev OMP

Plans:

New analysis using P.Pereslavtsev OP

Implementation in TALYS (version ?)

Conclusion

Experimental triton energy distributions were analyzed using the proposed calculation method

The first results show the definite improvement of the modeling of triton spectra in nucleon induced reactions at intermediate energies

The module implemented now in ALICE/ASH should be added after the modification to TALYS