Oleg B. Tarasov
NCSL / MSU, USA

Measurement of production cross sections and momentum distributions @ MSU

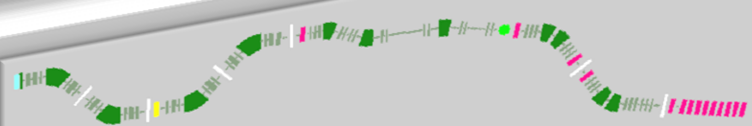
5th Fragment-Separator Experts Meeting
5th Fragment-Separator Experts Meeting

10-12 / 12 / 2013

LISE++

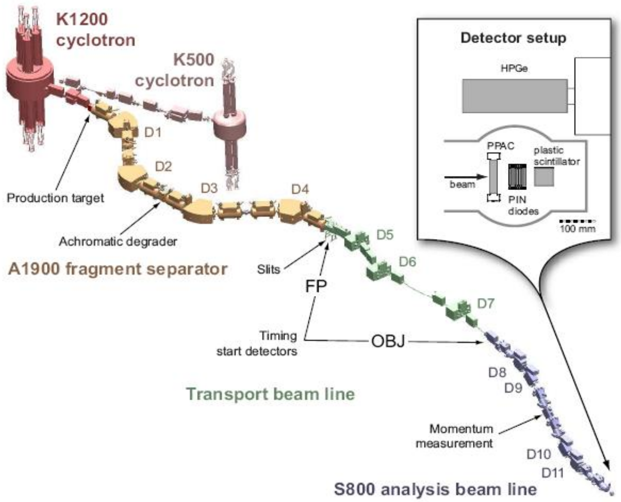
1. Introduction
2. Target thickness scanning approach to measure momentum distributions
3. Revision of target scanning approach
4. ^{76}Ge & ^{82}Se : momentum distributions
5. ^{76}Ge & ^{82}Se : cross sections
6. Isotope production close to the proton drip line
7. "Universal" model
8. Conclusion

NSCL



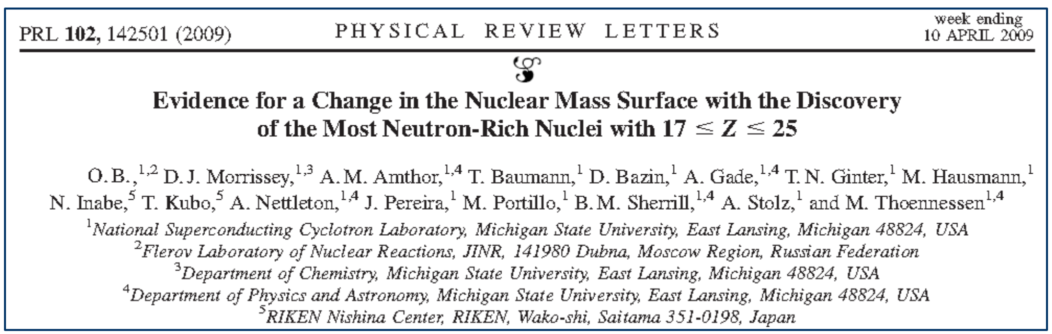
LISE++

^{76}Ge (130 MeV/u) experiment



15 new isotopes of elements 17 ≤ Z ≤ 25

^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn



PRL **102**, 142501 (2009) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2009

Evidence for a Change in the Nuclear Mass Surface with the Discovery of the Most Neutron-Rich Nuclei with 17 ≤ Z ≤ 25

O. B.,[1,2] D. J. Morrissey,[1,3] A. M. Amthor,[1,4] T. Baumann,[1] D. Bazin,[1] A. Gade,[1,4] T. N. Ginter,[1] M. Hausmann,[1] N. Inabe,[5] T. Kubo,[5] A. Nettleton,[1,4] J. Pereira,[1] M. Portillo,[1] B. M. Sherrill,[1,4] A. Stolz,[1] and M. Thoennessen[1,4]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
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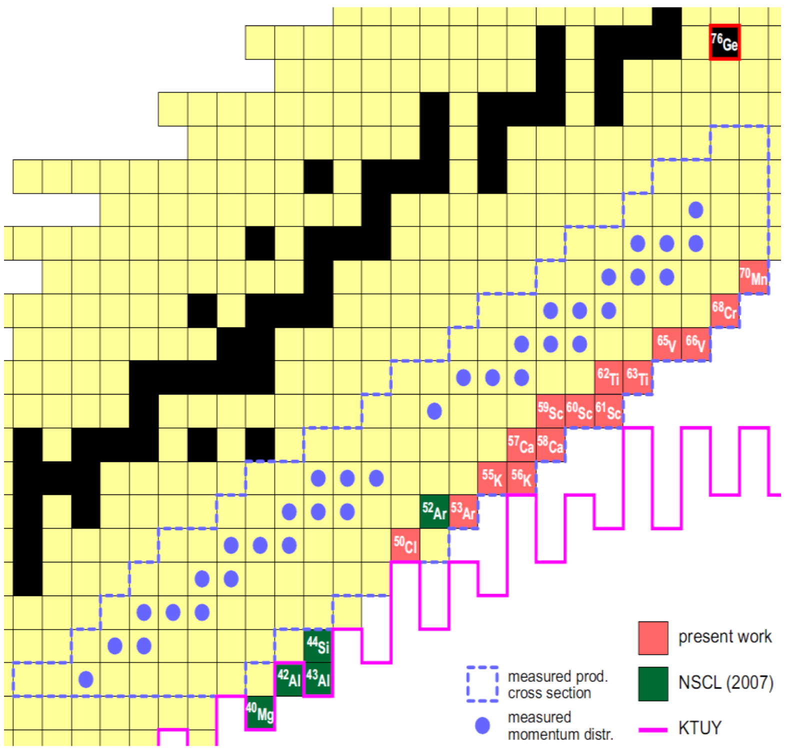
[4]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan*



Phys.Rev.Lett.	**102, 142501 (2009) :**	**New isotopes, Evidence for a Change in the Nuclear Mass Surface**
Phys.Rev.C.	**80, 034609 (2009) :**	**Set-up, cross sections, momentum distributions**
NIM A	**620, 578-584 (2010) :**	**A new approach to measure momentum distributions**

Experiment with the newly-developed ^{82}Se (139 MeV/u) beam

Beam	E (MeV/u)	I (pna)	N/Z
^{82}Se	139	35	1.412
^{76}Ge	130	20	1.375

ΔN / ΔZ=2

^{64}Ti, ^{67}V, ^{69}Cr, ^{72}Mn
^{70}Cr 1event & ^{75}Fe 1event

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW C **87**, 054612 (2013)

Production cross sections from ^{82}Se fragmentation as indications of shell effects in neutron-rich isotopes close to the drip-line

O. B.,[1,*] M. Portillo,[2] D. J. Morrissey,[1,3] A. M. Amthor,[2] L. Bandura,[2] T. Baumann,[1] D. Bazin,[1] J. S. Berryman,[1] B. A. Brown,[1,4] G. Chubarian,[5] N. Fukuda,[6] A. Gade,[1,4] T. N. Ginter,[1] M. Hausmann,[2] N. Inabe,[6] T. Kubo,[6] J. Pereira,[1] B. M. Sherrill,[1,4] A. Stolz,[1] C. Sumithrarachichi,[1] M. Thoennessen,[1,4] and D. Weisshaar[1]

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[2]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
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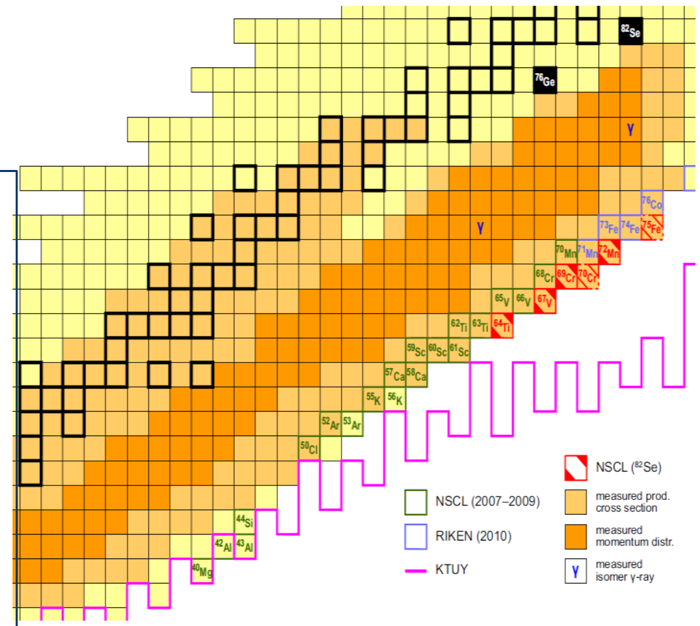
[5]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[6]*RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan*



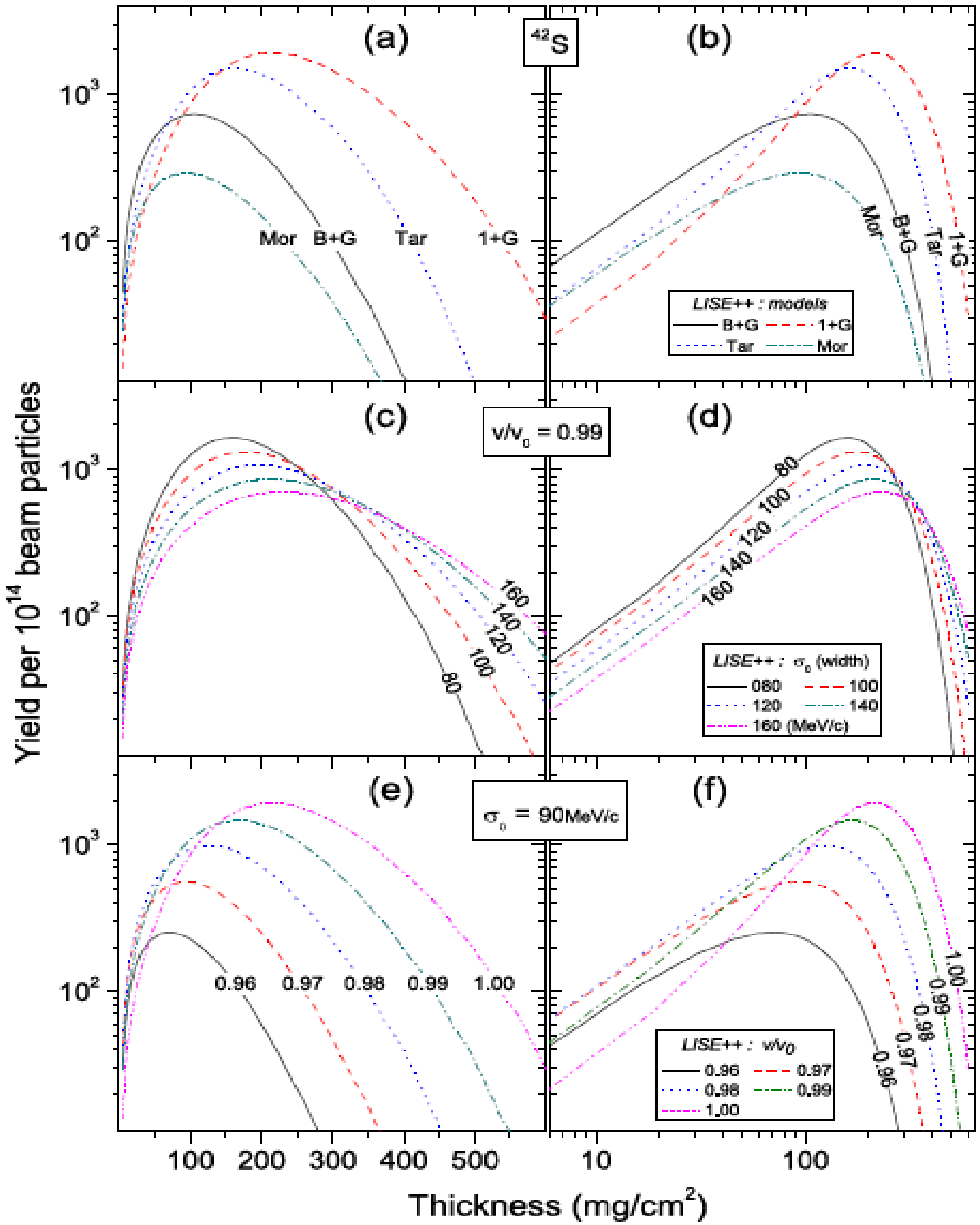
Phys. Rev. C 87, 054612 (2013) : **New isotopes, cross sections, momentum distributions, subshell closure at N = 34 around Z = 20**

NIM A (2014) : **momentum distribution measurement (detailed), revision of target thickness scanning approach to measure momentum distributions**

Momentum Distributions : Target thickness scanning method

New method:
- **Brho = const**
- **Target thickness variation**

"Classic: way:
- **Brho scanning**
- **thin target**

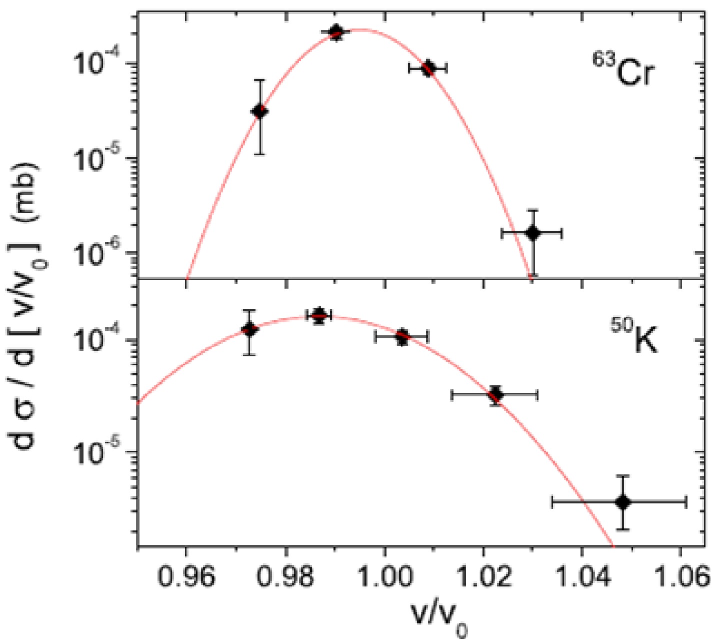


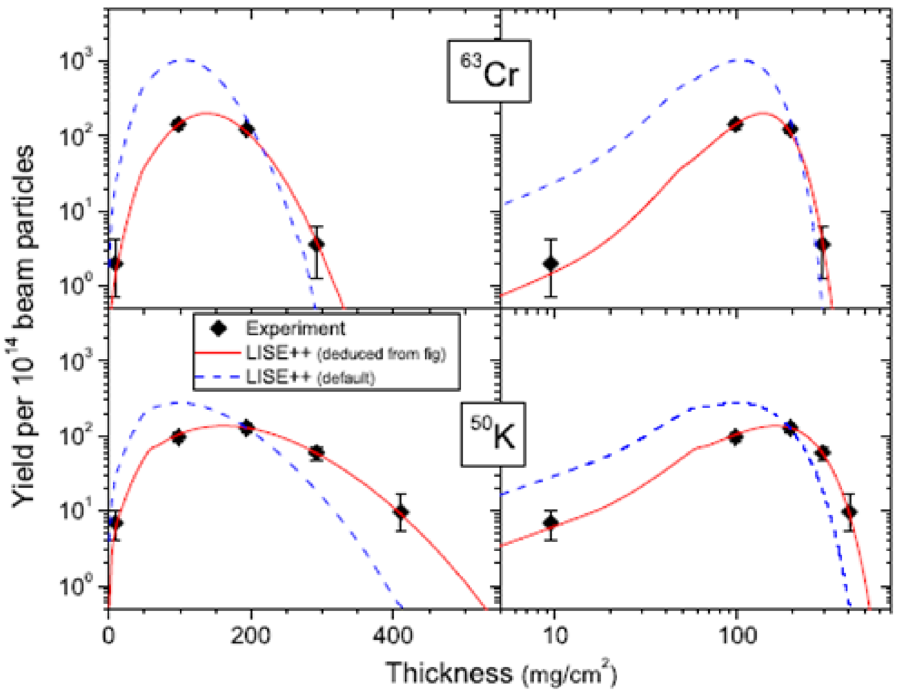
A number of simulations have been carried out in order to illustrate the sensitivity of the momentum distribution characteristics to varying target thicknesses.

The rigidity of the last dipole was kept constant at 4.3 Tm while using the "Optimum target thickness" (thickness corresponding to maximum yield) routine to calculate production yields.

^{76}Ge(130MeV/u) + Be : Momentum distribution

Run	Fragment of interest	Magnetic rigidity, $B\rho(Tm)$ $B\rho_{1,2}$	$B\rho_{3,4}$	$B\rho_{5,6,7}$	$B\rho_{8,9}$	$B\rho_{10,11}$	Target mg/cm^2	Stripper mg/cm^2	Wedge, Kapton	$\Delta p/p$ (%)	Time $hour$
1	^{43}S	4.3233	4.3233	4.3134	4.3036	4.3	Be 9.8	-	-	0.1	0.98
2							Be 97.5	-	-	0.1	2.03
3							Be 191	-	-	0.1	1.98
4							Be 288	-	-	0.1	1.85
5							Be 404	-	-	0.1	0.94

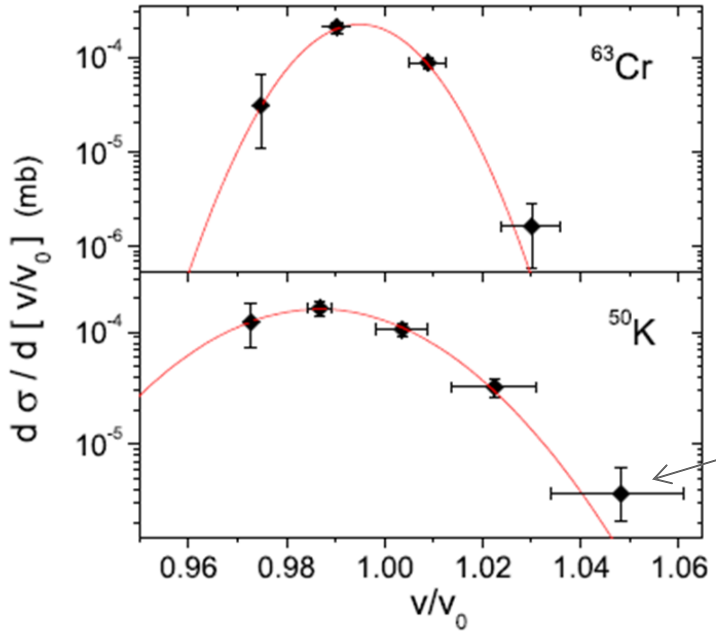




Comparison of momentum distribution measurement methods

Characteristics	$B\rho$ scanning $Thickness = const$	Target scanning $B\rho = const$
Fragment separator tuning for each measurement	Yes	No
Particle identification for each measurement	At least should be verified	PID is constant
Number of measured distribution points	Large	Small
Number of measured isotopes	Large	Small
Measuring exotic nuclei (smallest cross-sections)	Difficult	Straight forward
Contribution of energy loss in thick targets	Small	Large
Extracting longitudinal momentum distributions	Straight forward	Difficult
Applicable energy region	No restrictions	Constant cross-section region

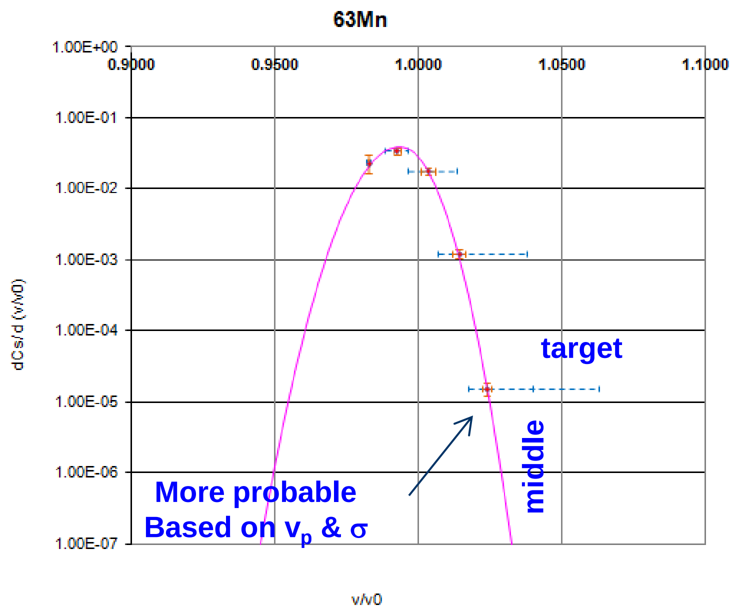
Momentum Distributions : Revision of Target scanning method

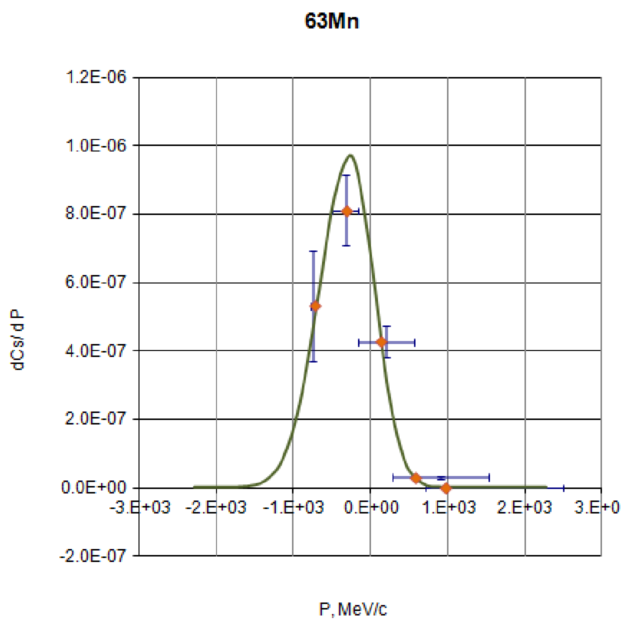


^{76}Ge : 5 targets (max 3 isotopes for one element)
^{82}Se : 7 targets (max 8 isotopes for one element)

**^{76}Ge analysis (2009) :
point for fit in the middle of target
or weights = const**

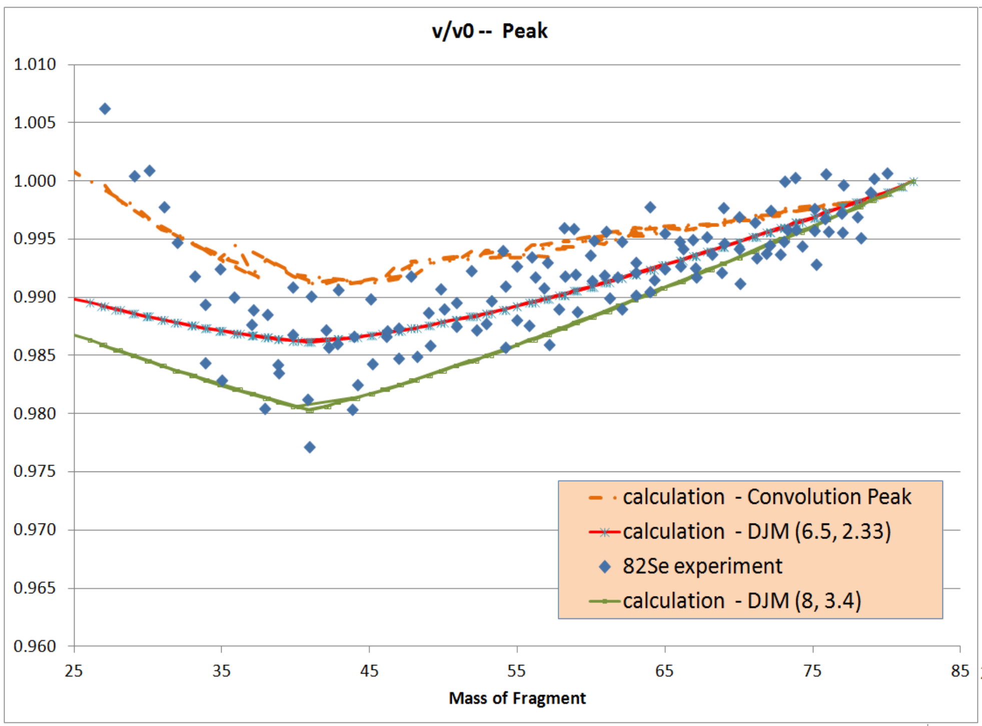
**2012 update :
using weights $F(v_p,\sigma)$ from the momentum distribution model with v_p,σ,**

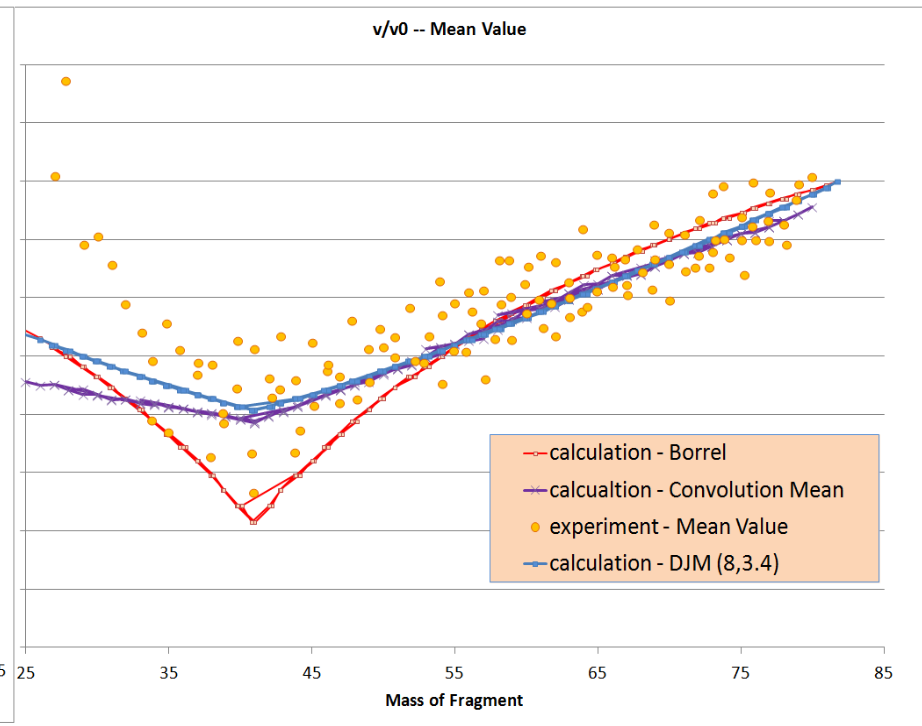




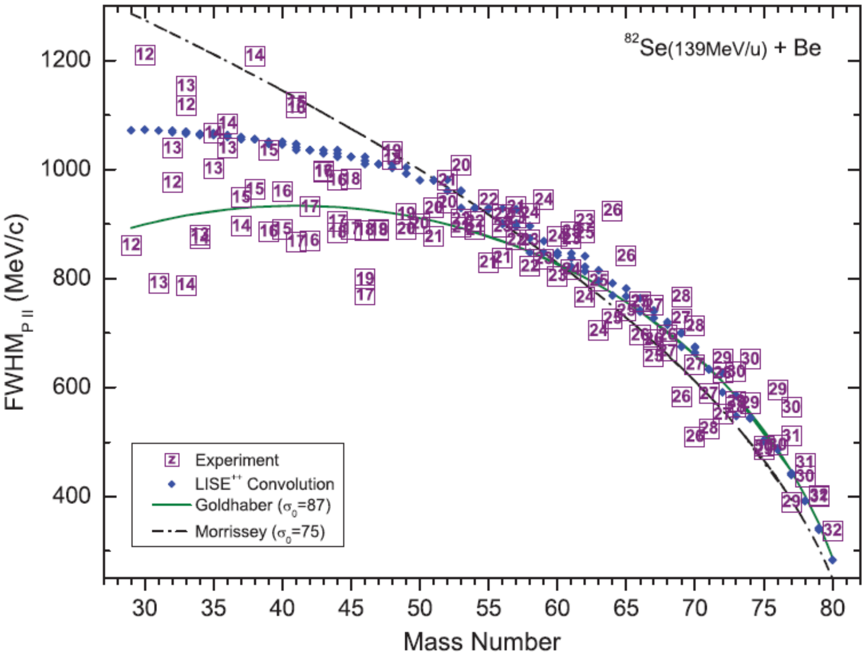
^{82}Se (139 MeV/u) + Be : Momentum Distributions – υ/υ_0

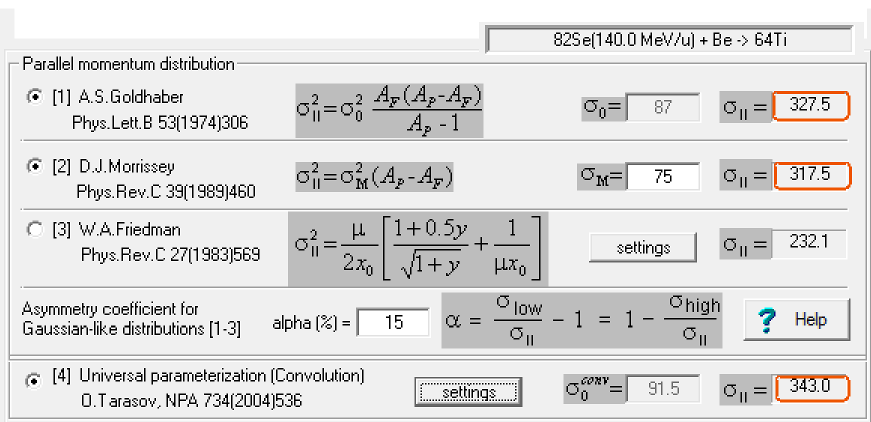
- ( ) Calculation - A [V.Borrel et al., Z.Pyhs.A314(1983)191] ***Borrel***
- ( ) Calculation - B [F.Rami et al., NPA 444(1985)349]
- ( ) Calculation - C [O.Tarasov, NPA 734(2004)536] ***convolution***
- ( ) Calculation - D [from two-body reaction]
- ( ) Calculation - E [D.Morrissey, PRC 39(1989)460] ***DJM***

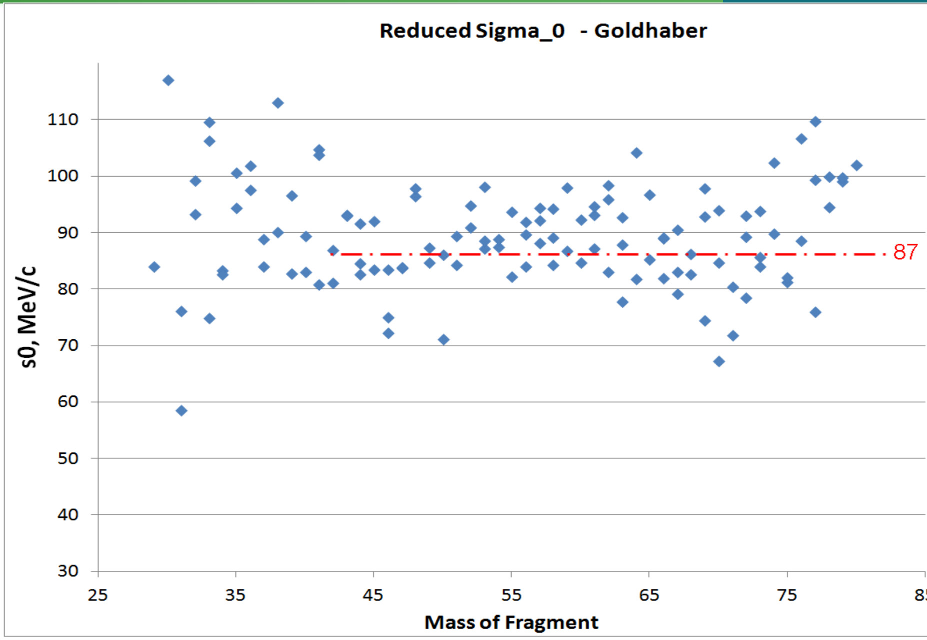


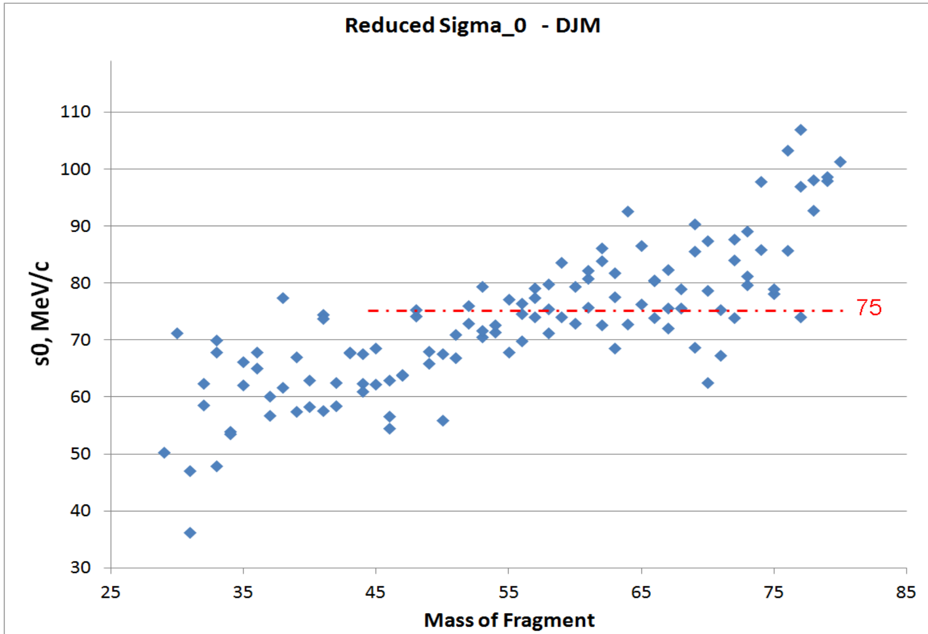


^{82}Se (139 MeV/u) + Be : Momentum Distributions – *Widths*







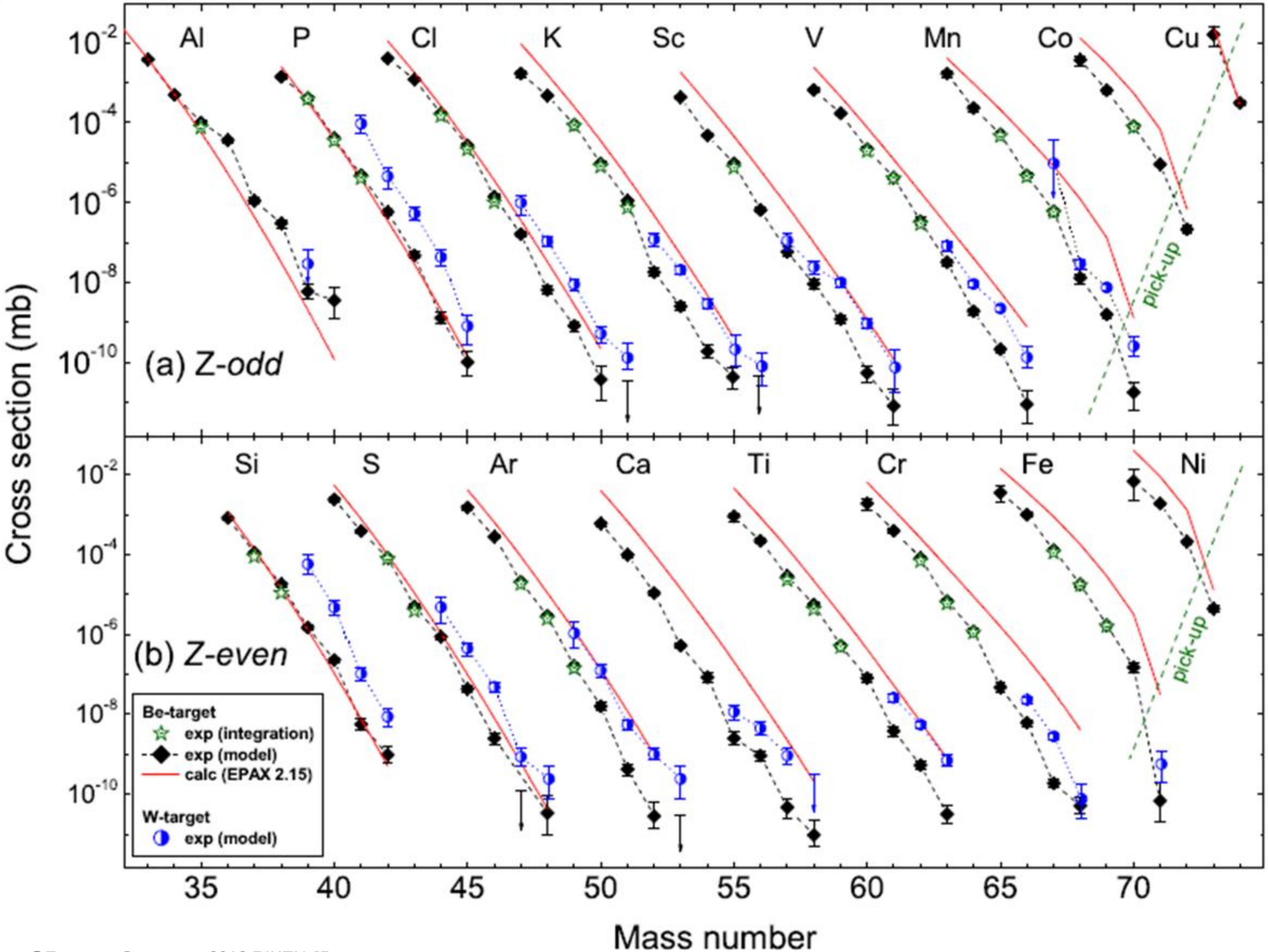


Momentum distributions analysis results

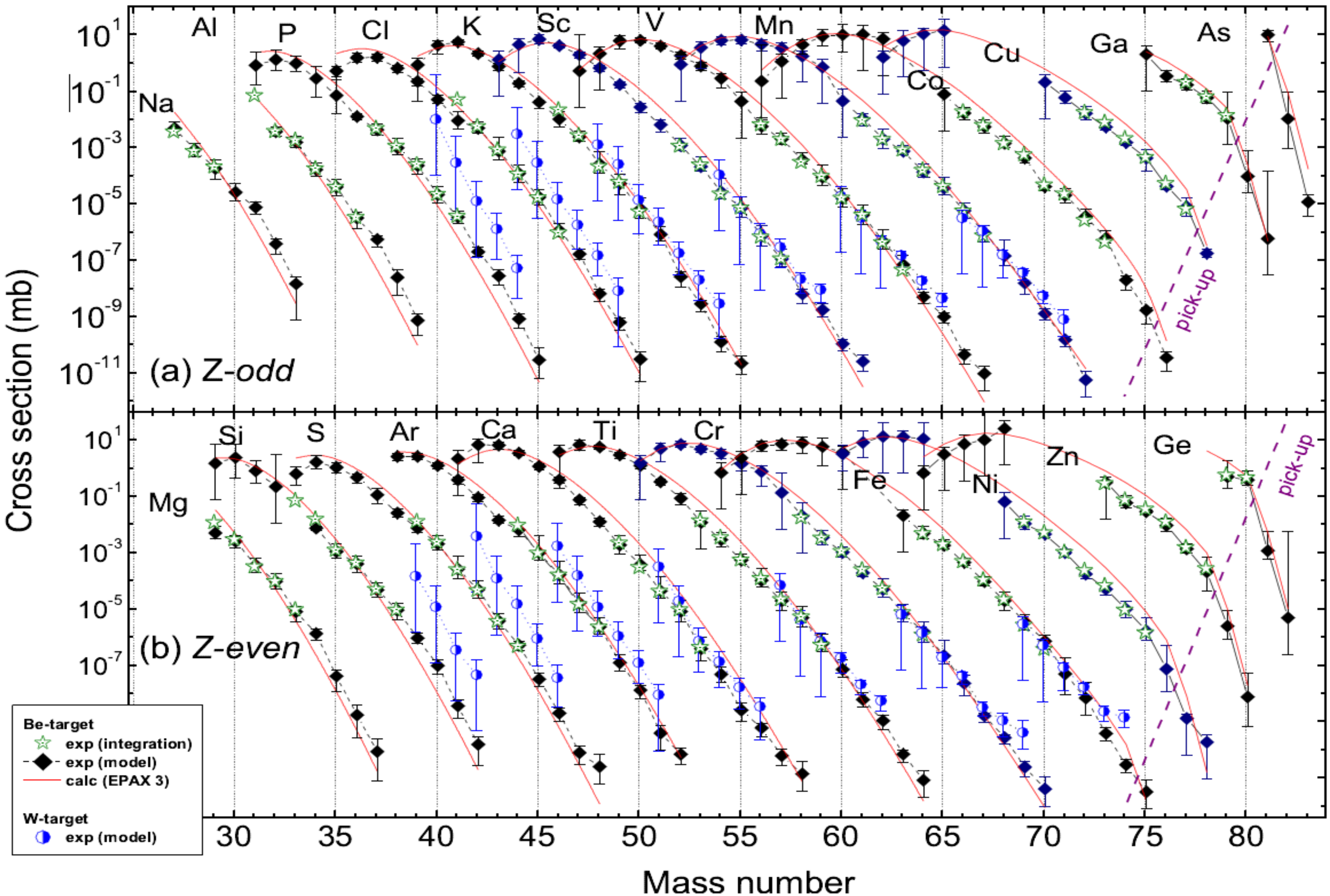
	82Se - asym	76Ge - new*	76Ge - old	default values
Number of isotopes	122	58	34	
velocity - DJM - peak	6.5 & 2.4			
velocity - DJM - mean	8 & 3.4	8 & 3.3	8 & 2.4	8 & 8
Velocity - Borrel (no fit, only for plot)	8	8		8
Average weighted				
G0_DJM	**75** -11+9	**73.1** ± 10.2	105 ± 15	86
G0_DJM * gamma		83.1		
G0_Goldhaber	**87** -13+9	**87.0** +- 7.9		90
G0_Goldhaber * gamma		98.9		

76Ge* -- target scanning re-analysis with weights use [February 17, 2012]

^{76}Ge (130 MeV/u) + Be, W : cross sections

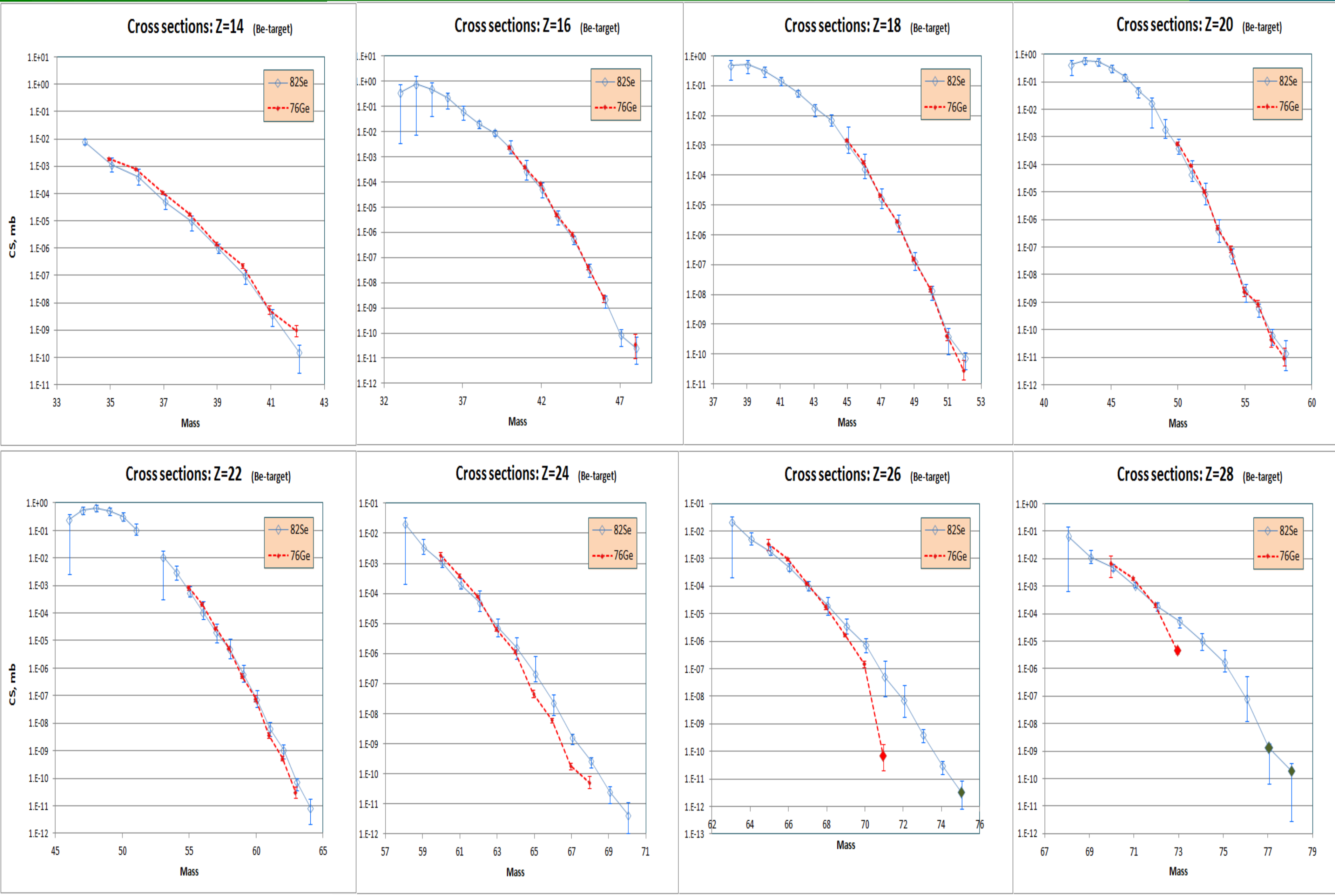


^{82}Se (139 MeV/u) : Production Cross Section

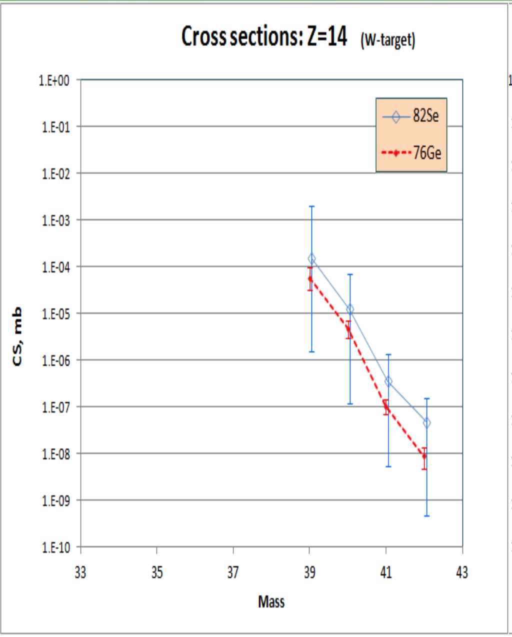


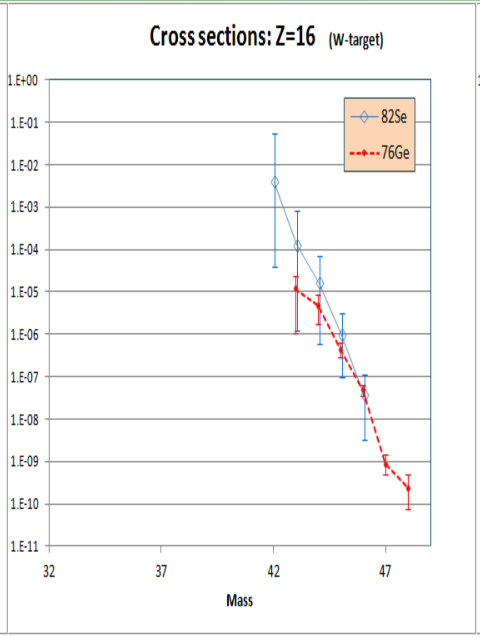
$N_W = 90$, $N_{Be} = 330$, $N_{Be\_Integral} = 126$

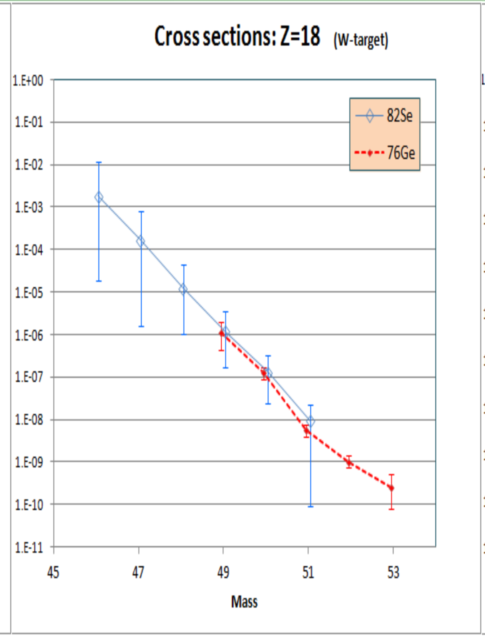
^{82}Se (139 MeV/u) vs. ^{76}Ge (130 MeV/u) : Be - target

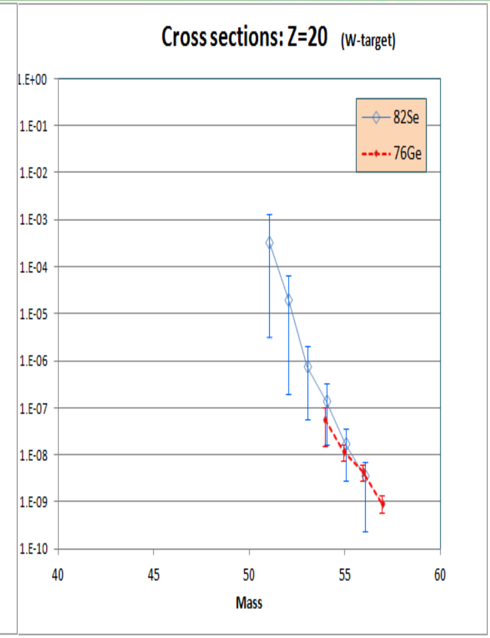


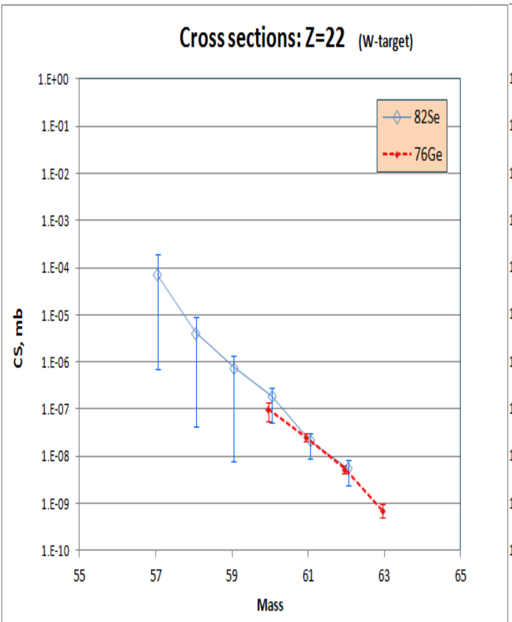
^{82}Se (140MeV/u) vs. ^{76}Ge (130 MeV/u) : W - target

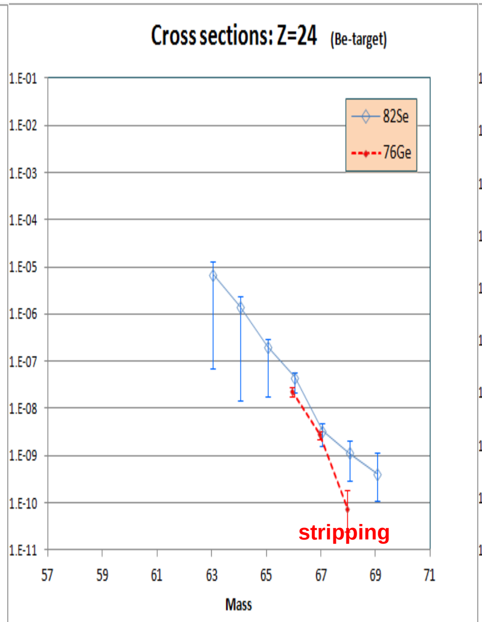


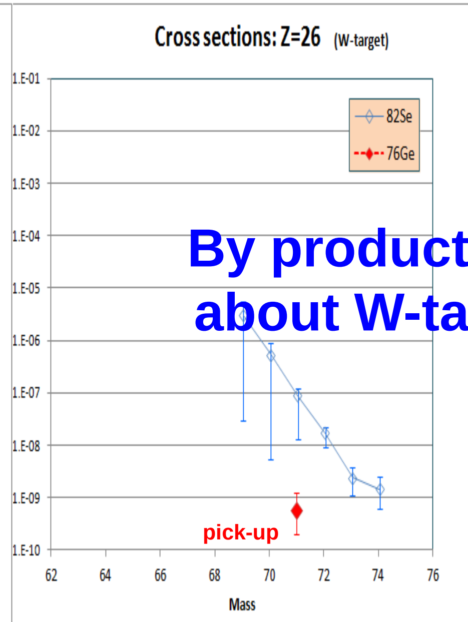






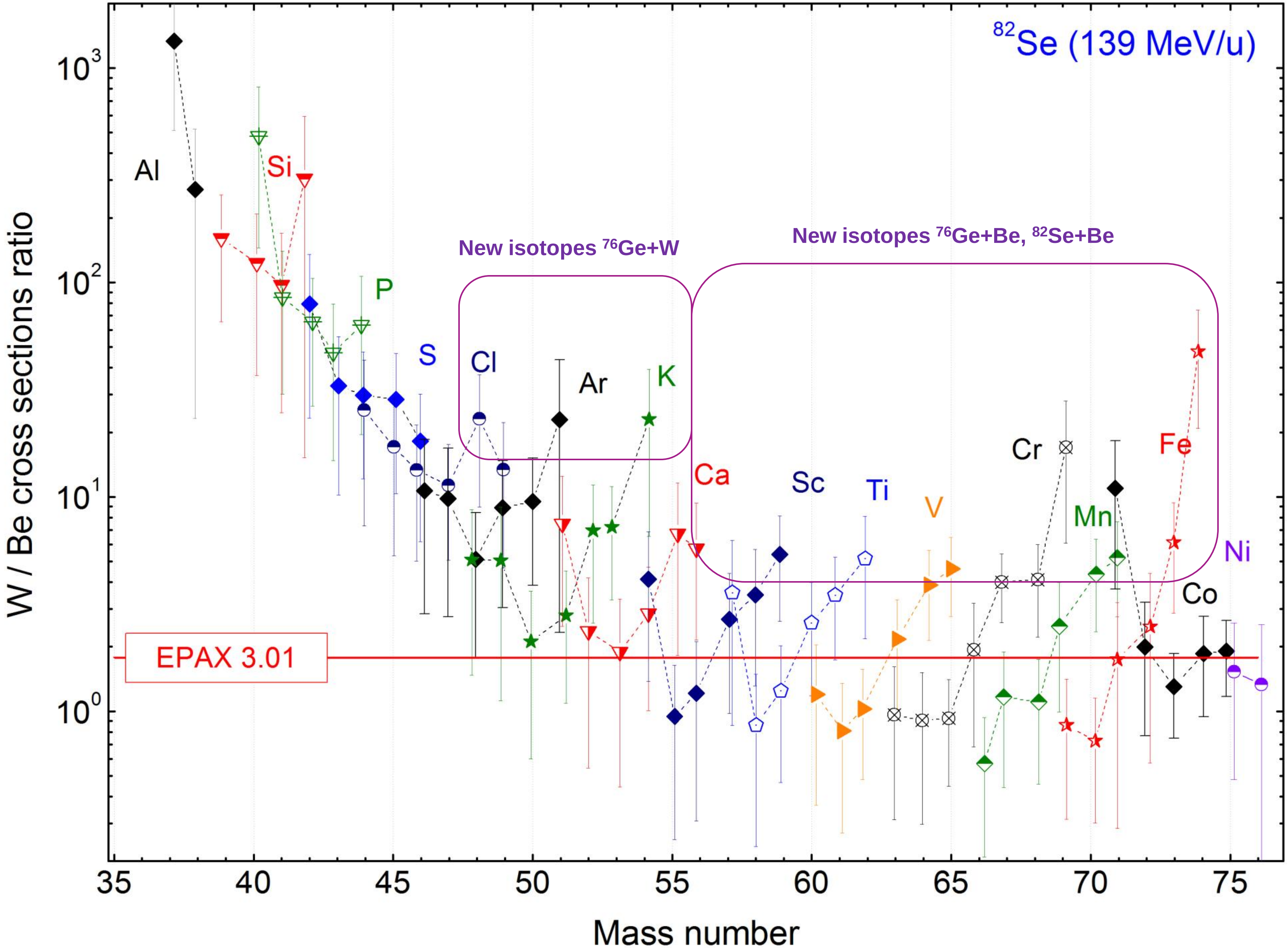




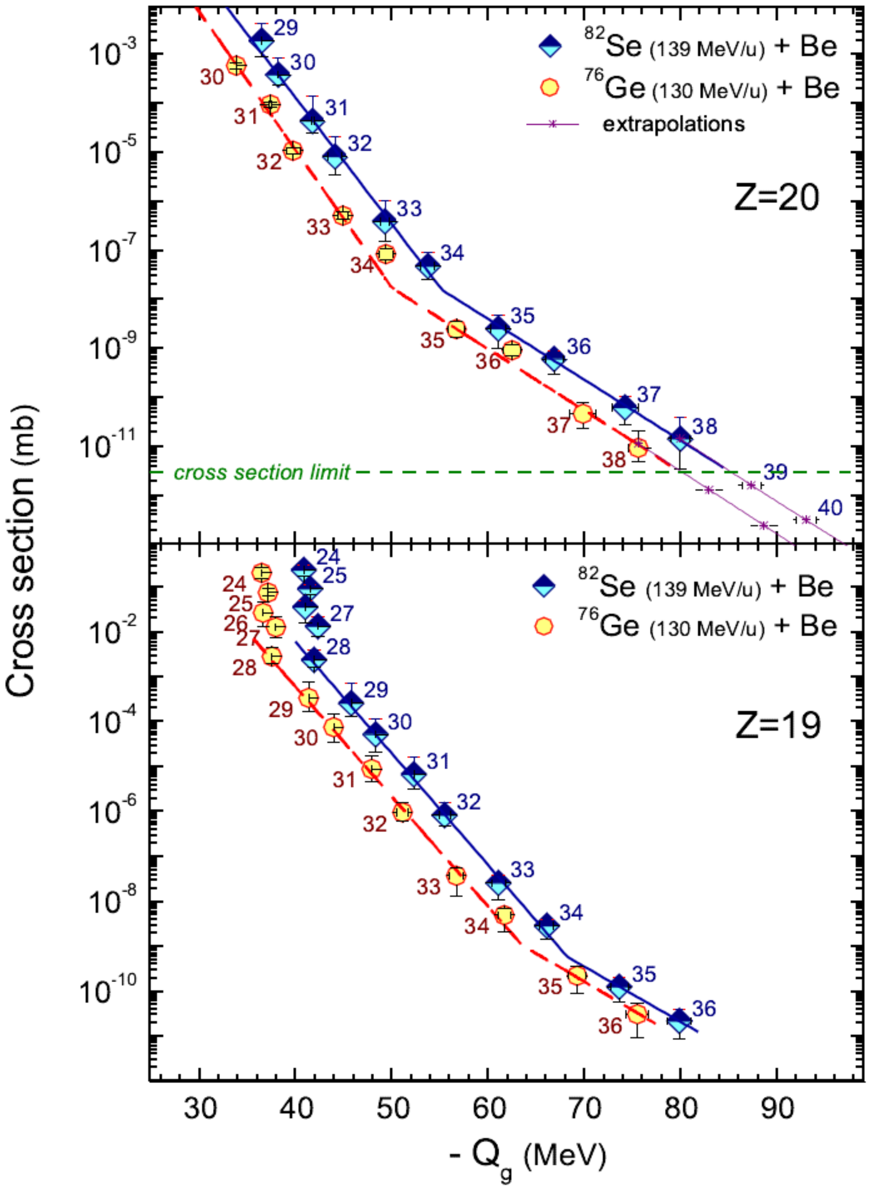


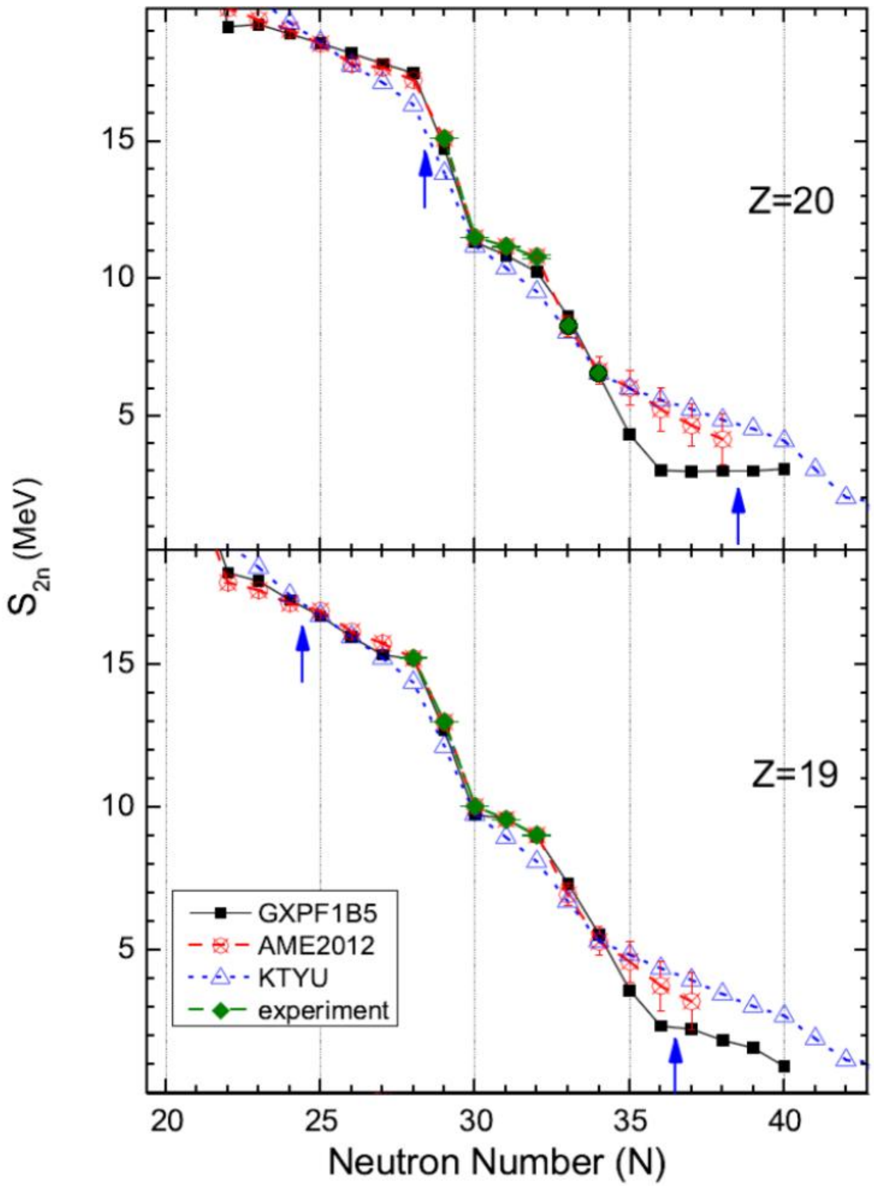
By product information about W-target lifetime

^{82}Se (139 MeV/u) : W vs. Be targets



Q_g systematics, Two-neutron separation energy





Experimental masses:
A.T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)
F. Wienholtz et al., Nature 498 (2013) 346

Global trends of cross sections

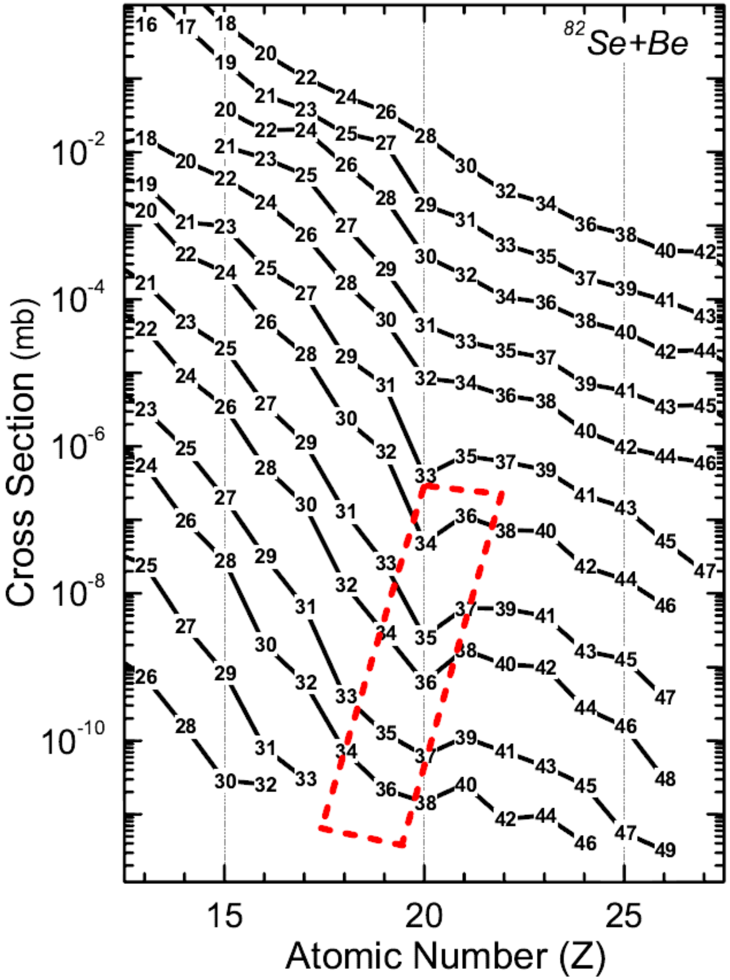


FIG. Production cross section versus atomic number (Z) for fragments from reaction of ^{82}Se with beryllium targets. **Lines are connected according to constant $N-2Z$**, while labels represent the neutron number.

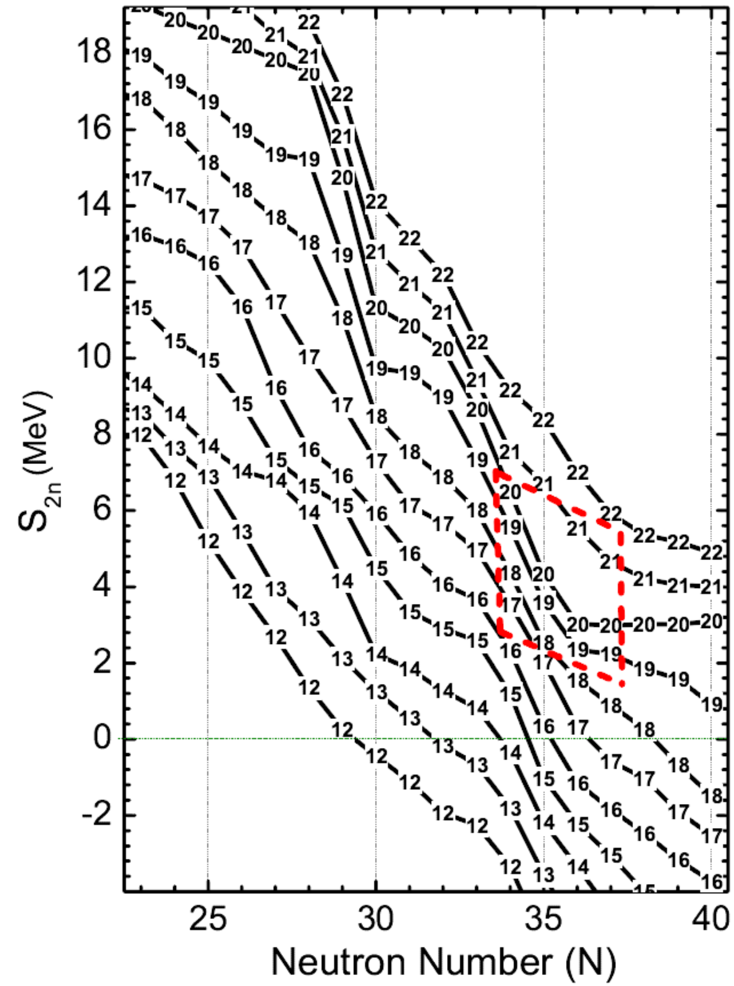
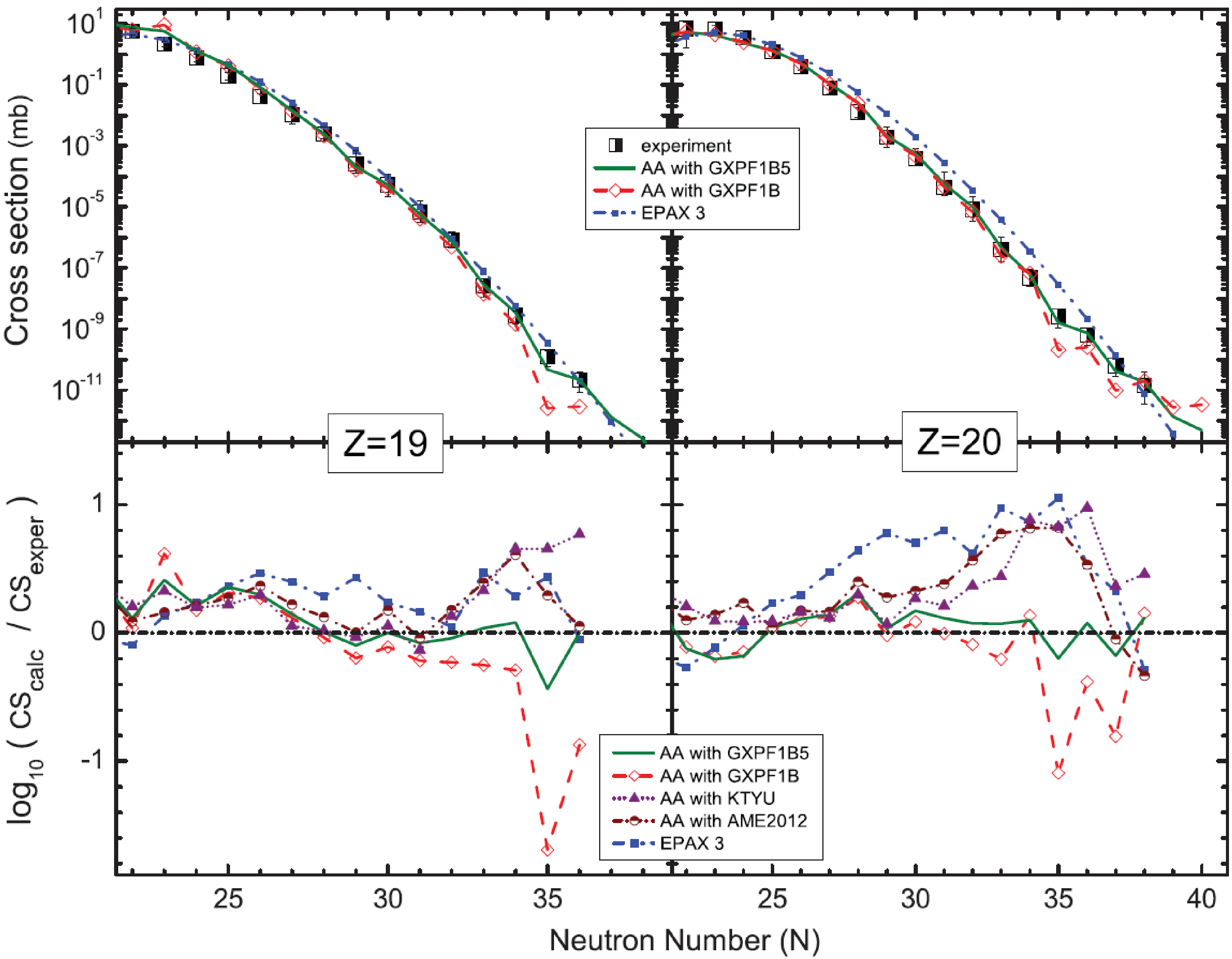


FIG. Two-neutron separation energy S_{2n} versus neutron number (N) for elements $12 \leq Z \leq 22$. Values are calculated using results from the GXPF1B5 model. Labels in the lines show atomic numbers of nuclei.

No such dump with other theoretical models

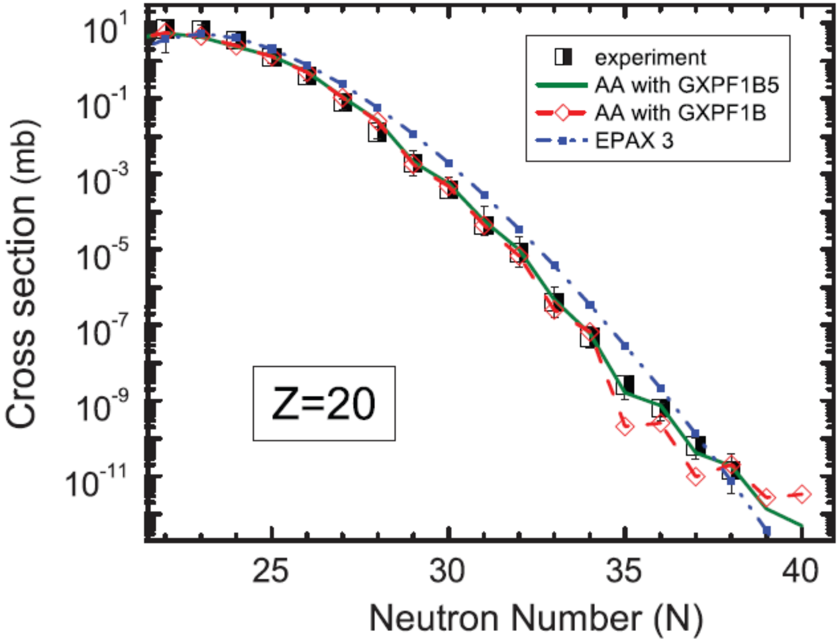
LISE++ Abrasion-Ablation model



Estimation of ^{60}Ca production cross section

$$\sigma(^{60}\mathbf{Ca})_{estimation} = 4(\pm 1) \times 10^{-16}\ \mathbf{b}$$

$$\sigma_{lowest\ measured\ @\ MSU} = 3 \times 10^{-15}\ \mathbf{b}$$



Primary beam	Estimation method	^{59}Ca cross section (mb)	^{60}Ca cross section (mb)
^{82}Se	AA	1.39e-12	4.83e-13
^{82}Se	Q_g	1.62e-12	3.19e-13
^{76}Ge	Q_g	1.36e-12	2.47e-13
^{82}Se	EPAX3	3.73e-13	1.65e-14
^{76}Ge	EPAX3	3.68e-13	1.71e-14

AA: Masses calculated with the GXPF1B5 interaction

^{17}Ne production with a ^{20}Ne beam @ NSCL

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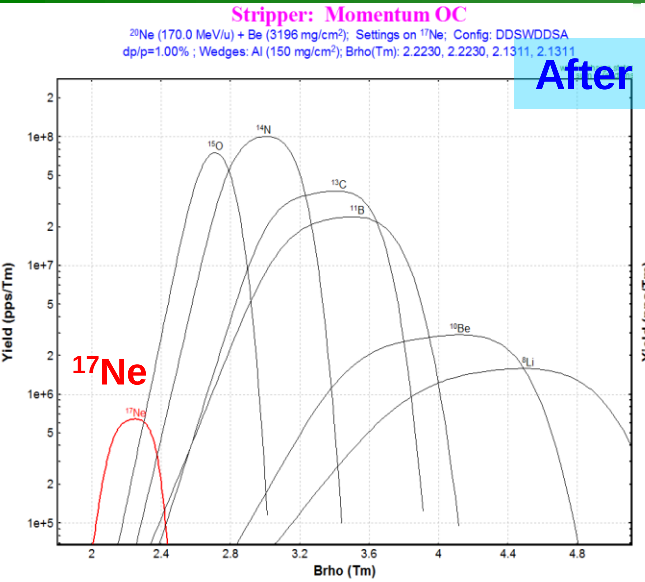
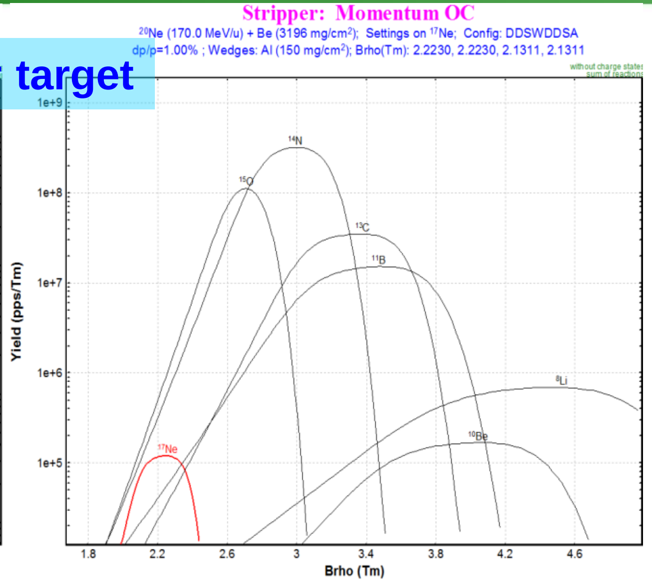
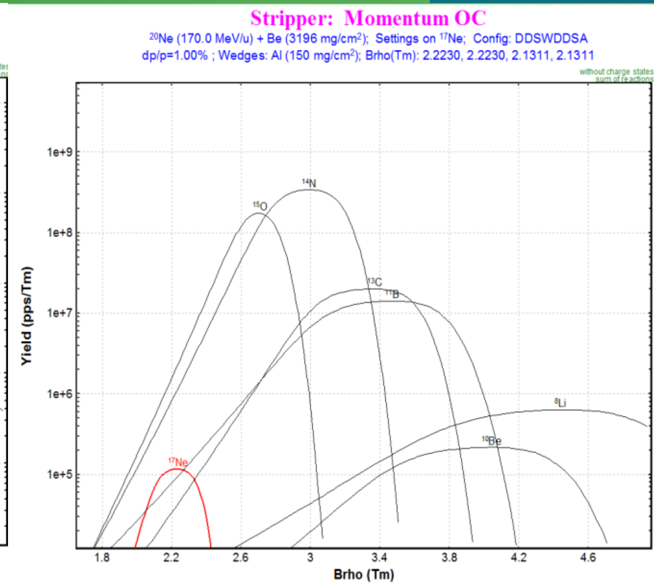
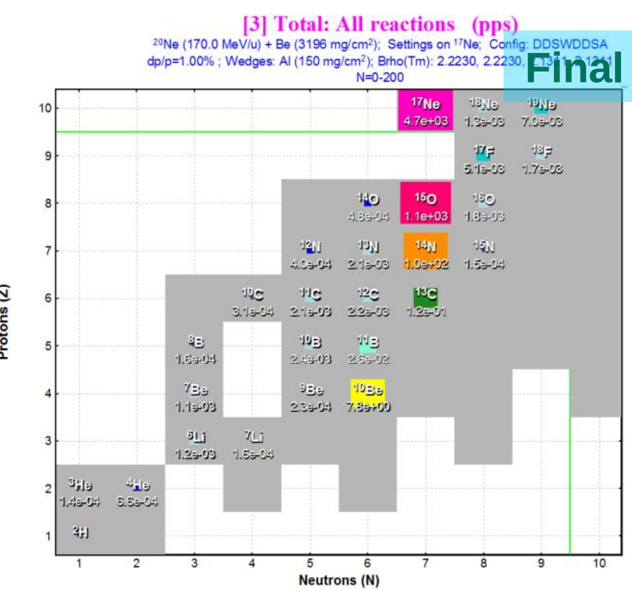
After target

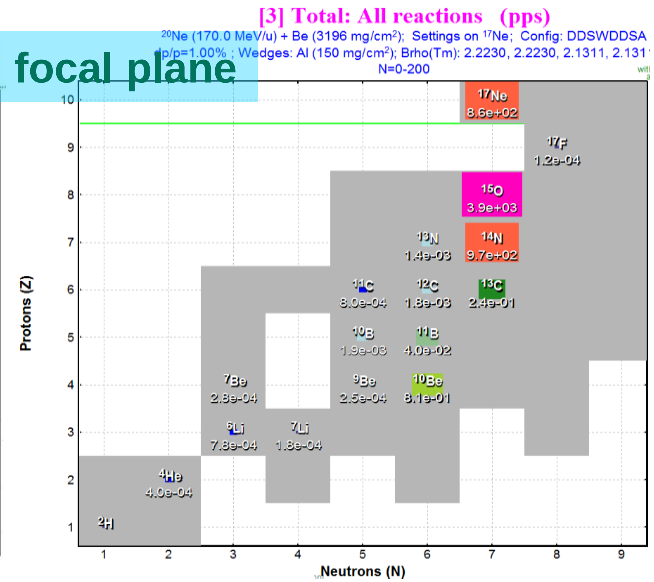


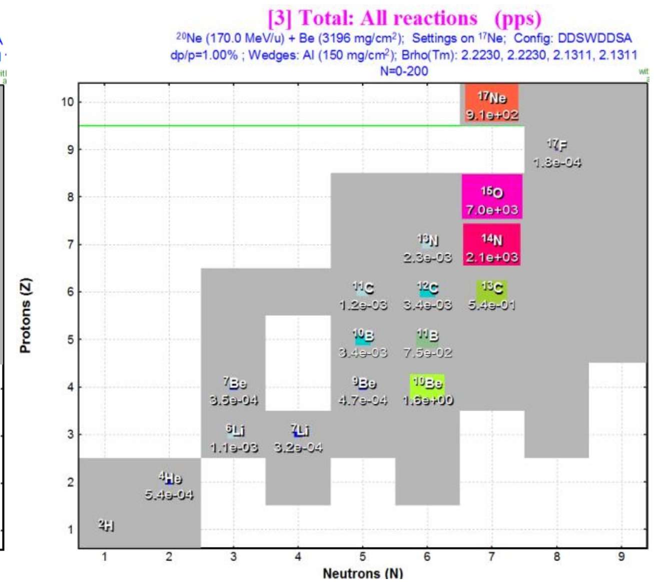




Final focal plane







^{17}Ne / all
82%

Default settings:
EPAX3
UP #1, coef=3

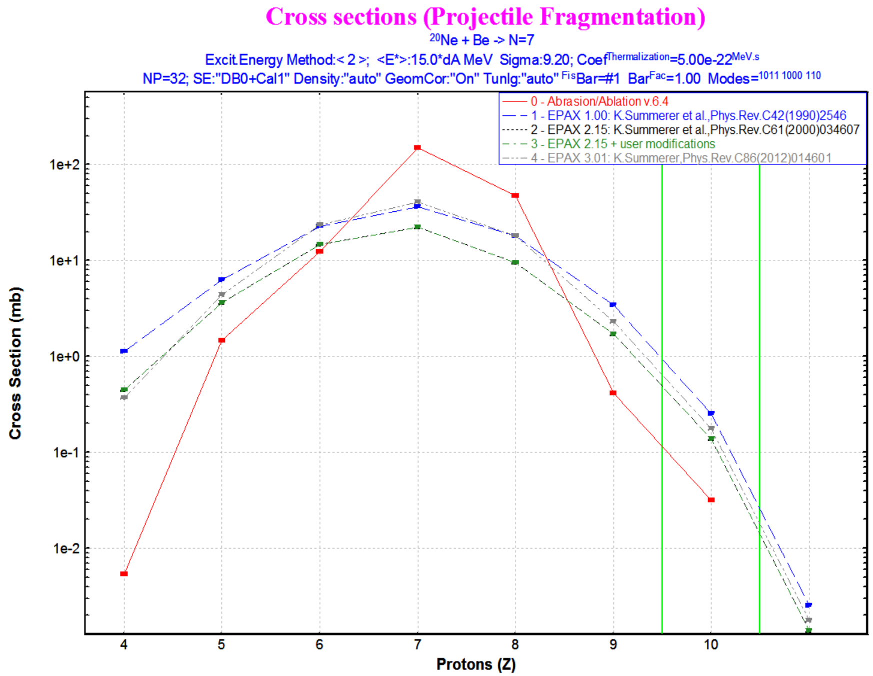
^{17}Ne / all
15%

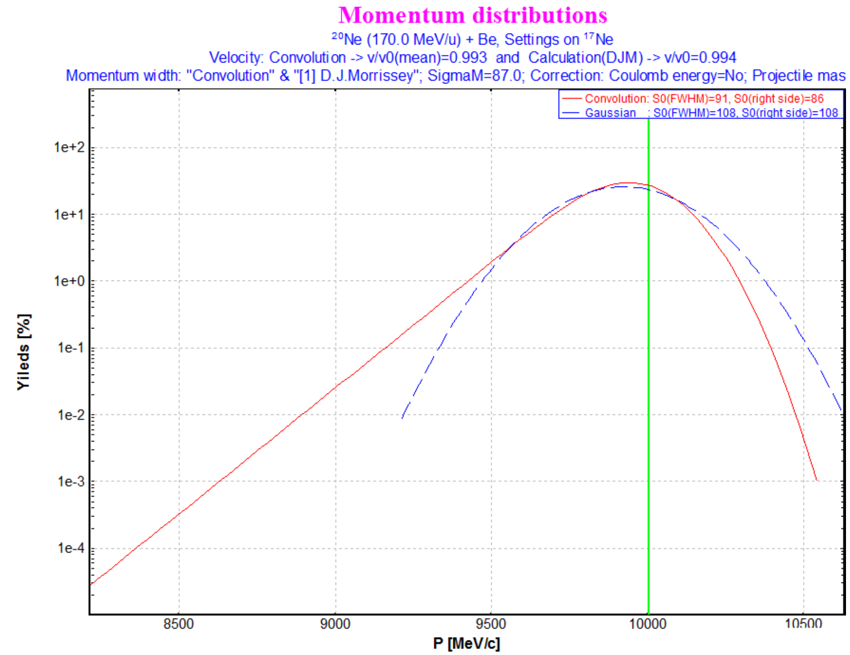
settings:
AA (15/9.4)
UP #1, coef=3.5

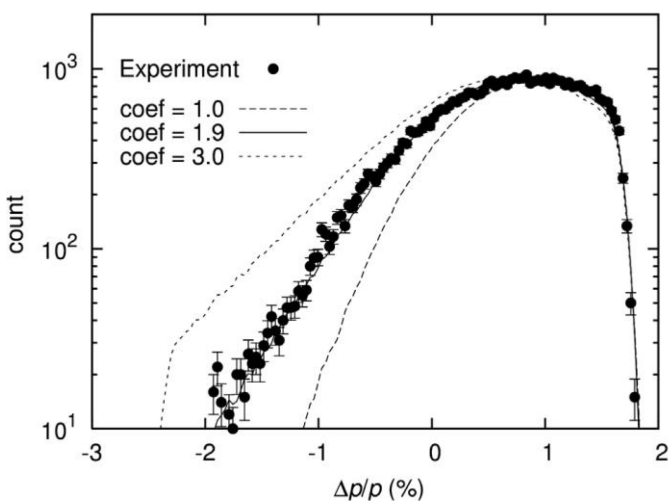
^{17}Ne / all
9%

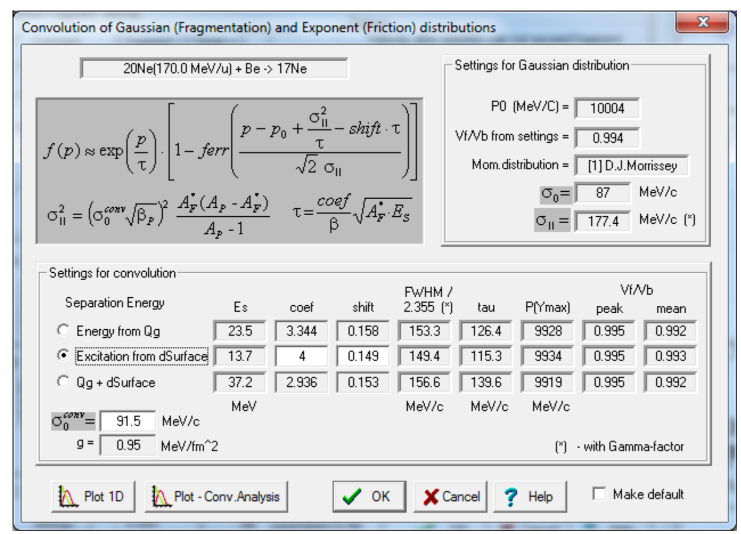
settings:
AA (15/9.4)
UP #1, coef=4.0

^{17}Ne production with a ^{20}Ne beam @ NSCL







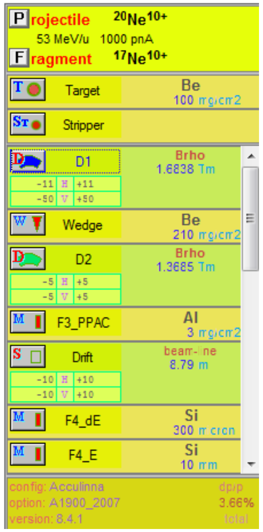


$$f(p) \approx \exp\left(\frac{p}{\tau}\right)\cdot\left[1 - ferr\left(\frac{p - p_0 + \frac{\sigma_{\parallel}^2}{\tau} - shift\cdot\tau}{\sqrt{2}\,\sigma_{\parallel}}\right)\right]$$

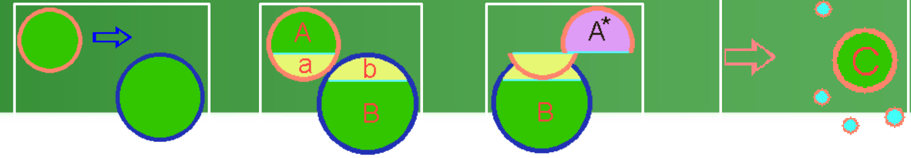
$$\sigma_{\parallel}^2 = \left(\sigma_0^{conv}\sqrt{\beta_P}\right)^2 \frac{A_F^{\bullet}(A_P - A_F^{\bullet})}{A_P - 1} \qquad \tau = \frac{coef}{\beta}\sqrt{A_F^{\bullet}\cdot E_s}$$

H. Suzuki et al., NIM B 317 (2013) 756–768

^{17}Ne production @ FLNR/JINR (estimation)



Beam	Target	Reaction	Cross section	result
20Ne	Be	EPAX2	1.39E-01	7.70E-01
20Ne	Be	AA	6.43E-02	3.56E-01
20Ne	Be	AA, Rt=7fm	4.03E-02	2.23E-01
20Ne	Ni	EPAX2	2.43E-01	2.43E-01
20Ne	Ni	AA, EE#0	1.68E+00	1.68E+00
24Mg	Be	EPAX2	8.63E-02	4.78E-01
24Mg	Be	AA	3.08E-02	1.71E-01
24Mg	Ni	EPAX2	1.42E-01	1.42E-01
24Mg	Ni	AA, EE#0	1.72E+00	1.72E+00
16O	3He	FR (20MeV/u)	6.00E-01	7.62E+00
20Ne	3He	FR	1.00E-02	1.27E-01
24Mg	3He	FR	4.00E-03	5.08E-02
24Mg	9Be	FR	2.00E-03	1.11E-02



3-step projectile fragmentation model

Process		Momentum distribution
1 Abrasion **Removal of the part "a" (statistics)**	**Gaussian**	$\psi(p_{pf}) = \frac{1}{\sqrt{2\pi}\,\sigma_{pf}} \exp\left(\frac{-(p_{pf}-p_{0pf})^2}{2\sigma_{pf}^2}\right)$
2 Friction - loss of kinetic energy **Transformation into the internal degrees of freedom.** **Exchange of nucleons**	**Exponential attenuation**	$\phi(p_1, p_2) = \frac{1}{\tau}\exp\left(-\frac{p_2 - p_1}{\tau}\right)$
3 Ablation **light nuclei emission, gamma-emission**	**Broadening**	**velocity peak maximum does not shift**

$$f(p) = \phi \otimes \psi \cong \exp\left(\frac{p}{\tau}\right) \cdot \left[1 - ferr\left(\frac{p - p_0 + \frac{\sigma_{pf}^2}{\tau} - s\cdot\tau}{\sqrt{2}\,\sigma_{pf}}\right)\right]$$

Where $\tau = coef \cdot \sqrt{A_{PF} \cdot E_S} / \beta$, and

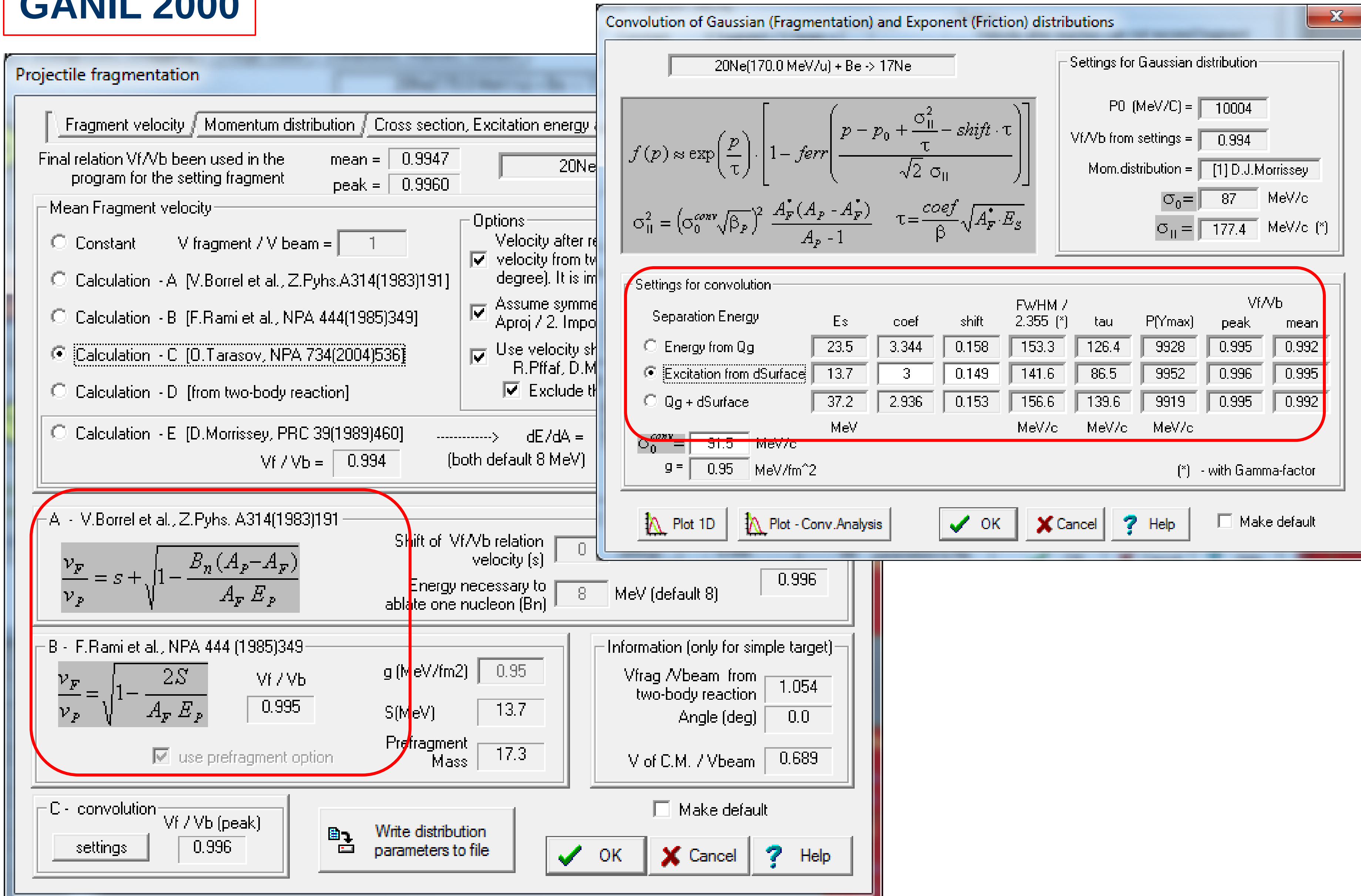
$$\sigma_{pf}^2 = \beta\sigma_0^2 \frac{A_{PF}(A_P - A_{PF})}{A_P - 1}$$

E_S is the energy spent to split the projectile (mass difference, surface energy excess)

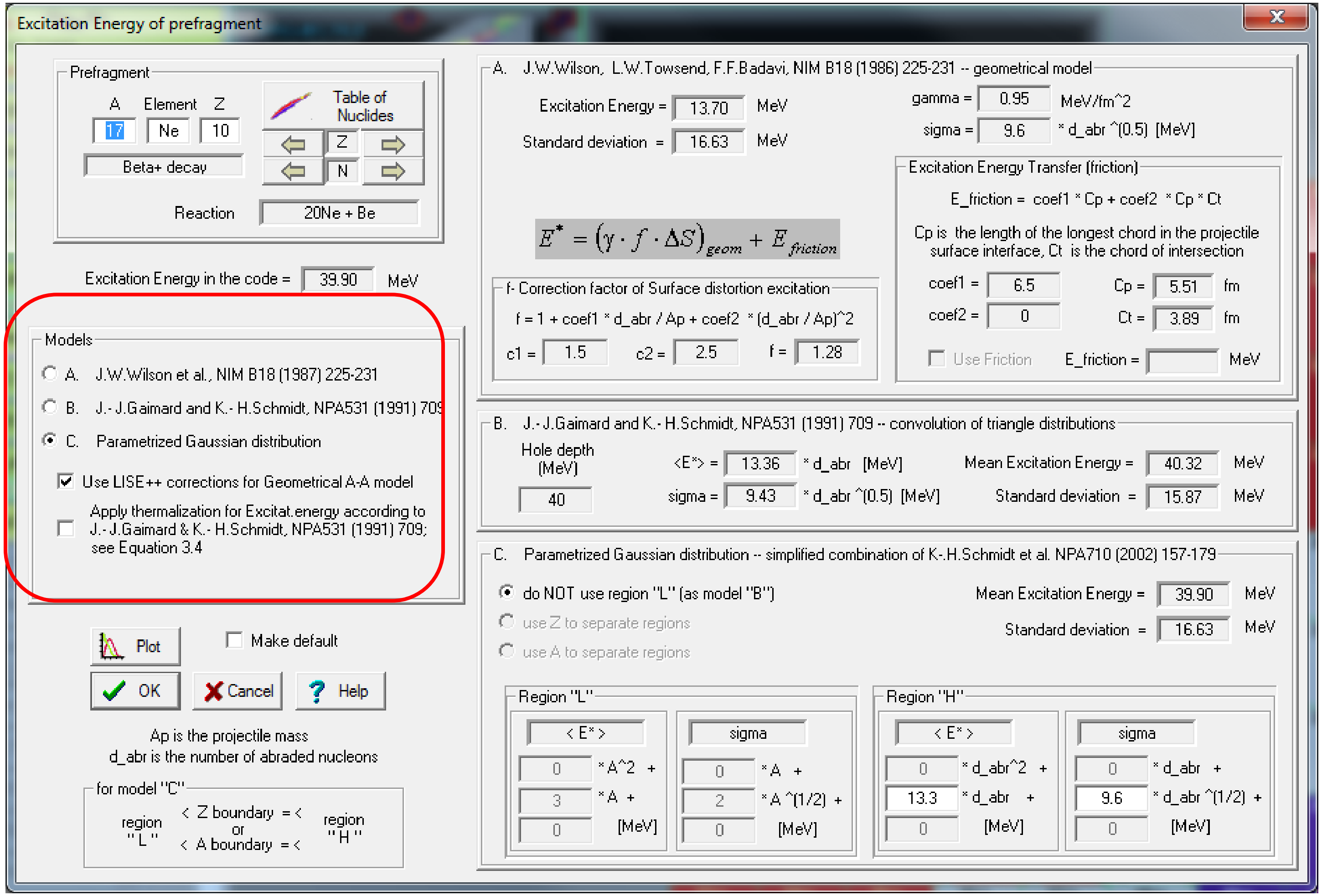
A_{PF} is the mass number of the prefragment. Three parameters to fit: **σ_0, s, coef.**

Universal parameterization : Excitation energy

GANIL 2000



Universal parameterization : Excitation energy



Should be revision for excitation energy in the "Universal parameterization"

Abrasion-Friction-Ablation

September 10, 2006. 30 years of Projectile Fragmentation workshop, ACS

What do we know from experiments?

1. Decreasing the projectile velocity → increase of production cross-section of neutron-rich isotopes
2. Increasing target mass → increase of production cross-section of neutron-rich isotopes
3. Low Exponential tail in momentum distribution is due to dissipative processes

Why do cross-sections increase?

From the AA formalism:

Increasing excitation low-energy tail.

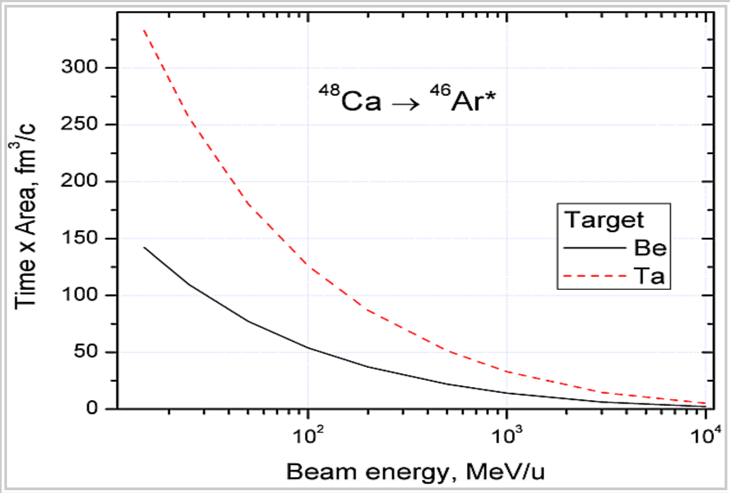
Broadening or/and shift of excitation energy distribution take place due to **friction?**

If assume dissipation processes it is possible to answer on preceding questions:

1. Dissipation Time is increasing
2. Dissipation Time and Touching Area are increasing due to target size

Time of dissipation	~ to beam velocity & Chord_max
Touching area is	~ to Chord_min^2
Target thermal capacity	~ target mass

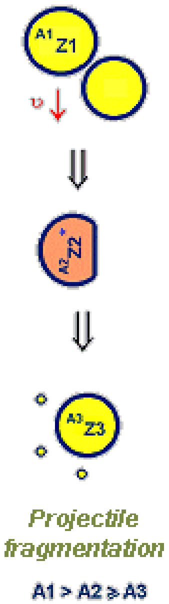
$$dQ = -K \frac{dT}{dx} dS\, dt$$



MICHIGAN STATE UNIVERSITY

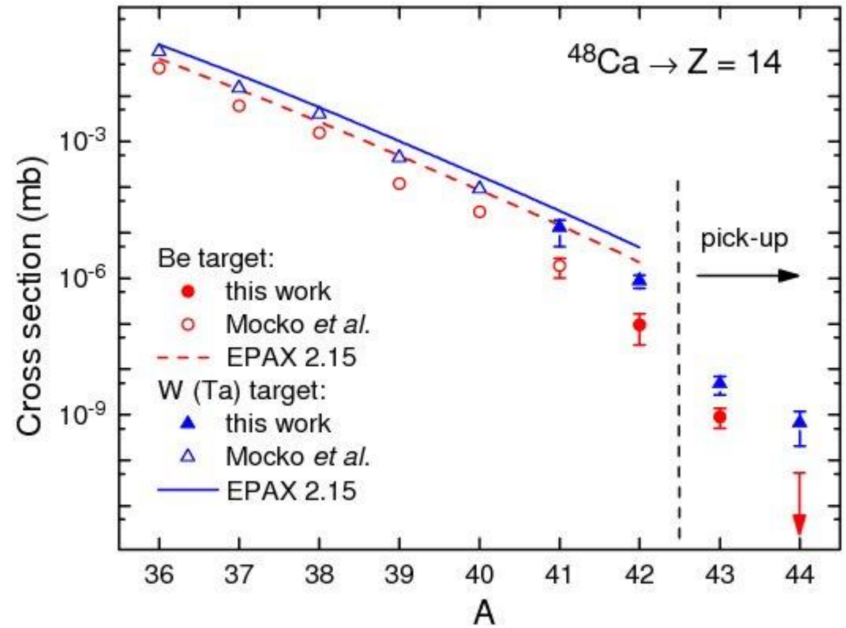
LISE++

EMIS. 24-29.06.07, Deaville, France



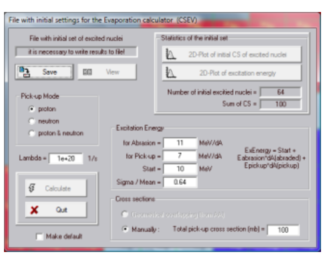
NSCL / MSU

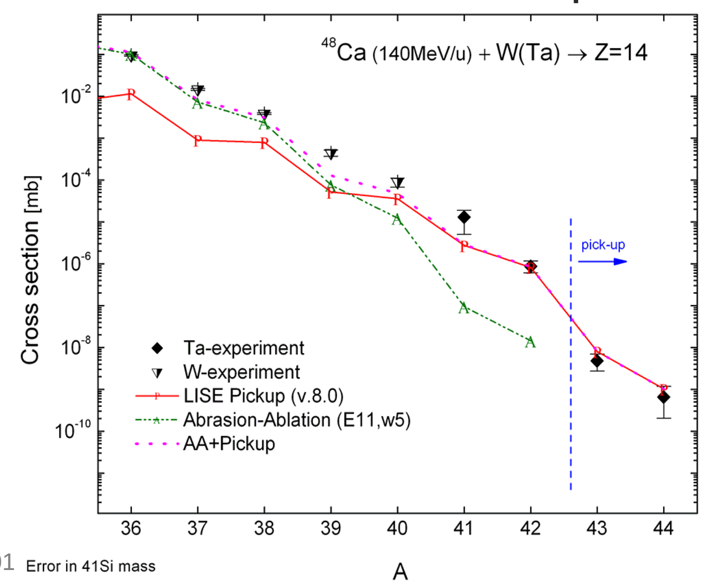
^{40}Mg, ^{42,43}Al	Nature 449 (2007) 1022
^{44}Si	Phys. Rev. C 75, 064613 (2007)

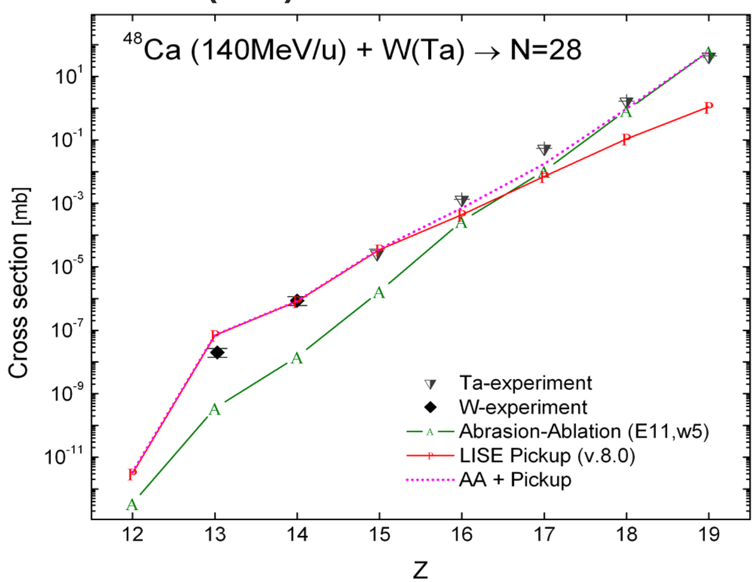


LISE^{++} Abrasion-Ablation cannot explain production cross section dependences from target properties (size, N/Z ratio) and projectile energy. No explanation for pickup contribution

LISE++ Abrasion-Dissipation-Ablation model (ADA) /under construction/







Error in 41Si mass

Just ONE

Universal model for

cross sections and

momentum distributions

should be developed…

Summary

of the present study of fragmentation of ^{76}Ge and ^{82}Se beams

^{76}Ge

- **New 15 neutron-rich isotopes ($17 \le Z \le 25$)**
- **Evidence for a Change in the Nuclear Mass Surface**
- **Cross sections and Momentum distributions**
- **A new approach to measure momentum distributions**
- **New parameters for DJM momentum distribution model**

^{82}Se

- **Isotopes ^{64}Ti, ^{67}V, ^{69}Cr, and ^{72}Mn were identified for the first time. One event was registered consistent with ^{70}Cr and another one with ^{75}Fe**
- **The momentum distributions of 126 neutron-rich isotopes of elements with $11 \le Z \le 32$ were measured and compared to models**
- **The cross sections for 330 nuclei produced by the ^{82}Se beam were measured**
- **The experiment confirmed the trend of our previous experiment using a ^{76}Ge beam, where the most neutron-rich nuclei of elements with Z = 19 to 21 have been produced with an enhanced rate compared to the Q_g systematics**
- **This result has been explained with a shell model that predicts a subshell closure at N = 34 and a more pronounced one at Z = 20**
- **The measured cross sections were best reproduced by LISE^{++} Abrasion-Ablation model using masses derived from the full *pf* shell-model space with the GXPF1B5**
- **The cross section for production of ^{60}Ca using a ^{82}Se beam on beryllium has been estimated at $4(\pm1) \times 10^{-16}$ b**

This work was supported by NSF No. PHY-06-06007, PHY-06-06007, No. PHY-10-68217, and No. PHY-11-02511 grants.