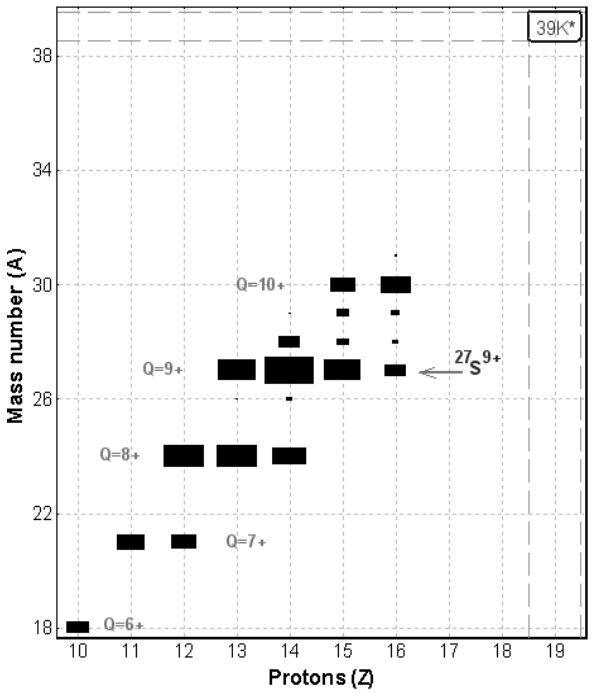
THE CODE LISE: version 5.15

www.nscl.msu.edu/lise
dnr080.jinr.ru/lise

East Lansing
08-MAR-2002

Fusion residue transmission



Plot of transmitted residues calculated by the LISE program for the reaction ^{12}C(37 MeV/u) + Al (4 mg/cm^2). Calculations were performed for the LISE spectrometer with the Wien velocity filter (E=2000 kV/m) set on the ion $^{27}S^{9+}$.

Contents:

1. How to calculate fusion residue transmission (step by step)

A new fusion-evaporation model "LisFus" for the fast calculations of fusion residue cross sections has been developed. This model is based on the Bass fusion cross-section algorithm [Bas74], the evaporation cascade code of Gaimard and Schmidt's Abrasion-Ablation model [Gai91], and the transport integral theory [Baz94]. The user has also the possibility to use fusion residue cross sections calculated by the program PACE, which has been incorporated in the LISE package. The code PACE [Gav80] (**P**rojection **A**ngular-momentum **C**oupled **E**vaporation) is a modified version of JULIAN - the Hillman-Eyal evaporation code using a Monte-Carlo method coupling angular momentum. The program LISE has now the possibility to calculate the transmission of fusion residues through a fragment separator. The transmission calculations have to be performed following the steps described below:

1. Choosing reaction type
2. Beam, Target, Residue settings
3. Options
4. Residue excitation function
5. Setting of residue ion charge
6. Target thickness
7. Separation

1.1. Choosing Reaction type

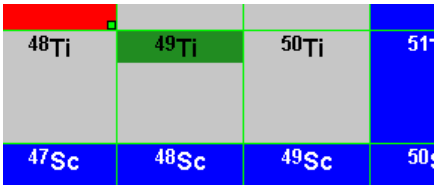
Choose the "Fusion → Residue" option in the "Production mechanism" dialog (menu "Options"). There are no other settings for the "Fusion → Residue" reaction in this. At this point the SETUP window will show:

A message "Fusion → Residue"

A new "C"ompound button

A "R"esidual button instead of "S"etting Fragment

The Compound cell in the table of nuclides is marked in green



1.2. Beam, Target, Residue settings

Input of next values:		*Example*
Beam	A, Z, Q	$^{40}Ar^{18+}$
	Energy	15 MeV/u
	Intensity	1000 enA
Target	A, Z (! No composite target!!!)	^{9}Be
	Thickness should be close to 0	50 micron
Residue	A, Z	^{42}Ca

The user can input an expected thickness target value if he or she is sure that this thickness will be satisfactory for this beam-target-residue combination, but it is recommended to calculate a thickness value by following the next steps.

1.3. Options

1.3.1. The "Preferences" dialog

For fusion residue reactions it is strongly recommended to **SET** the **"Charge State"** option **ON**! To decrease the calculation time (fusion calculations take more time than fragmentation) it is recommended to use the following values:

Calculation WITH charge states	≤ 64
Number points for 'Optimal target' plot	≈ 32

1.3.2. The "Prefragment search and Evaporation options" dialog

The "Prefragment search" part of this dialog will be blocked when the reaction "Fusion→residue" has been chosen. For fast calculations it is recommended to use

Only three basic mode of decay	proton, neutron, alpha
Dimension of evaporation distribution	32
Modes Auto/Manual	auto

1.4. Residue excitation function

The next task is to determinate the excitation energy value of the compound nucleus corresponding to the maximum of the residue production cross section. To do this the user can load the subroutine to plot the excitation function one of two possible ways: from the "Fusion-residue information window" dialog (see Fig.1, item A), or from the "Plots → Cross section distributions" menu. If the reaction mode "Fusion → Residue" is selected, the "Cross sections" dialog (menu "Options"), and the "Cross section Plot" dialog (menu "Plots", see Fig.2) will correspond to the fusion-residue reaction.

As an example the excitation function of the ^{42}Ca residue from the ^{49}Ti compound is shown in Fig.3 (it takes only 20 seconds on average to perform these calculations!!!).

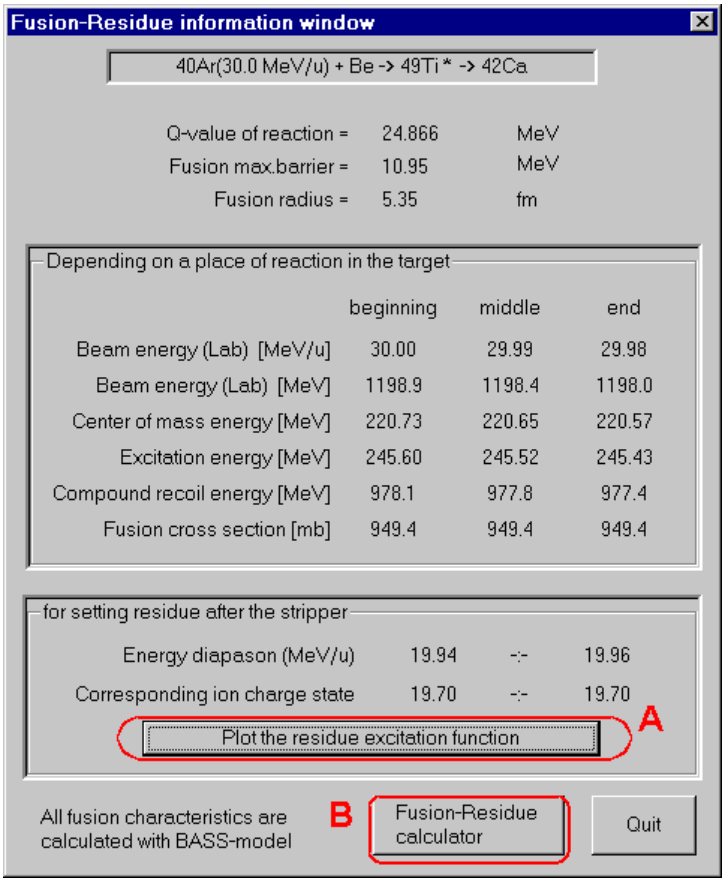


Fig.1. *The Fusion-Residue information window. It is activated by clicking the "C"ompound button in the SETUP window (see chapter 1.1.).*

Note: *It is possible to skip this step if the "Cross sections from file" option in the "Preferences" dialog is set, and set the input cross section value for the chosen residue independent from energy in the "Cross sections" dialog (menu "Options"). The program will automatically try to calculate "LisFus" fusion-residue cross sections and show them in the "Cross sections" dialog, but the user can break out of the calculation by clicking Cancel in the "Choose a range to calculate" dialog and input his or her own cross section value.*

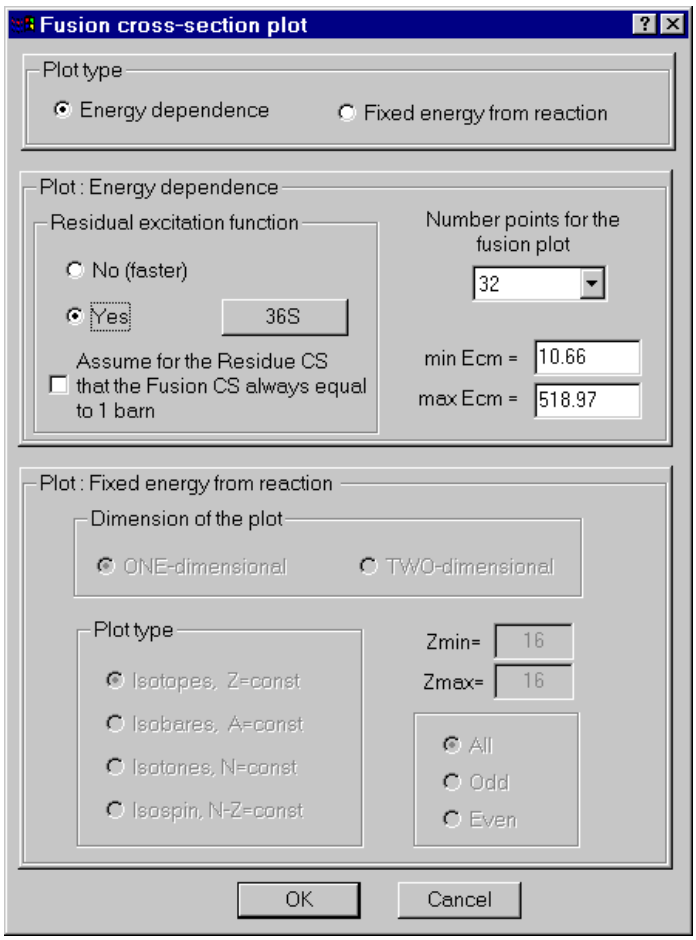


Fig.2. *The "Fusion cross section plot" dialog. To obtain the excitation function of a residue the user has to choose the options "Energy dependence" and "Calculate a residue excitation function – YES". The recommended number of points for the fusion plot is 32.*

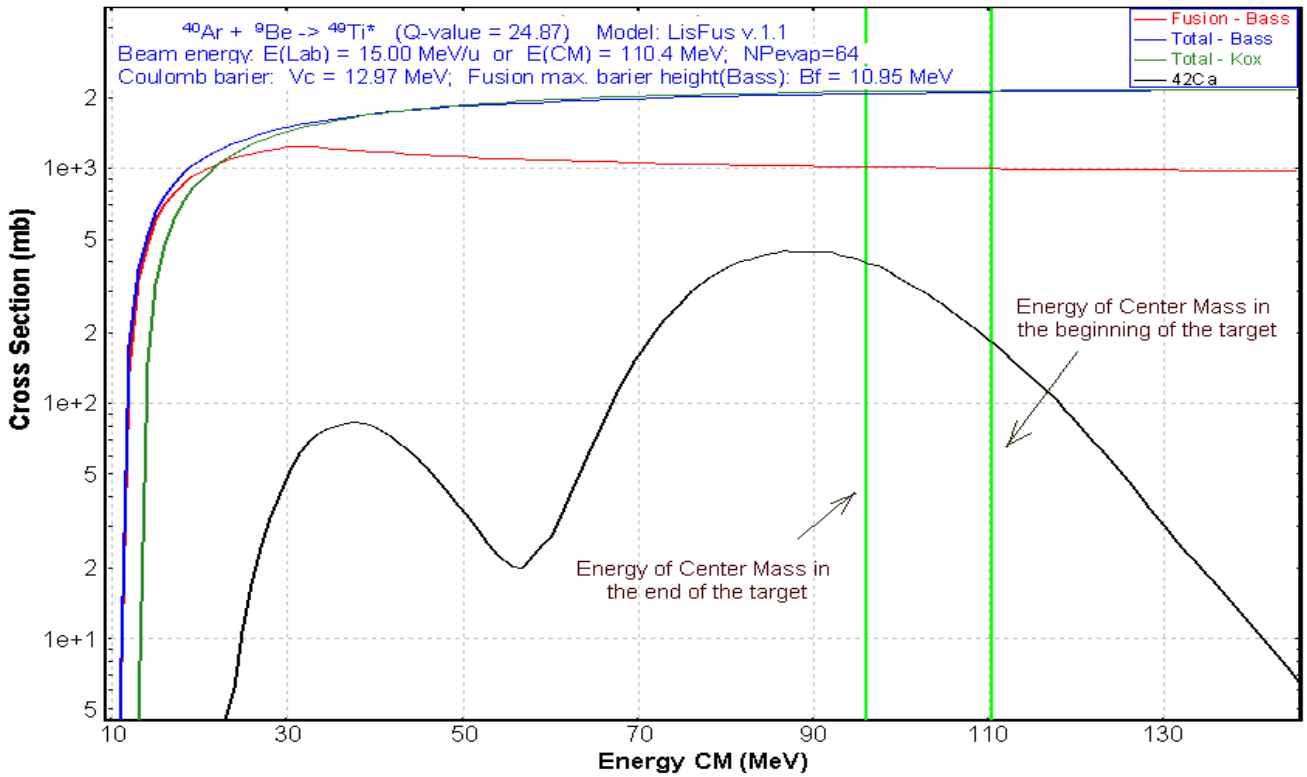


Fig.3. *The excitation function of ^{42}Ca residues from the ^{49}Ti compound is shown (black curve). Fusion, Total (Bass), and Total (Kox) cross section distributions for the reaction ^{40}Ar+ ^{9}Be are shown respectively in red, blue and green colors. The vertical green lines indicate the energy in center of mass at the beginning and the end of the target respectively. The two-peak shape of the ^{42}Ca excitation function can be explained by the domination of the α-channel from intermediate nucleus ^{46}Ti at an energy of 40 MeV (in CM), whereas at an energy of 100 MeV the final residue is created by p- & n-channels (see "Evaporation calculator" for details). This phenomenon has been seen also by Michael Thoennessen using the programs EVAP (UNIX-version of the PACE code) and CASCADE.*

1.5.Setting of residue ion charge

In the case of fusion reactions attention should be paid to the ionic charge of the residue, as fusion reactions take place at lower energies than fragmentation. The present step is to estimate the ionic charge after the target based on the excitation function obtained during the previous step. For this purpose a Fusion-Residue calculator has been developed (see Fig.4). In our example the maximum cross section for ^{42}Ca production from Fig.3 corresponds to 90 MeV (CM). The ion charge of the residue obtained at this energy is equal to 19.04 using the Fusion-Residue calculator. The initial beam energy in our example is higher and it is assumed that the energy lost in the target slows the beam down to the optimum energy of 12.23 MeV/u. To increase the yield of a residue the target thickness can be increased, which will lower the charge state even further. Thus it is better to round off the ionic charge to the smallest integer.

The calculated ion charge of the residue (i.e. $^{42}Ca^{19+\ 19+}$) has to be entered in the Residue setting dialog ("R"esidual button in the "SETUP" window, see chapter 1.1.).

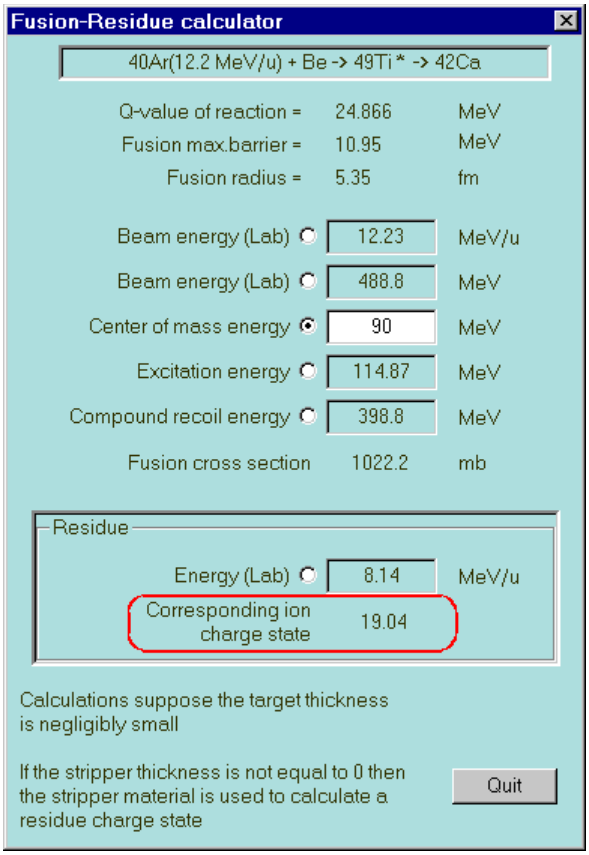


Fig.4. *The "Fusion-Residue calculator" dialog helps the user to get transformations from one of six fusion→residue reaction characteristics to the others. This dialog can be activated from the "Fusion information" window (see Fig.1, item B), or via the "Calculations" menu.*

1.6. Target thickness

The subroutine "Optimal target plot" (menu "Calculations") is used to get the maximum rate of the chosen residue. The target thickness calculations for the residue $^{42}Ca^{19+\ 19+}$ are shown in Fig.5. The user can click the button to put the calculated values into the program settings.

This step is the most time consuming. A benchmark table (Table 1) for various configurations is given below. A Pentium III (600 MHz, 128MB RAM) computer has been used for the calculations.

Table 1.

Dimension of evaporation distributions	N. points for optimal plot	Dimension of transmission distributions	Evaporation channels	Setting residue	Time, sec	coef
32	**32**	**64**	**3**	**$^{42}Ca^{19+}$**	**46**	**1**
32	64	64	3	$^{42}Ca^{19+}$	80	1.74
64	32	64	3	$^{42}Ca^{19+}$	89	1.93
32	32	64	8	$^{42}Ca^{19+}$	70	1.52
32	32	128	3	$^{42}Ca^{19+}$	65	1.41
32	32	64	3	$^{35}Ar^{17+}$	72	1.57
64	64	128	8	$^{42}Ca^{19+}$	360	7.83

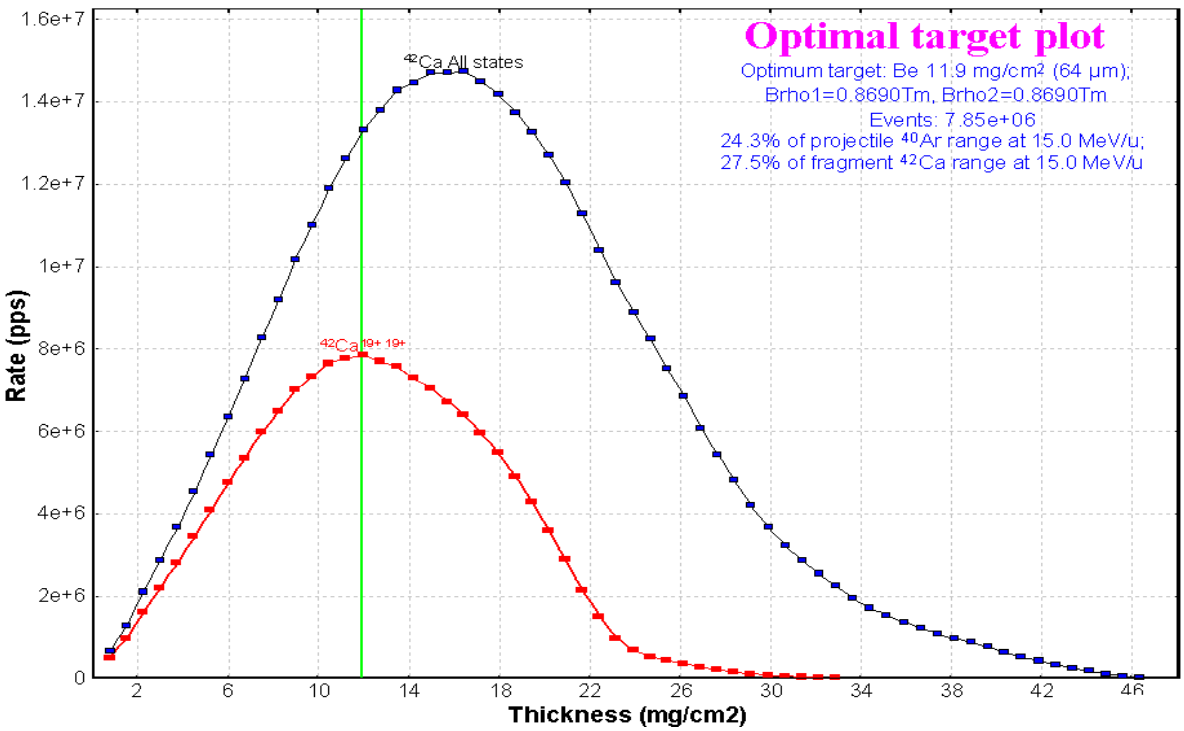


Fig.5. *Yield of the* $^{42}Ca^{19+\ 19+}$ *ion (red line) as a function of target thickness in the reaction* ^{40Ar}*(15 MeV/u)+Be* $\rightarrow$ $^{49}Ti^{*}$ $\rightarrow$ ^{42}Ca*. The blue line corresponds to the sum of all charge states of* ^{42}Ca *when the fragment separator is tuned on* $^{42}Ca^{19+\ 19+}$*.*

1.7. Separation

The final step is the calculation of the selection of the chosen residual by the separation devices to maximize transmission and purity. In today's version, four methods of separation are available in the program LISE: magnetic rigidity, energy loss in a wedge located in the dispersive focal plane, Wien velocity filter, and combination of a Wien filter and a dipole. The most popular method of separation for small energies is velocity separation (velocity filter). At small energies using energy loss in a wedge is ruled out. In the future electrostatic and gas-filled separators will be available in the program LISE. A comparison of different methods of selection is shown in Table 2 and Fig.6, where it is apparent that the "Velocity Filter + Dipole D6" (VAMOS) method gives the best results: best purification and highest intensity of the chosen residue.

Table 2. *Comparison of the performance of different kinds of low-energy residue selection.*

Selection	Output of $^{42}Ca^{19+}$ [1/s]	Sum output of all ions [1/s]
Dipole (dp/p=3%)	4.1e+6	1.7e+7
Dipole & Wien	2.0e+6	2.4e+6
Dipole & Wien+D6	4.1e+6	4.3e+6
Wien+D6 (VAMOS)	2.4e+7	2.6e+7

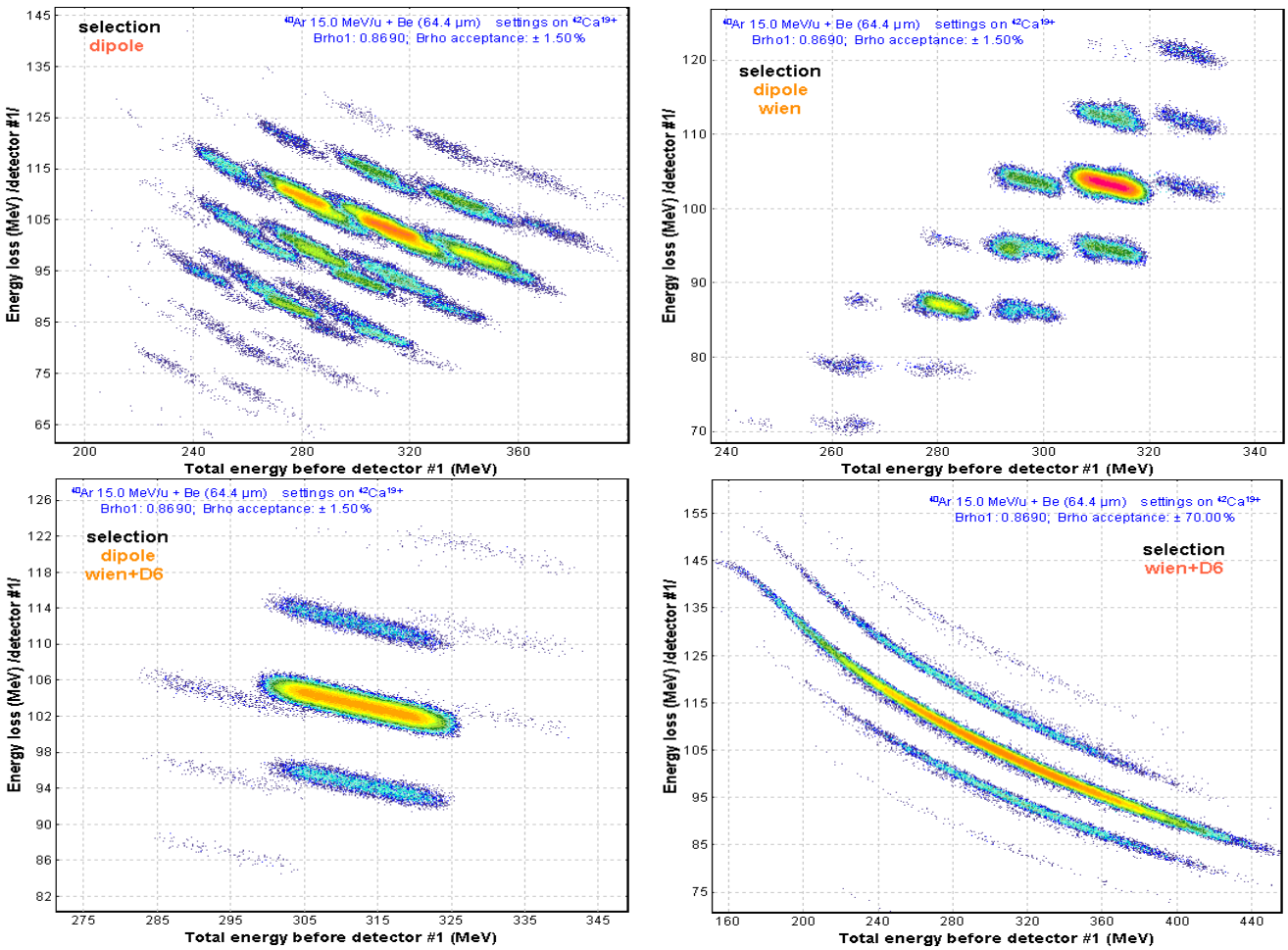


Fig.6. *ΔE-E plots for different types of selection. The most intense peak on all pictures corresponds to the ion* $^{42}Ca^{19+}$.

2. Characteristics of fusion residue calculations

The yield of reaction products (I_{sec}) selected by a fragment separator depends from the primary beam intensity (I_{beam}), the number of atoms in the target (N), the production cross section (CS), and the transmission ($coef$) through the fragment separator: $I_{sec} = I_{beam} \cdot CS \cdot N \cdot coef$. Assuming I_{beam} and N are constant the remaining parameters to calculate are the cross section of residue production and the transmission. In order to calculate the transmission it is necessary to know:

a) The kinematics distributions
   1) Momentum distribution (average velocity and momentum distribution width for gaussian distributions)
   2) Angular distributions (widths of parallel and perpendicular momentum distributions)

b) The charge state distribution of the residue (calculated as for fragmentation reactions)

This chapter is devoted to the principles of cross section and kinematics distribution calculations.

2.1. Kinematics distributions of fusion residues

2.1.1. Momentum distribution

The residue velocity after reaction (fusion and evaporation of light particles) is assumed to be equal to the compound nucleus recoil velocity. A Maxwell distribution of velocities is used to calculate the

root-mean-square velocity after evaporation of light particles. To simplify calculations and to get the result in an analytical form it was assumed that:

- Each step represent only one-nucleon evaporation
- The excitation energy of the daughter nucleus on each step is a delta function
- The separation energy of one nucleon is equal to $(ME_{compound} - ME_{residue})/(A_{compound}-A_{residue})$

In this case it is possible to consider the final distribution as the convolution of $(A_{compound}-A_{residue})$ gaussian distributions with $\sigma_i = \sqrt{\tau_i / aem} / A_i$. Thus the width of the final gaussian distribution is equal to $\sigma_f^2 = \sum_{i=A_{compound}-1}^{A_{residue}} \sigma_i^2$ and the root-mean square velocity is determined as $\bar{\upsilon}_f^2 = 3\sigma_f^2$ (the parallel and perpendicular components of the momentum distribution are $\bar{\upsilon}_{\parallel f}^2 = \sigma_f^2$ and $\bar{\upsilon}_{\perp f}^2 = 2\sigma_f^2$ respectively).

The initial excitation energy of the compound nuclei is taken as the average of excitation energy between the beginning and the end of the target. A root-mean-square velocity calculation subroutine has been added to the PACE4 program for the "beam & target" mode to check this assumption (see Fig.7).

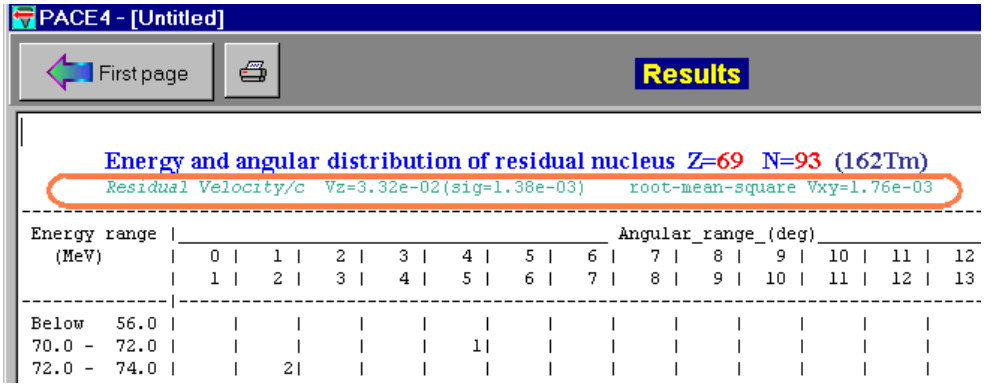


Fig.7. *Fragment of the PACE4 result window. The results of the root-mean square velocity subroutine are shown in a red rounded rectangle.*

Comparisons between the LISE and PACE4 calculations were made for different combinations of "beam & target & excitation energy". The residue velocity calculations performed by the PACE4 program using a Monte Carlo method are close to the LISE simplified model (see examples in Fig.8). Some discrepancies are observed for high excitation energies of heavy compounds (see the right bottom plot in Fig.8) but for the fast calculations performed in the LISE program the agreement is acceptable. The results from the PACE program were used only for nuclei which output exceeded three hundred events.

2.1.2. Angular distributions

Angular distributions in the center of mass system are assumed isotropic. The calculated widths of longitudinal and transverse momentum distributions are used with the formula from the work [Bor83] to get the angular distributions of residues.

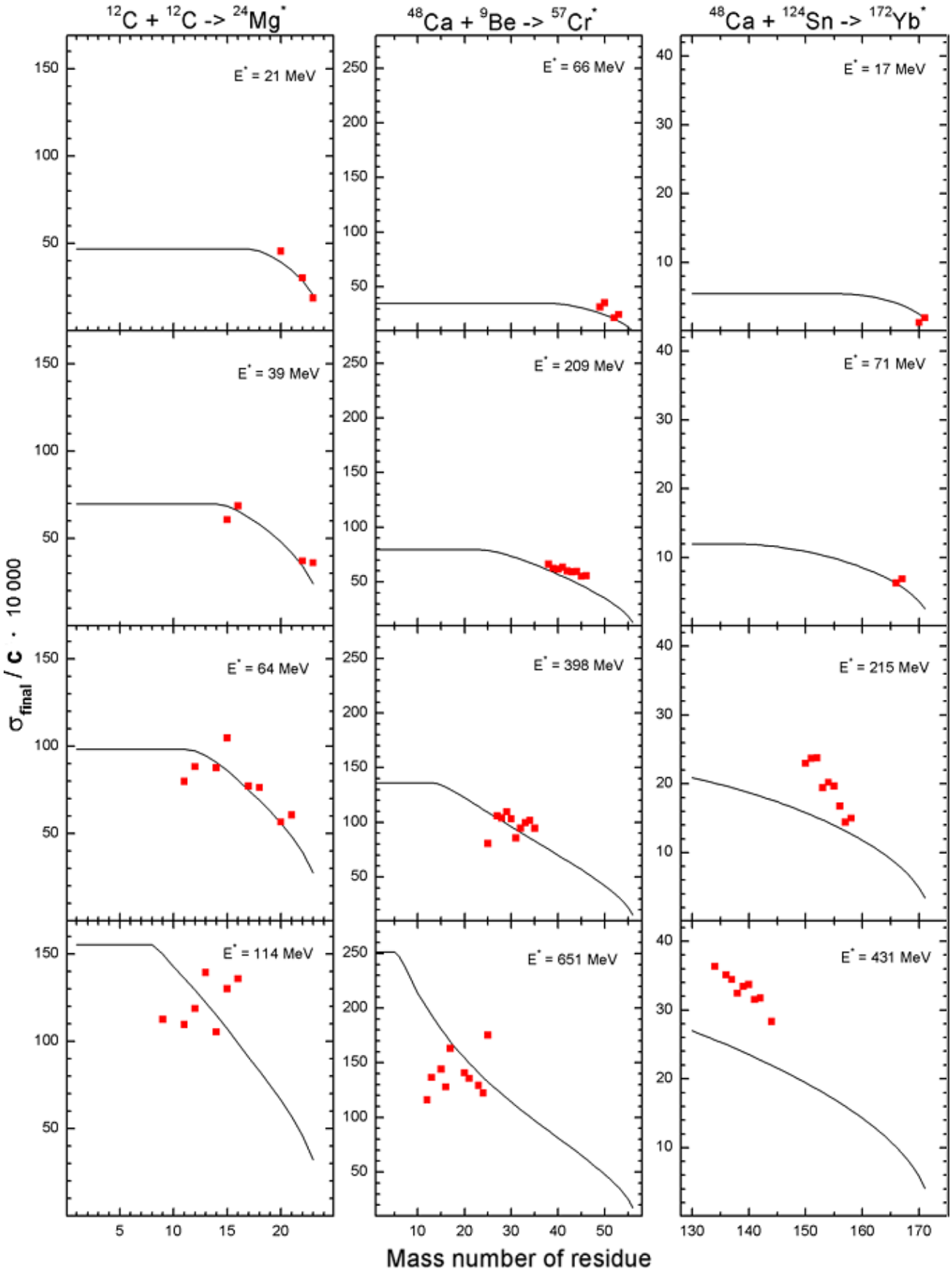


Fig.8. *The widths of velocity distribution versus the mass number of residue calculated by the PACE4 code (red rectangle) and the LISE program (black curve) for three different reactions* $^{12}C+^{12}C$ *(left),* $^{48}Ca+^{9}Be$ *(middle), and* $^{48}Ca+^{124}Sn$ *(right) at several excitation energies.*

2.2. Fusion residue cross sections

The program assumes that the targets used are thin enough and that the cross section of residue formation is constant within the target thickness. Since the calculation of the cross section is the most time consuming, this assumption greatly shortens the overall calculation time. The program is performing the following steps to calculate the cross section of a fusion residue:

- The target is divided into N slices (N is the dimension of the evaporation distribution defined in the "Search of prefragment and evaporation options" dialog)
- The energy of the primary beam (E_i) is calculated for each slice i of target thickness due to energy loss
- The excitation energy of the compound nucleus (E_i^*) is calculated from the primary beam energy (E_i);
- The fusion cross section (σ_i) is calculated;
- The $\sigma(E^*)$ distribution (N+1 points) is filled with values of σ_i and E_i^*;
- The area of this distribution is normalized to the average value $\overline{\sigma} = \frac{\sum_{i=0}^{N} \sigma_i}{N+1}$
- This excitation function of compound nucleus is used as initial distribution to calculate the cross sections of residues with the help of the Abrasion-Ablation evaporation subroutine.

It is possible to see the evolution of the excitation functions using the Evaporation calculator in the mode "Excited nucleus evaporation".

In order to avoid long calculation times the program asks a minimum atomic number (Z) down to which to calculate the cross sections. The user can interrupt the calculations at any time by pressing the Escape key. In the case of the optimum thickness calculation the program automatically considers the cascade only down to the nucleus of interest. All values of calculated cross sections are kept in memory. The number of kept cross sections is displayed in the "Setup" window 

. These cross sections are not saved in the LIZ-file and are erased from memory if the following changes are made:

- Type of reaction, projectile or target
- Coefficients used for evaporation calculation
- Number of evaporation channels
- Dimension of evaporation distributions
- If the target thickness or the beam energy have been changed by at least 2%

2.2.1. Comparison between LISE and PACE4 fusion residue cross sections

The main advantage of the LISE code calculations ("LisFus") of residue formation cross section is the speed. The user can get the excitation function in a short time (typically less than one minute, if the residue is close to the compound nucleus, and the dimension of distributions is not to high). Only such type of fast calculations is suitable for the computation of the transmission and yield of fusion residues in a reasonable time.

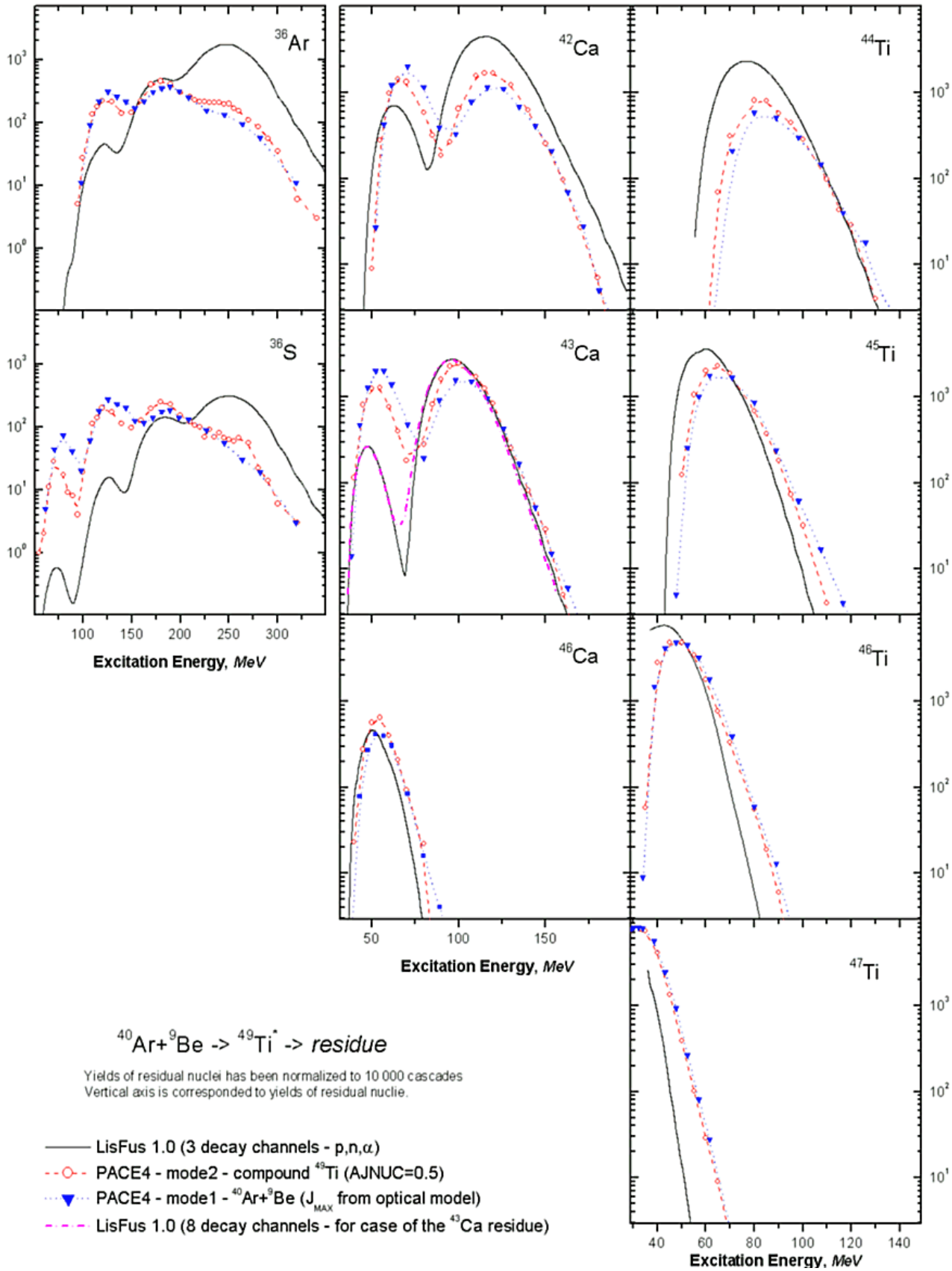


Fig.9. *Excitation functions of ^{36}S, ^{36}Ar, $^{42,43,46}Ca$, $^{44,46,46,47}Ti$ fusion residues in the reaction ^{40}Ar + ^{9}Be are shown. The fusion barrier is equal to 10.95 MeV. The Q-value of the fusion reaction is equal to 24.87 MeV.*

In order to test the validity of the approximations used in the LisFus model, comparisons with calculations from the PACE program were made for the reaction $^{40}Ar + ^{9}B$ at various energies of the primary beam. The maximum angular momentum was taken from the optical model used in the PACE4 calculations. The calculations for the ^{49}Ti excited compound nucleus were carried out at a maximum spin of 0.5 $\hbar$. The excitation functions of some residues from the reaction $^{40}Ar + ^{9}Be$ are shown in Fig.9. Overall there is a quite good agreement between the calculations from the LisFus model and the PACE4 program except for the titanium isotopes. All excitation functions of the LisFus model for titanium isotopes have a systematic shift in the region of low excitation energies. This can be explained by the fact that at small excitation energies the program PACE predicts the deexcitation of nuclei by emission of gamma-rays, whereas in the LisFus model this decay channel is not included, as the only evaporation channels are emission of light particles.

2.3. Transmission of the primary beam

If the primary beam is among the transmitted in fusion residue mode, then the LISE program automatically switches to the fragmentation mode to calculate the transmission of the primary beam. It then returns in the fusion residue mode to get the transmission of this nucleus assuming it arose from the de-excitation of the compound nucleus.

The user can get the transmission window corresponding to the primary beam by clicking the right button of the mouse on the primary beam cell in the table of nuclides (see Fig.10). Both types of reactions can be seen, assuming that their transmission is not equal to zero. A label indicating what kind of reaction is responsible for the given charge states of the nucleus has been added after the transmission parameter number 24 (see the rounded rectangle in Fig.10). This option has been made especially to prevent from sending the primary beam into the detectors. The magnetic rigidity distributions of the transmitted charge states of ^{40}Ar ion are shown in Fig.11.

statistics 40Ar

40Ar Stable (Z=18, N=22)

Qt	18	17	18	17
Qw	18	17	18	17
Energy after 2-nd dipole, MeV/	26.35	23.54	26.35	23.54
00 Angular transmission (%)	100.00%	100.00%	52.40%	52.40%
01 Brho transmission (%)	100.00%	100.00%	100.00%	100.00%
02 Wedge transmission (%)	100.00%	100.00%	100.00%	100.00%
03 Wien transmission (%)	100.00%	100.00%	100.00%	100.00%
04 Total transmission (%)	99.86%	99.86%	52.32%	52.32%
05 Cross section (mb)	1.3e+06	1.3e+06	9.2e-05	9.2e-05
06 Qtarget ratio (%)	100.00%	0.00%	99.60%	0.40%
07 Qwedge ratio (%)	100.00%	100.00%	100.00%	100.00%
08 Production rate (pps)	3.5e+11	1.7e+03	1.2e+01	4.9e-02
09 Sum of charge states (pps)	3.5e+11	3.5e+11	3.5e+11	3.5e+11
10 Y Brho transmission (%)	100.00%	100.00%	100.00%	100.00%
11 Y Wedge transmission (%)	100.00%	100.00%	100.00%	100.00%
12 No 'dead' target (%)	100.00%	100.00%	100.00%	100.00%
13 X-target ang.transmis.(%)	100.00%	100.00%	62.85%	62.85%
14 Y-target ang.transmis.(%)	100.00%	100.00%	46.94%	46.94%
15 X-wedge ang.transmis.(%)	100.00%	100.00%	97.38%	97.38%
16 Y-wedge ang.transmis.(%)	100.00%	100.00%	95.57%	95.57%
17 X-wien ang.transmis.(%)	100.00%	100.00%	100.00%	100.00%
18 Y-wien ang.transmis.(%)	100.00%	100.00%	100.00%	100.00%
19 X-target slits (%)	100.00%	100.00%	100.00%	100.00%
20 Y-target slits (%)	100.00%	100.00%	100.00%	100.00%
21 CS in stripper (mb)	1.0e+20	1.0e+20	0.0e+00	0.0e+00
22 Reactions in Target (%)	0.14%	0.14%	0.15%	0.15%
23 Reactions in Wedge (%)	0.00%	0.00%	0.00%	0.00%
24 Second.Reactions /coef/	1.0e+00	1.0e+00	1.0e+00	1.0e+00
reaction	Fragmt	Fragmt	FusRes	FusRes

Fig.10. *The transmission window of ^{40}Ar nucleus.*

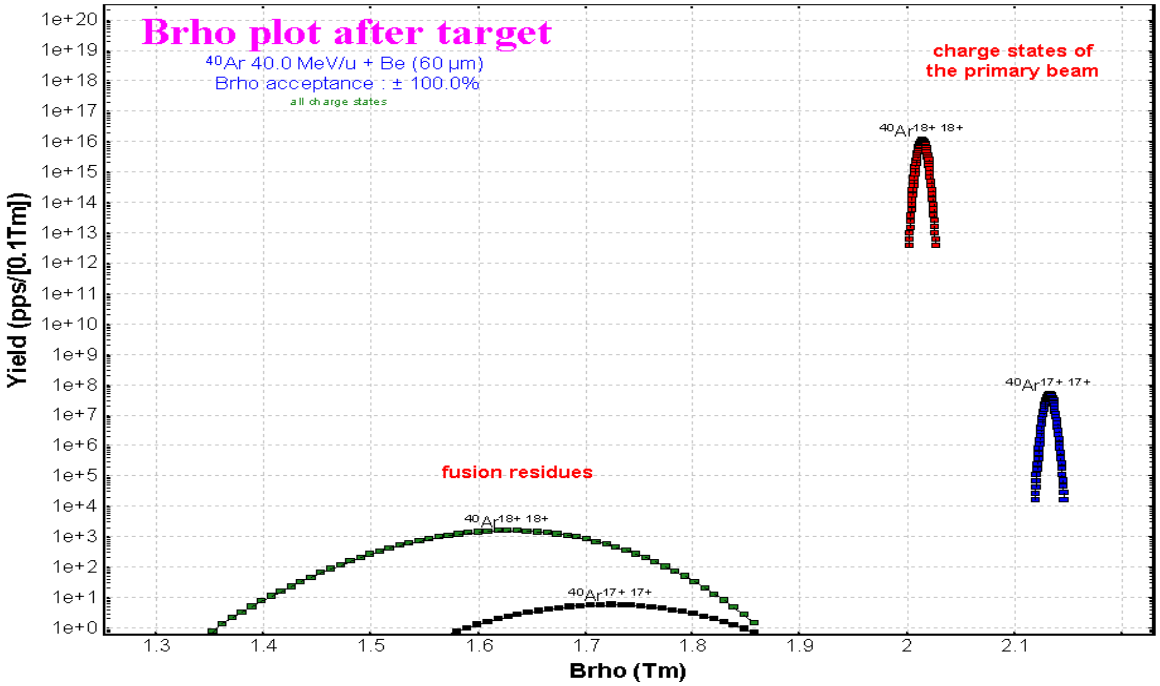


Fig.11. *Magnetic rigidity distributions of charge states of the ^{40}Ar nucleus after the target in the reaction ^{40}Ar (40 MeV/u) + Be (60 microns). The charge states of the primary beam calculated in fragmentation mode dominate in this setting of the fragment separator.*

It is also interesting to compare the outputs of fragmentation and fusion-evaporation reaction products and their energy distribution not only for the case of the primary beam, but for other nuclei as well. Performing this comparison requires the following conditions:

- The energy of the primary beam should neither be too high, so that the cross section for fusion–evaporation is still significant, nor too low, so that projectile fragmentation can still occur
- The overlap region between fragmentation and fusion-evaporation corresponds usually to a residue far enough from the compound nucleus, where the excitation energy of the compound is high
- Both reactions coexist only for light targets where the compound is not too far from the primary beam
- The nucleus of interest to be produced from projectile fragmentation must have less neutrons and protons than the primary beam

As an example the reaction ^{40}Ar (40MeV/u) + ^{9}Be (75mg/cm^2) —› ^{32}Al has been chosen. The energy distributions of the ^{32}Al ions after the target for both types of reactions are shown in Fig.12. For this case the products from both reactions can be well separated in the experiment. The velocity of the projectile fragment was assumed to be equal to the beam velocity and the Goldhaber momentum distributions was used to calculate the ^{32}Al energy distribution for the fragmentation reaction.

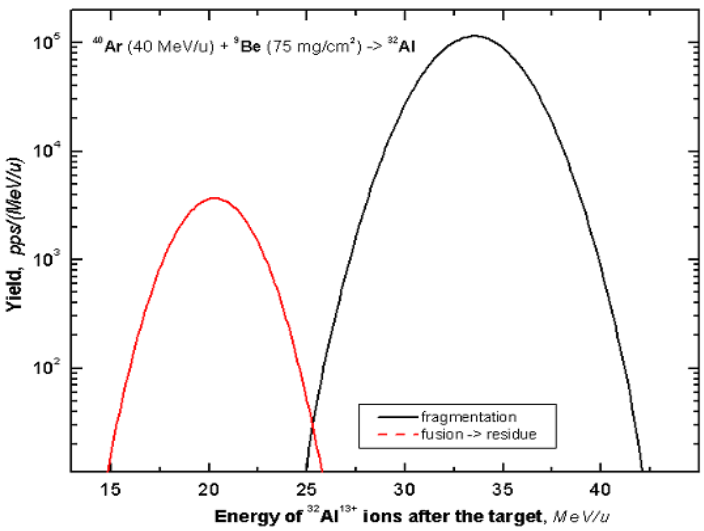


Fig.12. *Energy distributions of ^{32}Al ions after the target in the reaction ^{40}Ar (40 MeV/u) + Be (75 mg/cm^2). The energy distribution for the fragmentation reaction is shown by the black curve, and for the fusion residue reaction by the red curve.*

3. Other topics

3.1. Two-dimensional plots for cross sections, transmission and database characteristics

It is now possible to build two-dimensional plots of cross sections, transmission and database characteristics. Before plotting the data the user can choose in the dialogs what kind of plot he or she wishes. An example of a two-dimensional plot is shown in Fig.13.

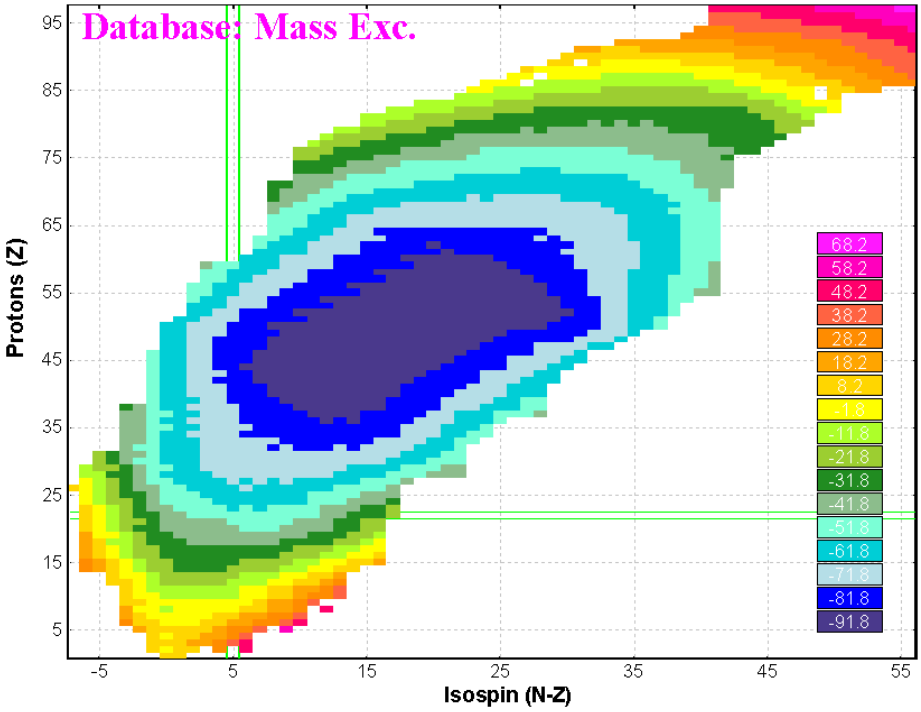


Fig.13. *Mass excess values in a two-dimensional plot from the built-in database.*

3.2. Modification of evaporation calculation procedure

A considerable change has taken place in the calculation of the daughter nuclei excitation functions of the evaporation cascade model. In the previous versions it was assumed that each i-th point of an intermediate nucleus excitation function had only one projection in the daughter nucleus excitation function:

$$\left(E^*_{daugh}\right)_i = \left(E^*_{parent}\right)_i - S - B - 2\tau_i \,, \qquad /1/$$

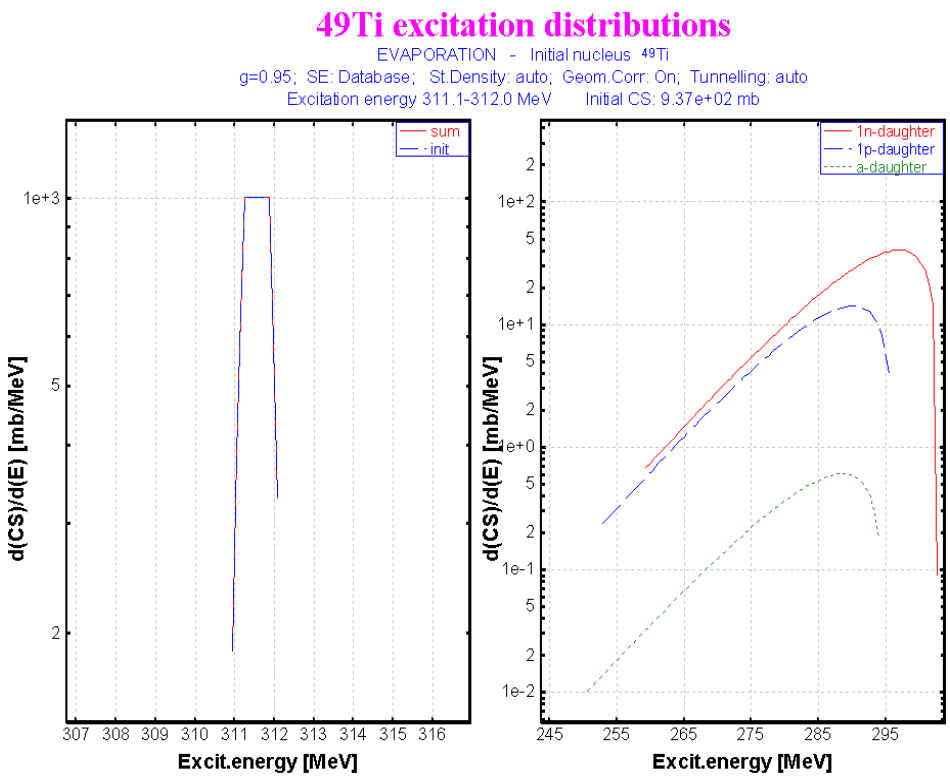


Fig.14. *The initial excitation function of the ^{49}Ti parent nucleus (left picture) is chosen close to a delta-function, and its daughters excitation functions calculated with the new method (right picture).*

where S is the separation energy, B is the reduced coulomb barrier in the case of a charge particle evaporation, and τ is the temperature of the daughter nucleus. The value in this i-th point of the daughter distribution was equal to the multiplication of the i-th value of the intermediate nucleus and the probability for this daughter evaporation channel:

$$f\left[\left(E^*_{daugh}\right)_i\right] = \phi\left[\left(E^*_{parent}\right)_i\right] \cdot P\left(E^*_{parent}\right)_i . \qquad /2/$$

In the new version each i-th point of parent distribution is represented as a distribution following the Maxwell law with the an area normalization of /2/. Then all $NP_{evap}+1$ partial daughter distributions are summed up to one final daughter distribution. The final result is shown in Fig.14. The initial excitation function was chosen as a very narrow rectangle (close to a delta function).

3.3. LISE.xls – stopping power functions

Stopping power functions (dE/dx) have been incorporated in the *lise_xls.dll* library and can be loaded as a function in Excel through the *LISE.xls* file (see Fig.15).

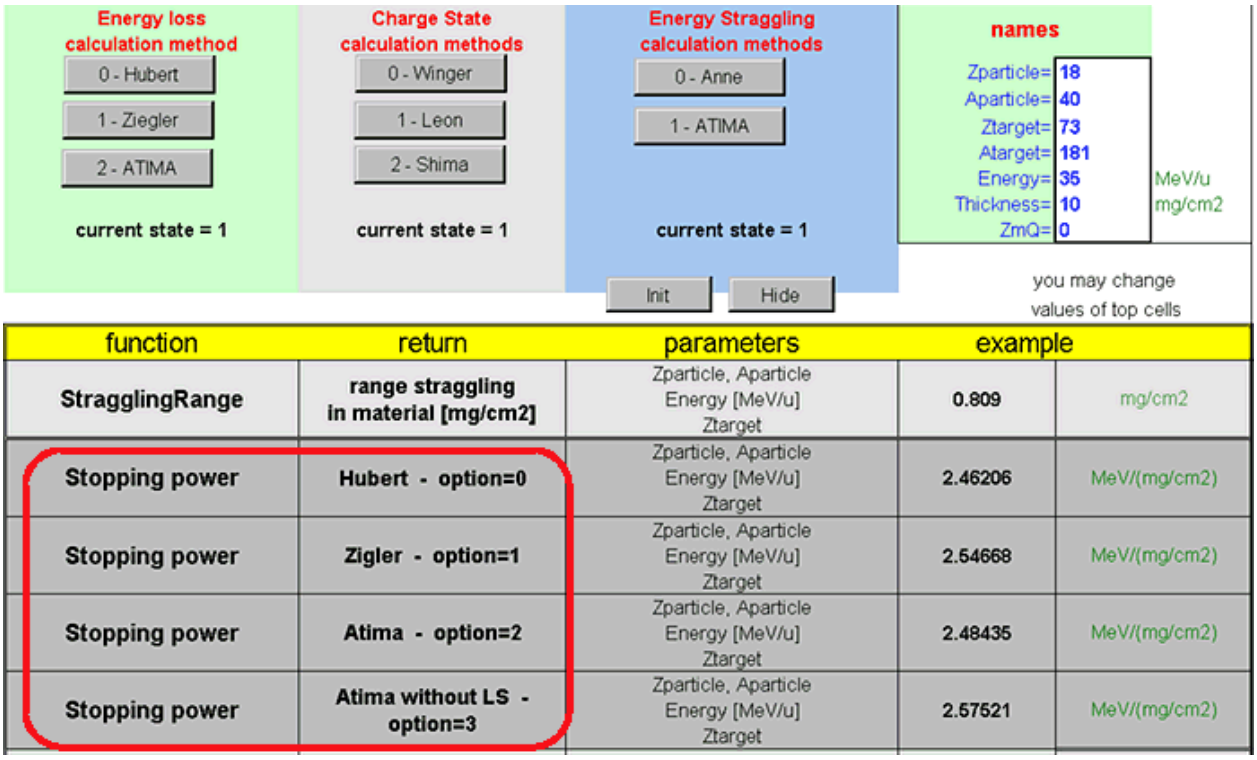


Fig.15. *Fragment of the Excel window. The block with new functions "Stopping power" is indicated by the red rounded rectangle.*

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References:

[Bas74] R.Bass, Phys.Rev.Lett. **39** (1977) 265.
[Baz94] D.Bazin and B.Sherrill, Phys.Rev. **E50** (1994) 4017-4021.
[Bor83] V.Borrel et al., Z.Phys.**A 314** (1983) 191.
[Gai91] J.-J.Gaimard, K.-H.Schmidt, Nucl.Phys. **A531** (1991) 709-745.
[Gav80] A.Gavron, Phys.Rev. **C21** (1980) 230-236; (see ftp://ftp.nscl.msu.edu/lise/PACE_source).