



version 6.3

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## 1. Charge states calculations

### 1.1. "GLOBAL" (charge states calculations)

GLOBAL is a program to calculate ionic charge-state distributions of projectiles traversing solid and gaseous targets. The program was developed for the interaction of projectiles having a nuclear charge larger than 28 with any target. Details of the underlying physics as well as of a comparison between experiment and predictions by GLOBAL can be found in [Sch98]. The main advantages of the code comparing with the "Charge" code for example appear the next features:

- possibilities to calculate charge states up to 28;
- take into account energy loss of incoming particle in matter.

In the following, a short description of the program as well as of the underlying physics is given in <http://www-aix.gsi.de/~scheid/GLOBAL.readme.html>. Some fragments of this file are given below.

The different parameters are:

- For the projectile: The nuclear charge  $Z$ , the mass number  $A$ , the number of orbital electrons  $Q_e$ , and the incident energy  $E/A$ .
- For the target: The nuclear charge  $Z$ , the mass number  $A$ , and the target thickness  $D$ .
- Projectile  $Z$  and target  $Z$  can be given using the element symbol.

The program proposes for each change of either the charge  $Z$  or the mass  $A$  a new values for the respective other parameter. The projectile mass number  $A$  determines only the energy loss and should be in reasonable limits with respect to the nuclear charge  $Z$ . The charge state  $Q_e$  is limited to  $Q_e = 0 \div 28$ . This includes K, L, and M shells.

The energy can vary between 30 MeV/u and 2000 MeV/u. The low-energy limit is defined by the applicability of the atomic cross-section calculations, whereas the high-energy limit is due to the energy-loss relations. If, during the calculations, the program reaches the low-energy limit, it stops. The target charge and mass can be changed between  $Z=1$  and  $Z=96$  with the respective mass numbers. The thickness is limited by the number of integration steps possible (1.e9), i.e. the maximum allowed target thickness depends on the target material, but is of the order of 100g/cm<sup>2</sup>.

There are three different basic output options:




1. The charge state distribution of a projectile as defined by the projectile parameters at the exit of the target.
2. The charge state distribution of the projectile after having reached the equilibrium charge-state distribution.
3. The user can follow the charge-state evolution of the projectile throughout the target.

In order to facilitate comparison for different projectiles, incident energies, numbers of incident orbital electrons, targets, or target thicknesses, one can use loops over these different parameters. In this case, the user can specify the range of the scan. For the incident energy and the target thickness, the program takes the value from the menu as the maximum loop value. For the projectiles and targets, all elements up to  $Z=96$  can be scanned, one for the incident number of orbital electrons values of up to 28 are pos-

sible. For the basic option of charge-state evolution, the user can influence the amount of adata output (Frequency of Output) by choosing an output after ten integration steps, after hundred, thousand, or ten thousand integration steps. During the integration through the target, the program takes into account the energy loss of the projectile in the target material.

### 1.1.1. "GLOBAL" for "Windows"

The code "Global" has been translated in C++ and is now part of the "LISE++" package. The original source code (FORTRAN) was kindly provided by colleagues from GSI. The dynamical library "LISE\_Global.dll" contains charge state calculations which can be used in different applications such as the LISE code or MS Excel. This library is found in the windows\system32 directory.

The "Global" code (executable version for Windows) can be loaded by clicking the icon  in the toolbar or in the menu "Utilities". The program can also be loaded from LISE's folder using the Start → Programs on the desktop menu. The program interface window is shown in Fig.1. The calculation results are saved by default in the file "untitled.goutput". The user can save he input data to a file  (extension of input file is "ginput"). The result file gets the same name as the input file with the extension "goutput". The results can be printed immediately from the code .

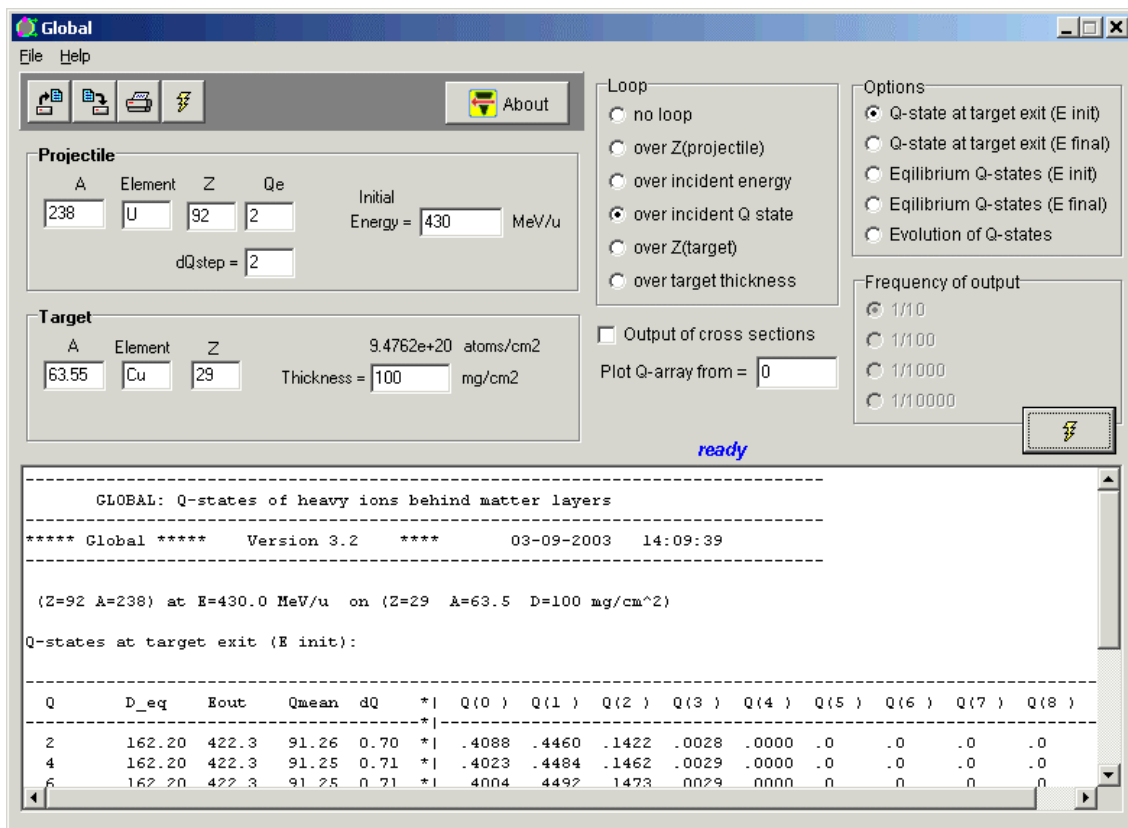


Fig.1. The "Global" code (version for MS Windows) in action.

The C++ code has preserved the features of the original version and added some new possibilities which are presented in chapter 1.1.4.

### 1.1.2. Use of GLOBAL's calculations in LISE++

The new version of LISE++ uses Global's subroutines on the fragment transmission calculations with some restrictions connected with the low energy limit (30 MeV/u) of Global's calculations. Two new methods of charge states calculations have been implemented in LISE++. The first one (number 3 in LISE's charge state calculation method) uses Winger's calculations for the low energy region, and Global's calculations for the energy region above the upper boundary (UP). The upper boundary default value is 70 MeV/u. The user can change the UP value via the "Production mechanism" dialog (see Fig.2). The possible values of UB are in the energy range 35-100 MeV/u. In the intermediate energy interval 30-UB MeV/u the charge states are calculated using a linear combination of both methods proportionally to energy to insure a smooth transition between the two calculations:

$$P(Q_i) = \sum_{k=1}^2 P_k(Q_i) \cdot W_k, \text{ where } W_1 = \frac{UP - E}{UP - 30} \text{ and } W_2 = \frac{E - 30}{UP - 30}, \quad /1/$$

where  $E$  is the projectile energy after the material in MeV/u, the index 1 corresponds to the low energy method (Winger), and the index 2 to Global. Another new method (number 4 in LISE++) uses Leon's method for low energy calculations instead of Winger's.

There is also a low limit for the atomic number of the fragment in Global's calculations. If the atomic number of the fragment is lower than this limit (default value of Z-limit is 29) then the low energy method (Winger's or Leon's) will be used instead of Global to calculate the Q-states.

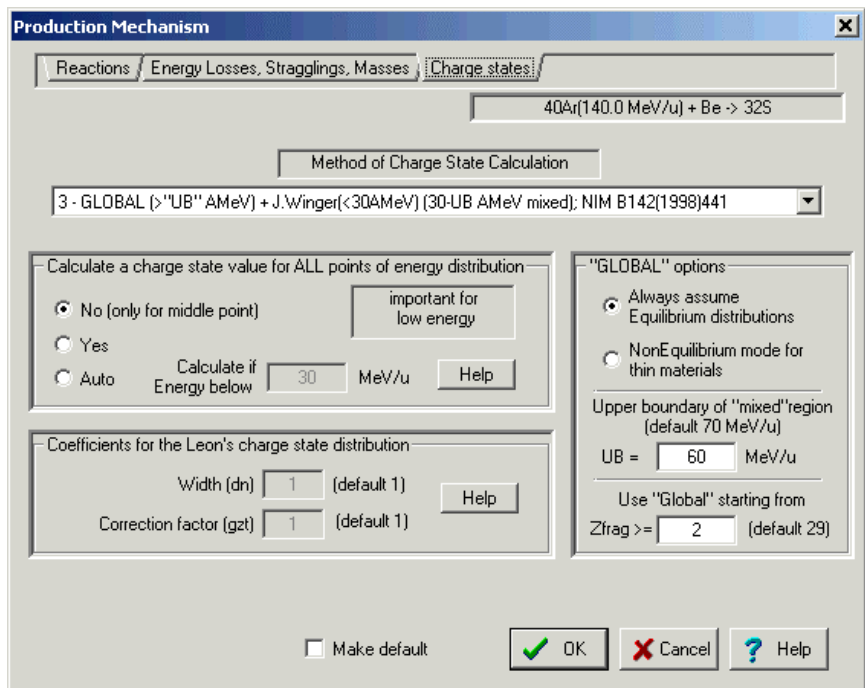


Fig.2. The Charge state panel of the Production mechanism dialog.

Since version 4.6 LISE calculates the charge state ratio for each point of the energy distribution after the target (stripper) ([http://groups.nsl.msu.edu/lise/4\\_6/lise\\_4\\_6.html#g2](http://groups.nsl.msu.edu/lise/4_6/lise_4_6.html#g2)). It is rather important for energies below 50 MeV per nucleon, whereas for high energy it is possible to assume that the charge state ratio is homogeneous for all points of the energy distribution after the target. The new version can avoid this time-consuming calculation for high energy and gives the possibility to choose the energy region in which to apply the charge state calculation to each point of the energy distribution (see the "Calculate a charge state value for ALL points of energy distribution" box in Fig.2).

It is possible to calculate the nonequilibrium charge state distributions after a material using Global's method. The user can set "NonEquilibrium" mode also via the "Production mechanism" dialog (see the right bottom box in Fig.2). More details about this mode in chapter 1.3.

### 1.1.3. "GLOBAL" in LISE.XLS

GlobalCode(ZmQ\_out; Aparticle; Zparticle; ZmQ\_in; Energy; Atarget; Ztarget; Thickness; Option; Fast)

names		Description
ZmQ_out=	103	Option (see bottom table)
Aparticle=	238	Mass of projectile
Zparticle=	92	Element number of proj.
ZmQ_in=	2	initial input charge
Energy=	300	MeV/u (init or final : depends from option*)
Atarget=	63.55	Mass of target
Ztarget=	29	Element number of target
Thickness=	300	mg/cm2
Option=	3	0/1- at target (Einit/Efinal); 2/3 -equilibrium (Einit/Efinal)
Fast=	2	0-slow / 1-fast / 2 -superfast
<b>RESULT=</b>	<b>312.35</b>	

E init : initial energy of projectile before Equilibrium thickness  
 E final : final energy of projectile after Equilibrium thickness

Options		RESULT	Description	Dimens
ZmQ_out=	103	312.354	Energy after/before target	MeV/u
ZmQ_out=	102	139.378	Equilibrium thickness	mg/cm2
ZmQ_out=	101	0.763	dQ /st.deviation/	
ZmQ_out=	100	90.797	<Q> /average/	
ZmQ_out=	0	0.18847	Z - Q = 0	part
ZmQ_out=	1	0.44164	Z - Q = 1	part
ZmQ_out=	2	0.34914	Z - Q = 2	part
ZmQ_out=	3	0.02016	Z - Q = 3	part
ZmQ_out=	4	0.00056	Z - Q = 4	part
ZmQ_out=	5	0.00000	Z - Q = 5	part
ZmQ_out=	6	0.00000	Z - Q = 6	part
ZmQ_out=	27	0.00000	Z - Q = 6	part
		<b>1.0000</b>		

If result is equal -776,-777 or -778 --- you got error!  
 check input parameters

GlobalCode(ZmQ\_out; Aparticle; Zparticle; ZmQ\_in; Energy; Atarget; Ztarget; Thickness; Option; Fast)

Fig.3. The sheet "Global" of the file "LISE.xls" demonstrating uses of the Global code in Excel

The sheet "Global" of the file "LISE.xls" (Fig.3) is an example how the user can use the Global program in Excel, including calculations of nonequilibrium processes. In fact it is possible to consider this sheet as the shell of Global in Excel, the user can get any result in a cell by setting the corresponding index. The indexes 0-27 correspond to charges Z-Q, and the meaning of indexes 100-103 are shown in (Fig.3). By analogy to the program LISE the methods 3 (Global+Winger) and 4 (Global+Leon) also are accessible in EXCEL. Examples of use of these functions (ChargeState, ChargeState\_Option, Charge\_Qmean, Charge\_dQ) are shown in the sheet "Base" (Fig.4). However these methods always assume equilibrium processes. To calculate nonequilibrium process, use the function "GlobalCode".

**Energy loss calculation method**

0 - Hubert

1 - Ziegler

2 - ATIMA

current state = 1

**Charge State calculation methods**

0 - Winger

1 - Leon

2 - Shima

3 - Global+Winger

4 - Global+Leon

current state = 1

**Energy Straggling calculation methods**

0 - Anne

1 - ATIMA

current state = 1

**names**

Zparticle= 50

Aparticle= 120

Ztarget= 73

Atarget= 181

Energy= 70 MeV/u

Thickness= 10 mg/cm2

ZmQ= 0

you may change values of top cells

Charge State *	%	Energy [MeV/u] Zparticle, Ztarget Zpart-Qpart	2.352	%
Charge State * with option	%	Energy [MeV/u] Zparticle, Ztarget Zpart-Qpart, Option	9.343	%
Charge Mean Value *		Energy [MeV/u] Zparticle, Ztarget, option	48.342	
Charge dQ *		Energy [MeV/u] Zparticle, Ztarget, option	0.987	

Equilibrium distribution is suggested

Fig.4. The sheet "Base" of the file "LISE.xls".

### 1.1.4. GLOBAL's new features

#### 1.1.4.1. Options for final energy projectile

By default the Global code calculates Q-states for the energy before the material. The final energy is calculated based on the material thickness. However the LISE code always needs the charge state distributions after the material assuming the equilibrium distributions. Two new options have been incorporated into Global to calculate the Q-state at target exit and the Equilibrium Q-states when the user gives the final energy after the material. The code calculates the initial energy of projectile before the target and shows this value in the results window of the code. LISE inputs to Global the final energy after the material, the thickness of material and initial Q-states distribution before the material in order to calculate nonequilibrium Q-states. **The initial Q-states distribution is a the new option** in Global because the original code used just one initial charge state.

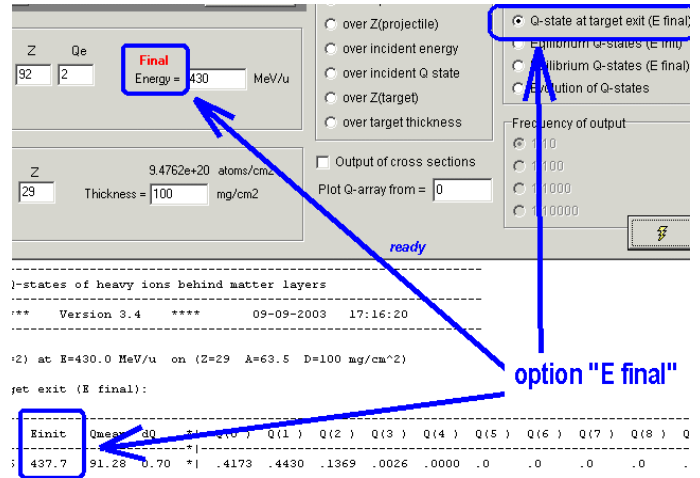


Fig.5. The "Global" code with the option "Q-states: Energy final".

#### 1.1.4.2. Optimization for a thick target

An optimization of the calculations is done in the program in case of a thick target. It is based on the assumption that it is not necessary to calculate the Q-states for all points of a thick target, but only the equilibrium Q-states at the end of the target. This procedure goes as follows:

- Calculate the equilibrium thickness for the initial energy. If the target thickness is three times less than the equilibrium thickness, then the program does a regular calculation.
- Calculate the final energy  $E_{final}$  after the target and the range  $R_0$  in the material corresponding to this energy.
- Calculate the equilibrium thickness  $T_{equil}$  for  $E_{final}$ .
- Calculate the energy  $E_{3d}$  corresponding to the range  $R_0 + 3 \cdot T_{equil}$ .
- Calculate Q-states with the initial energy  $E_{3d}$  for the target with thickness  $3 \cdot T_{equil}$ .

The optimization allows not only to speed up calculations but also to avoid critical cases, when the program reaches the maximum possible number of cycles for the given accuracy of calculations, and stops calculating.

#### 1.1.4.3. Calculations for a projectile with atomic number lower than 29

As already mentioned the Global code was developed for projectiles with the atomic number greater than 28. The program has been modified to overcome this restriction<sup>1</sup>. The default value of Z-limit in LISE++ for Global's calculations is 29.

The **principal** modifications done to use projectiles with  $Z < 29$  (for those who know Global's source) are the following:

<sup>1</sup> However the user gets a warning message in the Global code if he uses a projectile with an atomic number less than 29.

<p><i>Subroutine "GLOBAL"</i></p>	<ul style="list-style-type: none"> <li>• <math>J = \min(ZF-1, J);</math> // (dimension of Q-arrays)</li> <li>• to determine the step of calculations instead</li> </ul> <p>"AUX = DE / NT / MIS;" <i>to insert</i></p> <pre> if( J &lt; 10 )AUX = DE / NT / KIS; else if( J &lt; 28 ) AUX = DE / NT / LIS; else     AUX = DE / NT / MIS; </pre>
<p><i>Subroutine "CROSS"</i> conditions to calculate KRD &amp; LRD</p>	<pre> KRD = (ZF&gt;2 ? (LIU-KIB)/(KEX*LIU+KMETA) : 0); LRD = (ZF&gt;10 ? (MIU-LIU)/(LEX*MIU+LMETA) : 0); </pre>
<p><i>Subroutine "CAPCROSS"</i> exclude negative values of reduced Z1 &amp; Z2 from the loop</p>	<pre> for(.....) {     ...     if(z1&lt;=0    z2&lt;=0) {         CEIK[JP][JT]=0;         continue;     }     ... } </pre>
<p><i>Subroutine "IONICRO"</i> comment the strings</p>	<pre> // if( SMIU == 0. ) SMIU = 1.E10; // if( SMIS == 0. ) SMIS = 1.E10; </pre>

Global's calculations for light projectile are found in good agreement with experimental results, as well as with the Charge program results. Examples will be given in chapter 4.1.

## 1.2. Q-state calculations: optimization for speed

With increasing number of optical blocks in a spectrometer the CPU time for transmission calculation is obviously increased, especially in case the "charge states" option is turned on. The simplest way to reduce the CPU time is to limit the number of points of the transmission distribution in the "Preferences" dialog, at the expense of the quality of calculations (by default 32 if the option "charge states" is on). Two alternative ways to accelerate the transmission calculation for different charge states of the fragment have been implemented.

### 1.2.1. Tabulation of Q-states

The code is able to save 65 results of Q-states results in memory (**only equilibrium** charge states can be used!). The tabulation set records the initial parameters (fragment mass, fragment atomic number, energy after material, target atomic number, and charge state model number) and an array of Q-states. Before calculating Q-states the program searches a record with identical initial parameters in the tabulation sets. If the record is not found then the charge states are calculated and kept in the tabulation sets.

### 1.2.2. Restrictions for improbable Q-states

The code has been modified to exclude fragments with low probability of charge states from ion transmission calculation. An ion ( $Z-Q = X_1, X_2, \dots, X_n$ ) is excluded from the next calculations if the probability of any charge state  $X_i$  of the ion after a material before an optical block is less  $1e-4$ . Also this ion can be excluded if the production of all its charge states  $\prod_{i=1}^n X_i$  is less than  $1e-7$ . For the primary beam ions these restrictions are set to  $1e-7$  (for one charge state) and  $1e-10$  (for all charge states).

### 1.3. Nonequilibrium charge state calculations

Nonequilibrium charge state calculations are available now in the code LISE based on GLOBAL's library. Nonequilibrium calculations can be used if all the following conditions are fulfilled:

1. The charge state model is 3 (Global+Winger) or 4 (Global+Leon);
2. Nonequilibrium mode is enabled on in the "Global's option" box of the "Production mechanism" dialog;
3. The final energy  $E_{final}$  after the material is greater than the value of  $UB$  (upper boundary) set in the "Global's option" box;
4. The fragment atomic number is more than  $Z$ -limit set in the "Global's option" box.

The code always assumes equilibrium Q-states in the mixed area ( $30 \div UB$  MeV/u).

The charge states are always assumed in equilibrium after the target, for the following reasons:

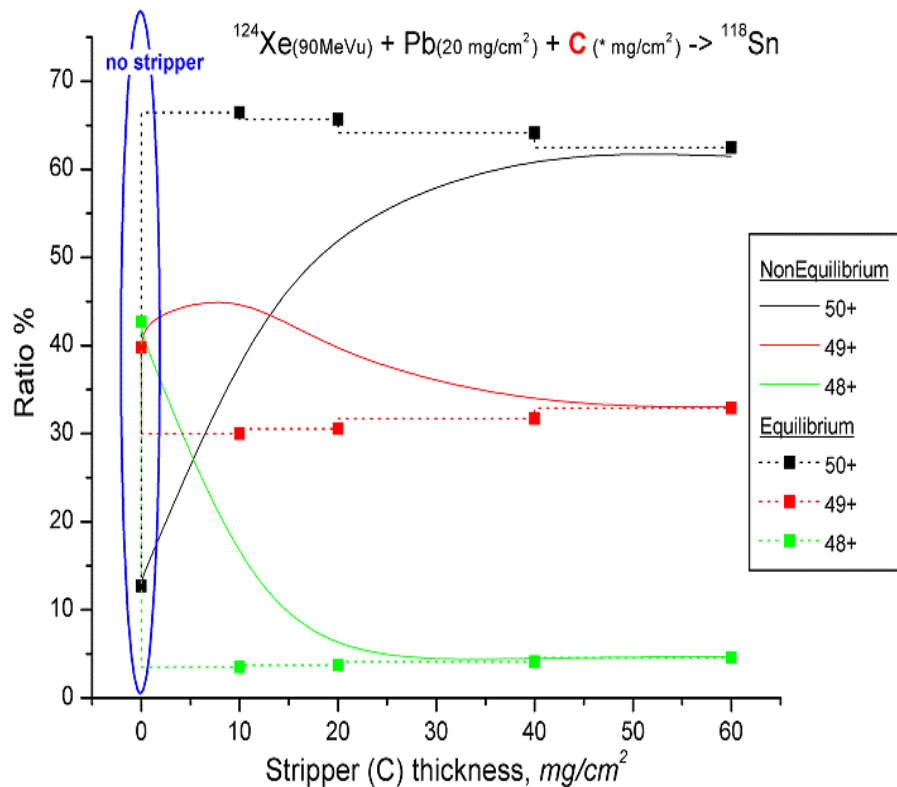
- As a rule the thickness of a target is more than the equilibrium thickness;
- It is too complex to calculate an initial charge state of the fragment at the instant of the reaction.

Therefore nonequilibrium Q-states are only calculated for a stripper after target and for materials located between optical blocks.

**Note:** nonequilibrium Q-states are not tabulated in memory, therefore the speed of transmission calculations in nonequilibrium Q-states mode is lower. Moreover, if some materials are located between optical blocks then the program calculates the Q-states after the last material in the equilibrium mode, and for **each** material in the non-equilibrium mode.

As an example, the charge state evolution of the fragment  $^{118}\text{Sn}$  after a C-stripper as a function of its thickness for Equilibrium and Nonequilibrium cases are shown in Fig.6, and after a material between optic blocks in Fig.7. The LISE++ file for these examples is located on the LISE web-site at:

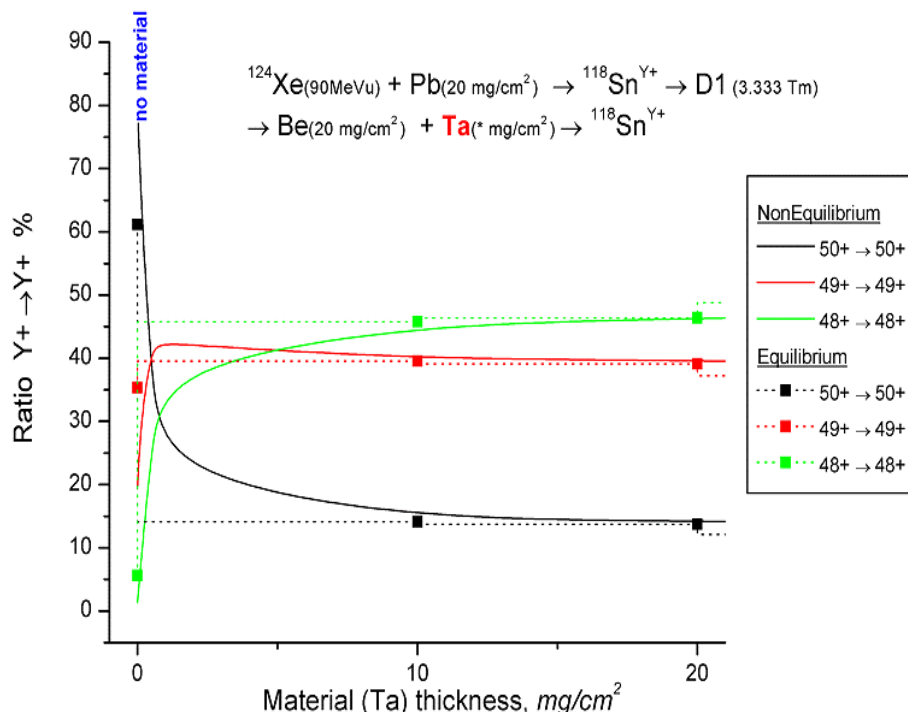
[http://groups.nsl.msu.edu/lise/6\\_3/examples/charge\\_test.lpp](http://groups.nsl.msu.edu/lise/6_3/examples/charge_test.lpp)



**Fig.6.** Charge state evolution of the fragment  $^{118}\text{Sn}$  after a C-stripper as a function of its thickness for equilibrium and nonequilibrium cases in the reaction  $^{124}\text{Xe}(90\text{ MeV/u})+\text{Pb}(20\text{mg}/\text{cm}^2)+\text{C}(x\text{ mg}/\text{cm}^2)$ .

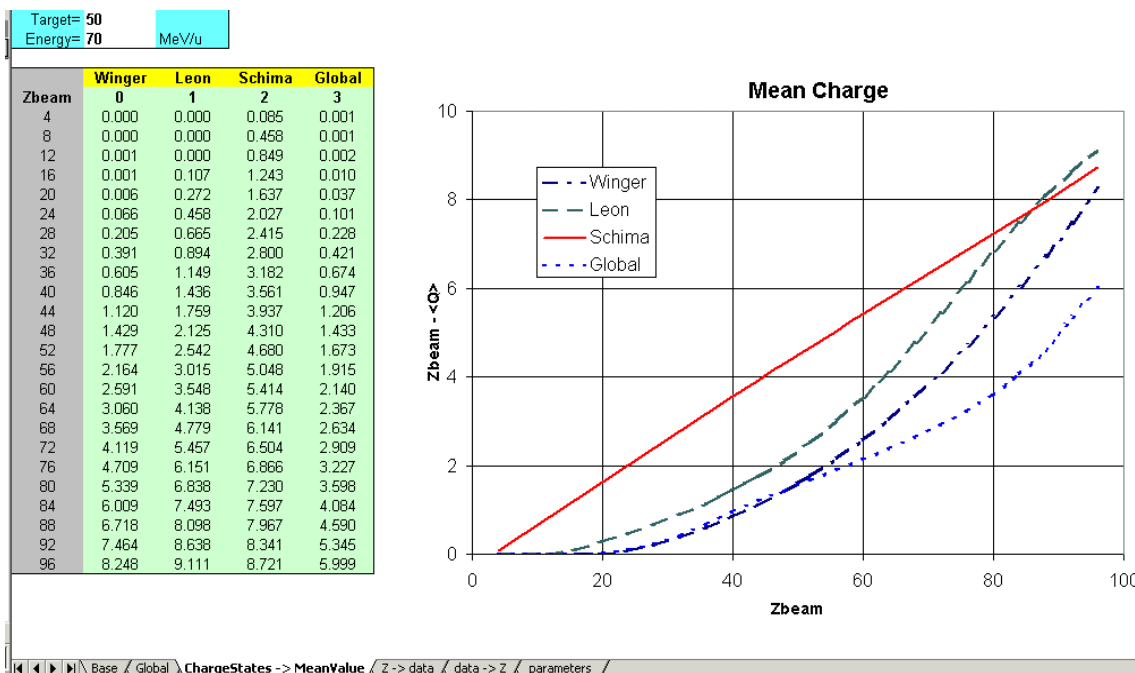


**Fig.7.** Charge state evolution of the ions  $^{118}\text{Sn}^{Y+Y+}$  after a Ta-material as a function of its thickness for equilibrium and nonequilibrium cases in the reaction  $^{124}\text{Xe} (90 \text{ MeV/u}) + \text{Pb}(20\text{mg/cm}^2) \rightarrow \text{Dipole} \rightarrow \text{Be}(20 \text{ mg/cm}^2) + \text{Ta}(x \text{ mg/cm}^2)$ .



### 1.4. Excel: new sheet and functions with charge states

Additional utilities have been created in the LISE.xls file. The new sheet “ChargeStates → MeanValue” allows to plot the mean values of the charge state distribution versus the atomic number of the projectile. It is possible to enter the energy of the projectile and the target atomic number to get the mean value of the equilibrium charge state distribution with different models (see Fig.8).



**Fig.8.** The sheet “ChargeStates → MeanValue” of the file “LISE.xls”. It is possible to enter the energy of the projectile and the target atomic number to get mean value of the equilibrium charge state distribution with different models.

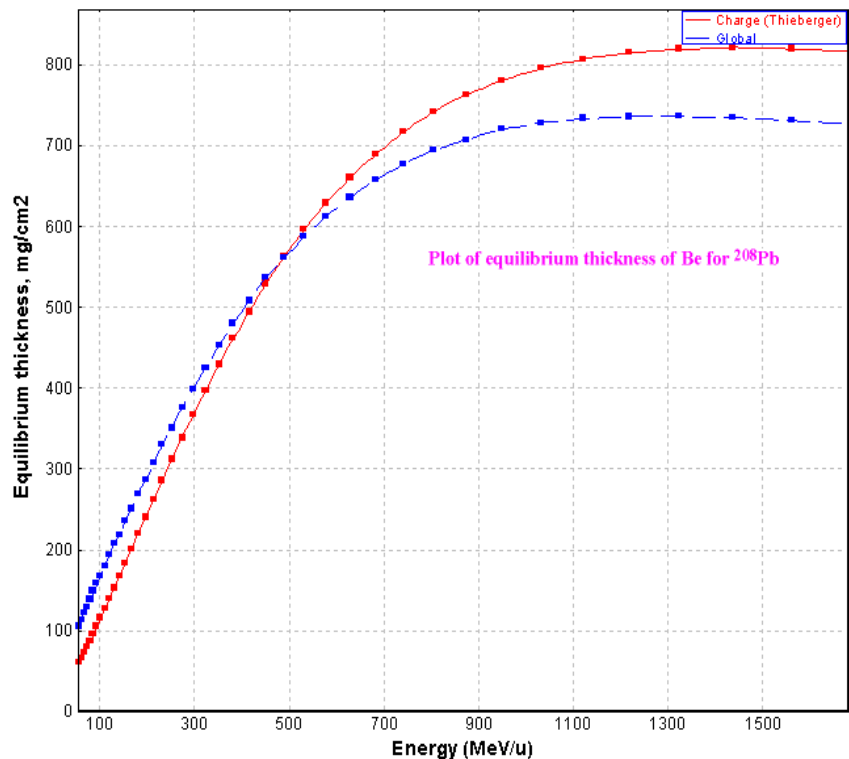
The functions *EnergyLossInMatter\_option*, *RangelnMatter\_option*, *ChargeState\_option*, *Charge\_Qmean*, *Charge\_dQ* have been implemented in the library of LISE.xls. The first three functions are identical to *EnergyLossInMatter*, *RangelnMatter*, *ChargeState*, but require to specify a model. The functions *Charge\_Qmean* and *Charge\_dQ* calculate the mean value and the dispersion of the charge state distribution.

*Note:* To use built-in LISE functions in Excel you have to set the options:

- Tools → Macro → Security → ”Low” or ”Medium”.
- Switch on the option “macros enabled” then load the Excel file in the security mode ”Medium”.

### 1.5. Equilibrium thickness plot

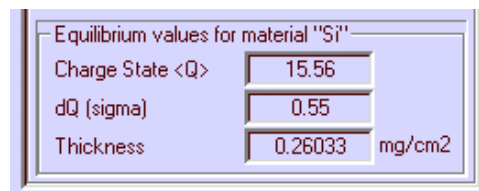
The “Equilibrium thickness versus projectile energy” plot can be viewed in LISE++ (menu “Utilities”). Two models calculate the equilibrium thickness: one from the Global code and the other from Thierberger’s [Thi85] definition of the equilibrium thickness in the code “Charge”. An example of the equilibrium thickness plot for the projectile  $^{208}\text{Pb}$  in Be is shown in Fig.9.



**Fig.9.** Equilibrium thickness of Be as a function of energy for a  $^{208}\text{Pb}$  projectile.

### 1.6. Physical Calculator Charge state values ( $\langle Q \rangle$ , $\Delta Q$ )

The Physical calculator dialog in the new version of the code shows the statistical characteristics of the equilibrium charge state distribution as well as the value of equilibrium thickness (see Fig.10). The equilibrium thickness is calculated based on Thierberger’s definition of the equilibrium from the Charge code.

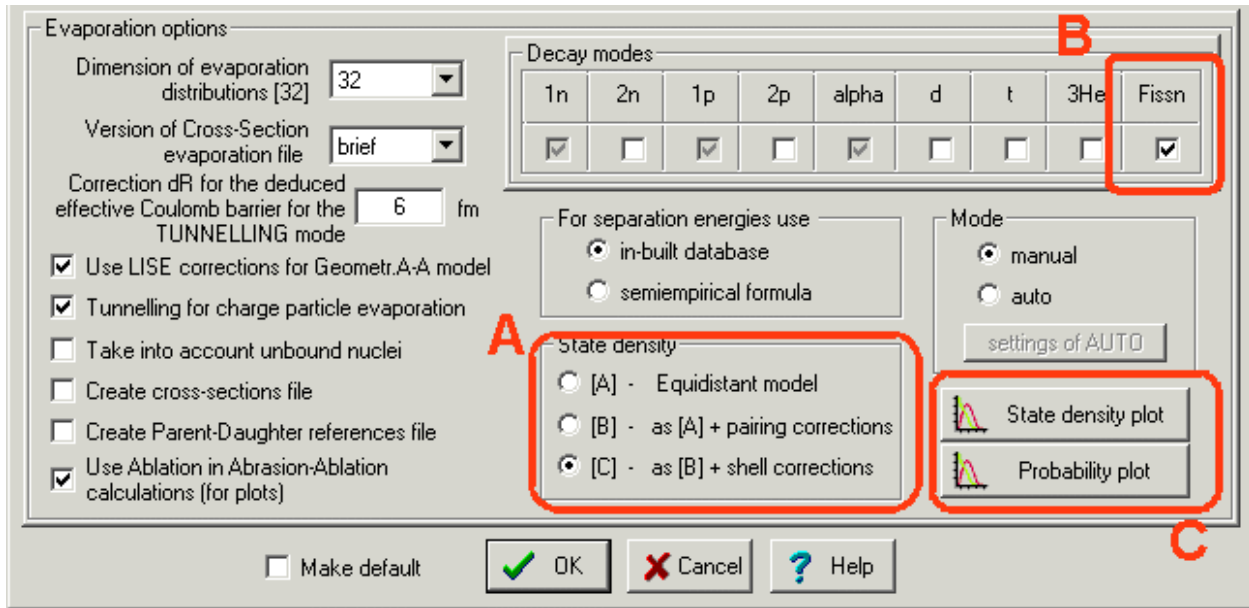


**Fig.10.** Fragment of the “Physical calculator” window with the results of equilibrium charge state distribution and equilibrium thickness of material. The thickness of material for the charge state calculation is assumed to be equal to 0.

## 2. Modification of evaporation calculations

### 2.1. Level density calculations

Level densities and decay widths from the statistical analysis of A.Iljinov et al [Ilj92] have been incorporated in LISE++. The code calculates decay widths instead of width ratios as was done in the previous version. This modification is necessary in order to add the fission channel in the evaporation cascade. The option to use shell corrections has been added to calculate the level density (see frame A in Fig.11).



*Fig.11. The “Evaporation options” dialog*

The shell corrections are calculated without collective effects following the results of level density analysis of Myers-Swiatecki shell corrections where the asymptotic level density parameter  $\gamma$  is equal to  $\tilde{a}/0.46A^{4/3}$  (see Table 3 in [Ilj92]).

Due to these modifications it is recommended to use the new values shown in Table 1 in the mode “AUTO” (see the “Settings of AUTO” dialog)

*Table 1. Recommended values for the mode “Auto” of evaporation calculations.*

	Abrasion-Ablation	Fusion-Evaporation	Previous value
Take into account unbound nuclei with A less than	40	300	40
Include pairing and shell corrections for nuclei with A greater than	2	2	70

#### 2.1.1. Level density and temperature plots

Level density and temperature versus an excitation energy plots can be viewed from the “Evaporation options” dialog (see frame C in Fig.11). The plots are drawn for all of three modes of state density available in LISE++: A) Equidistant model, B) “A” + pairing corrections, c) “C” + shell corrections, to give the user a possibility to compare them (see Fig.12).

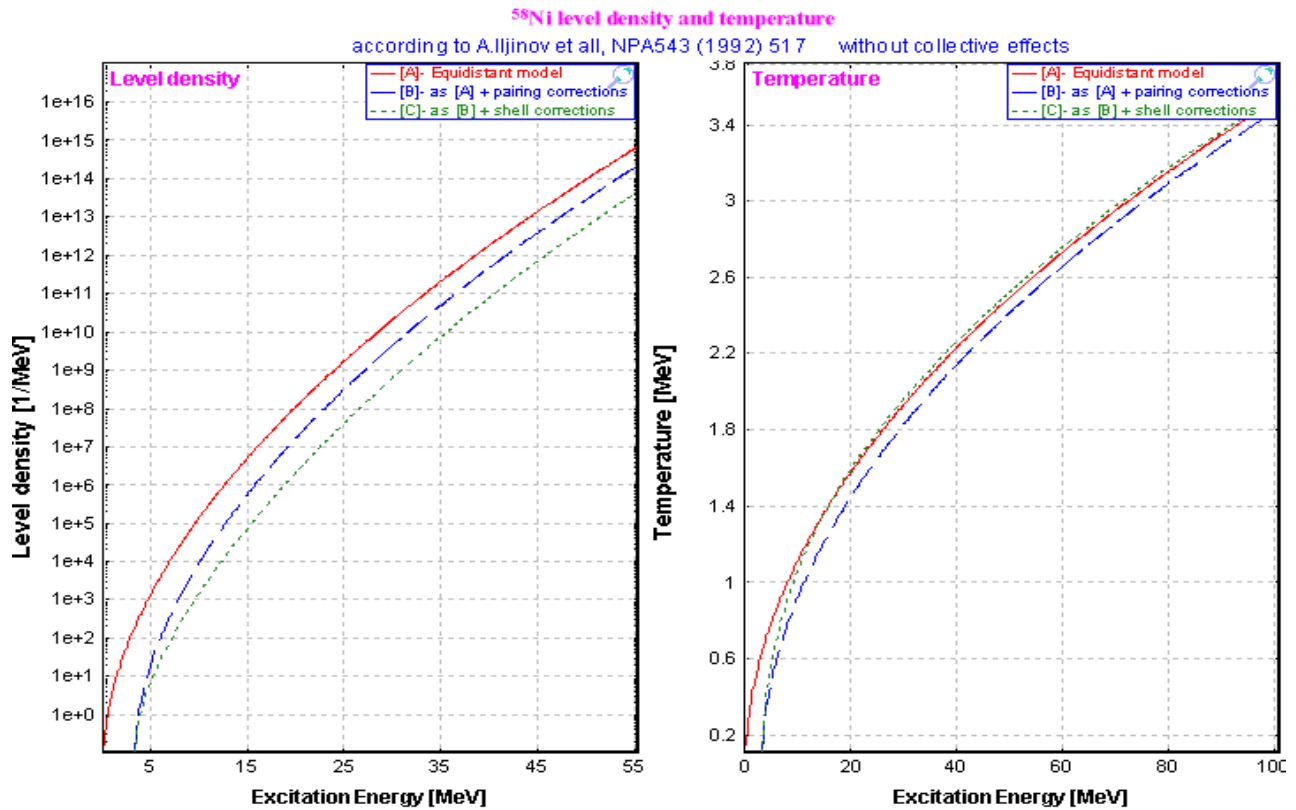


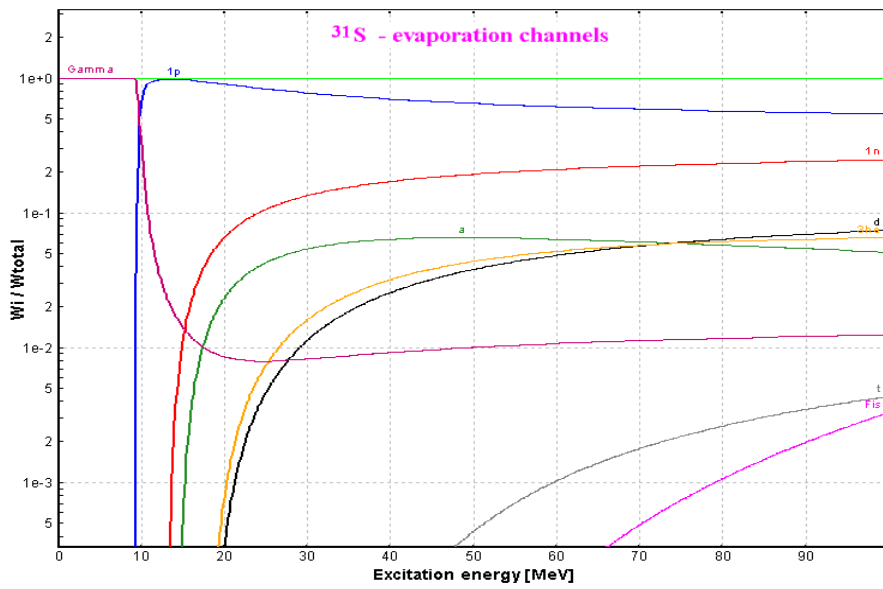
Fig.12. <sup>58</sup>Ni level density and temperature versus excitation energy.

## 2.2. Fission channel in evaporation cascade

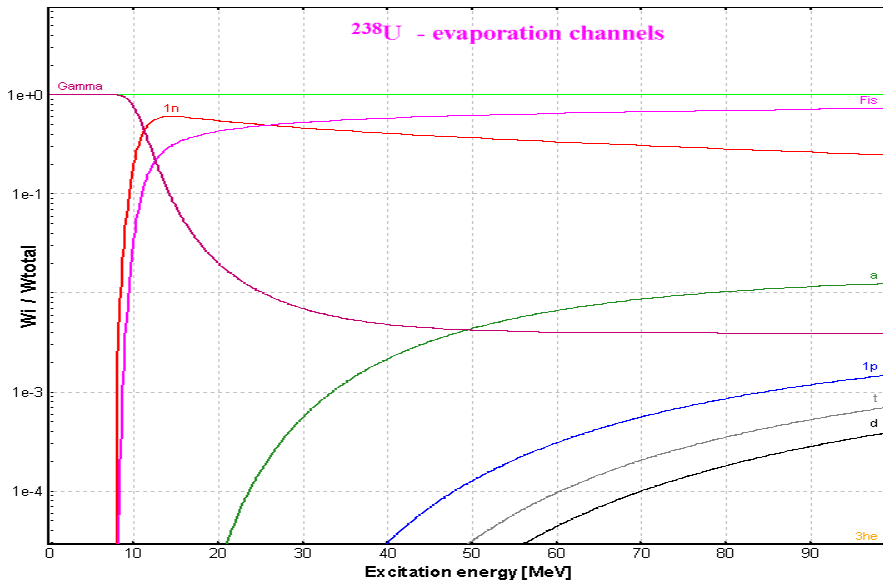
A fission channel has been added to the family of decay channels of LISE evaporation calculations, and is very important for excited heavy nuclei where fission is a dominant channel. The code does not take into account the angular momentum of the decaying nucleus in fission. The fission width is calculated according to the article [Ilj92]. The subroutine FISROT [Coh63] of the PACE code is used to calculate the fission barrier. It is possible to see the fission barrier value in the “Evaporation calculator” dialog. LISE uses the fission channel to determine the production cross section of evaporation residues, but the code does not calculate the transmission of fission fragments and therefore fission fragments. To use the fission channel in evaporation calculations the user has to check the fission checkbox in the decay modes frame (see frame B in Fig.11)

## 2.3. Plot of decay channel probabilities

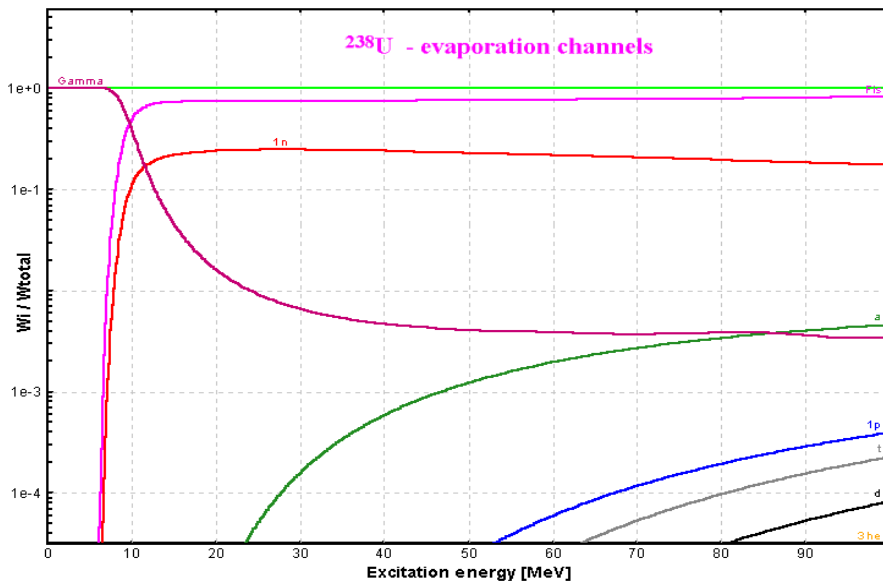
The energy dependence of decay channel probabilities can be plotted from the “Evaporation options” dialog by pressing on the “Probability plot” button. The plot is very useful to estimate the dominant channels and also to see the influence of different level density modes. Plots of the decay channel probabilities of <sup>31</sup>S and <sup>238</sup>U are presented in Fig. 13-15. Energy dependences in Fig.13 and 14 were calculated using the level density mode “C” (with pairing and shell corrections), the energy dependence in Fig.15 was calculated for the level density mode “A” (without any corrections).



**Fig.13.** Energy dependence of light particle and gamma emission probabilities for  $^{31}\text{S}$ . Calculations were performed using the level density mode “C” (pairing and shell corrections included).



**Fig.14.** Energy dependence of light particle and gamma emission probabilities for  $^{238}\text{U}$ . Calculations were performed using the level density mode “C” (pairing and shell corrections included).



**Fig.15.** Energy dependence of light particle and gamma emission probabilities for  $^{238}\text{U}$ . Calculations were performed using the level density mode “A”.

### 3. Other

#### 3.1. New angular transmission method

A new method to calculate the fragment angular transmission has been incorporated in LISE after discussions on how to analytically calculate the angular transmission depending on the shape of the angular acceptance. The LISE original method (named “jacobian”) is as follows:

- The fragment angular distribution  $d\sigma/d\Omega$  is transformed to the distribution  $d\sigma/d\theta$ .
- The angular transmission is equal to the ratio:

$$\varepsilon(m) = \int_0^m \left( \frac{d\sigma}{d\theta} \right) d\theta \bigg/ \int_0^{\pi/2} \left( \frac{d\sigma}{d\theta} \right) d\theta, \quad /2/$$

where  $m$  is the angular acceptance of the device. If the horizontal  $m_X$  and vertical acceptances  $m_Y$  are different then the code uses a geometrical average value  $\varepsilon = \sqrt{\varepsilon(m_X) \cdot \varepsilon(m_Y)}$  as total angular transmission.

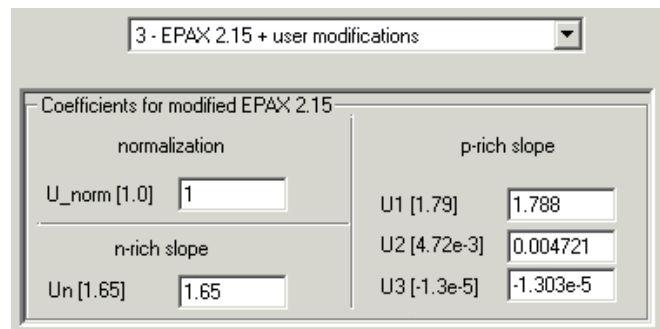
The new angular transmission labeled “projection” method is equal to  $\varepsilon = \zeta(m_X) \cdot \zeta(m_Y)$ , where  $\zeta(m)$  is defined by the relation:

$$\zeta(m) = \int_{-m}^m \left( \frac{d\sigma}{d\Omega} \right) d\theta \bigg/ \int_{-\pi/2}^{\pi/2} \left( \frac{d\sigma}{d\Omega} \right) d\theta. \quad /3/$$

The results from both methods are almost always identical. It is possible to interpret these two methods via the acceptance shape: the “jacobian” method corresponds to an oval acceptance, whereas the “projection” method corresponds to a rectangular acceptance. The angular transmission method can be selected in the “Preference” dialog. The “jacobian” method is chosen by default.



#### 3.2. Possibility to modify EPAX 2.15

The version 6.3 of LISE allows to adjust 5 parameters of EPAX 2.15 (model number 3 which can be selected in the “Projectile fragmentation” dialog – see Fig.16.). The parameters are named according to the article [Sum00]. Using this option it is possible to achieve better agreement between calculated values and experimental results and to fragment cross section based on actual measurements. Five parameters can be modified: three of them are used for to proton-rich nuclei, one for neutron-rich nuclei, and the last one to normalize all cross sections.



**Fig.16.** Fragment of the “Projectile fragmentation” dialog showing the new option of projectile fragmentation cross sections.

### 3.3. Monte Carlo plot saving and use by the "BI" code

The two-dimensional spectra created by the Monte Carlo method can be saved in ASCII formats: three columns file (\*.dat, \*.txt) or NCSL 2d-spectrum (\*.spa). It is possible to use the saved spectra (\*.dat, \*.txt) in several graphical software (for example Microcalc Origin) to build plots or to load spectra in the NSCL acquisition and analysis software (\*.spa). To save the two-dimensional Monte Carlo spectrum, click the icon  after the Monte Carlo acquisition has been stopped (Fig.17). Saved Monte Carlo spectra can be loaded in the Bi code  (see Fig.18). It is then possible to create contours to see the statistical characteristics of the peaks and make projections on horizontal and vertical axis. An example of a contour for a Monte Carlo spectrum is shown in Fig.18, and the projection of this contour on the vertical axis is shown in Fig.19.

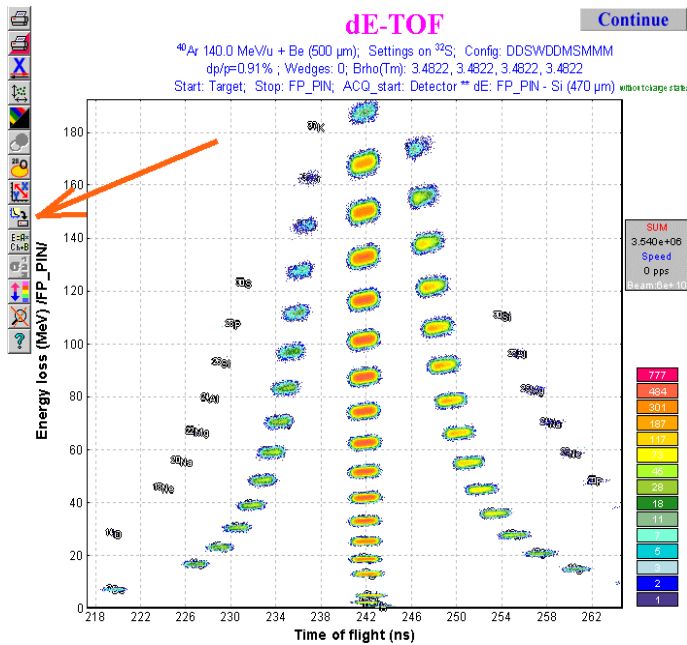


Fig.17. Monte Carlo identification plot.

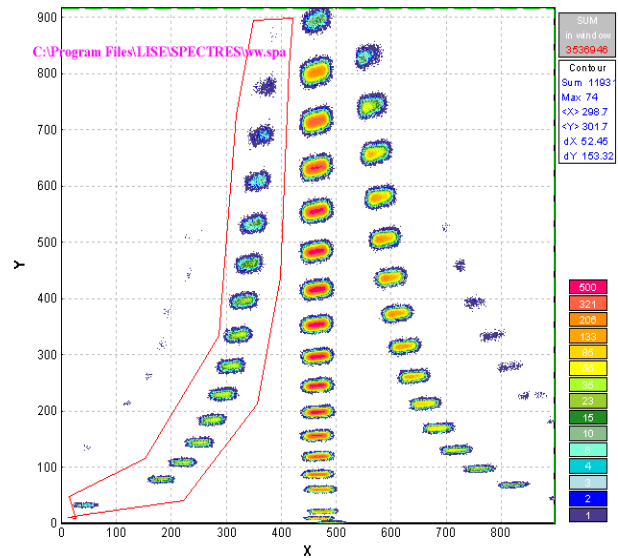


Fig.18. Input spectrum in the BI code. The spectrum was created from Monte Carlo plot (see Fig.17).

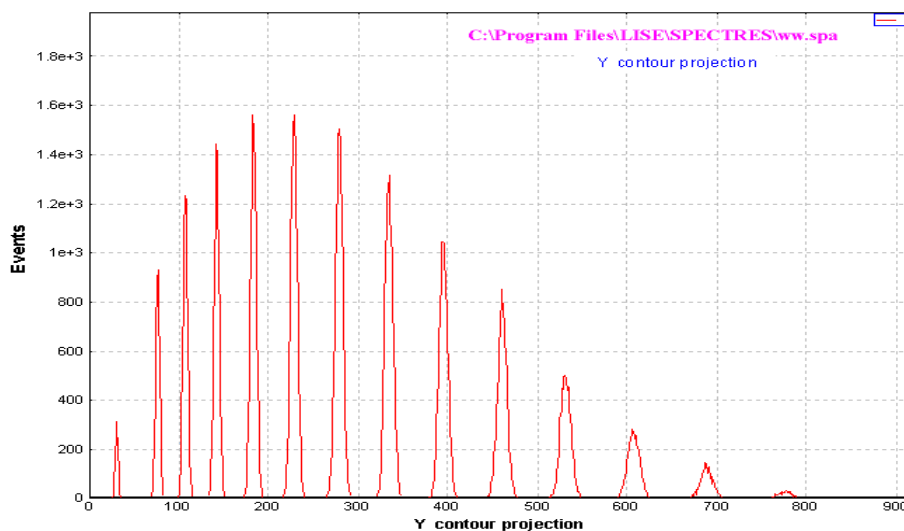


Fig.19. Vertical projection of the contour in Fig.18.

### 3.4. New configurations

Configuration	Subdirectory	Scientist who assisted to create or created the configuration
A1900_PAC27.lcn	NSCL	A.Stolz
RIPS	RIKEN	K.Yoneda
MSP-144*	Dubna	R.Kalpakchieva
ACCULINNA	Dubna	S.Stepantsov
Combas	Dubna	Yu.Sereda
FRS - new standard.lcn FRS - ESR.lcn FRS - FB07E to S8.lcn Super-FRS.lcn	GSI	H.Weik

\*The MSP-144 dialog was moved from the Kinematics calculator to the Utilities menu.

### 3.5. Bug corrections

<i>Thickness dialog</i>  A.Stolz (NSCL)	<p>The program rounded the thickness value in the material dialogs and was saving to the file only up to two digits after a decimal point.</p> <p>Rounding is now not made in material dialogs. Up to 6 digits after the decimal point are deduced.</p> <p>In the Setup window 7 characters are allocated for the material thickness (for example 500.233 or 1.678e+9)</p>
<i>Integration method of energy straggling calculations</i>  H.Weik (GSI)	<p>For thick enough materials a large difference in energy straggling was noticed when using the integration method. This is corrected but an insignificant deviation is still observed, therefore it is recommended to use the tabulation method for energy straggling calculations.</p>
<i>Problems with Windows XP</i>  H.Weik (GSI), T.Kibedi (Australian Nat.Univ.)	<p>The program is not loaded if the user has regular privileges but no administrative privileges. This is caused because the program tries to open a database file both for reading, and writing. In the new version the program checks the possibility to open the database file for writing. If forbidden, the file opens only for reading.</p>
<i>Database access in the PACE4 code</i>  G.Savard (Argonne)	<p>After modifying the access to the database (look above) in some cases the program (LISE and PACE) did not open the database file and used the built-in procedures. This is corrected</p>
<i>Energy straggling for Monte Carlo plots</i>  A.Stolz (NSCL)	<p>Problem corrected. Remember: detector resolution, material defect, timing resolution, and straggling are responsible for the peak width in an identification plot. Set all resolutions and defects to 0 to see the straggling contribution. You can also see the straggling contribution if choose the mode (2) "No energy straggling" in the "Reaction mechanism" dialog.</p>



## 4. Comparison between LISE calculations and experimental results

It is often asked what models describe better the fragment momentum distributions, charge state distributions, production cross sections, etc. Obviously it depends on the energy of the projectile and from the reaction mechanisms involved in the fragment production process. In this chapter comparisons of experimental results with calculations of the program LISE are presented for different models in LISE. The analysis is carried out for charge states distributions, parallel fragment momentum distributions, and production cross sections in the next sections.

### 4.1. Charge state distributions

NSCL experimental data for different energy regions have been used for charge state analysis.

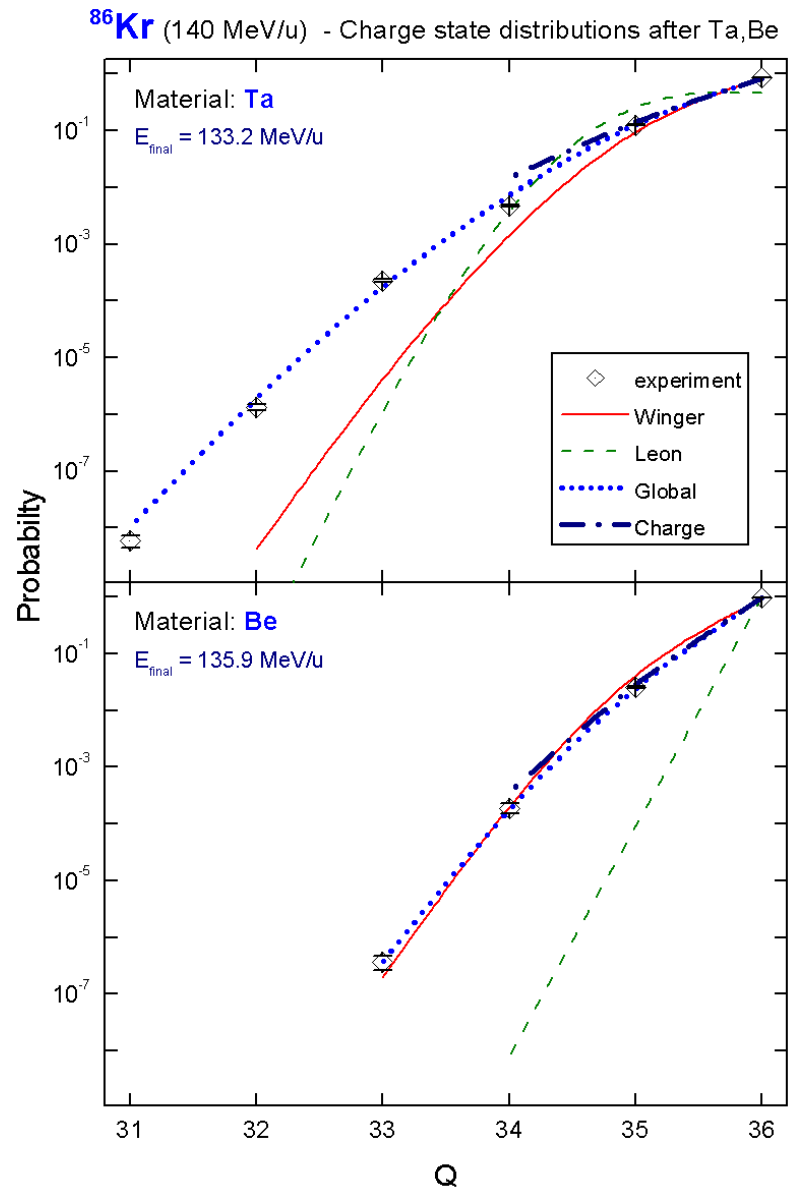
$^{86}\text{Kr}$  (140 MeV/u) equilibrium charge states distributions [Tsa03] after Ta-target (energy after the target 133.2 MeV/u) and Be-target (energy after the target 135.9 MeV/u) are shown in Fig.20.

$^{58}\text{Ni}$  (140 MeV/u) equilibrium charge states distributions [Tsa03] after Au, Ta, Nb, and Be are shown in Fig.21. The energies after targets are shown in the plots.

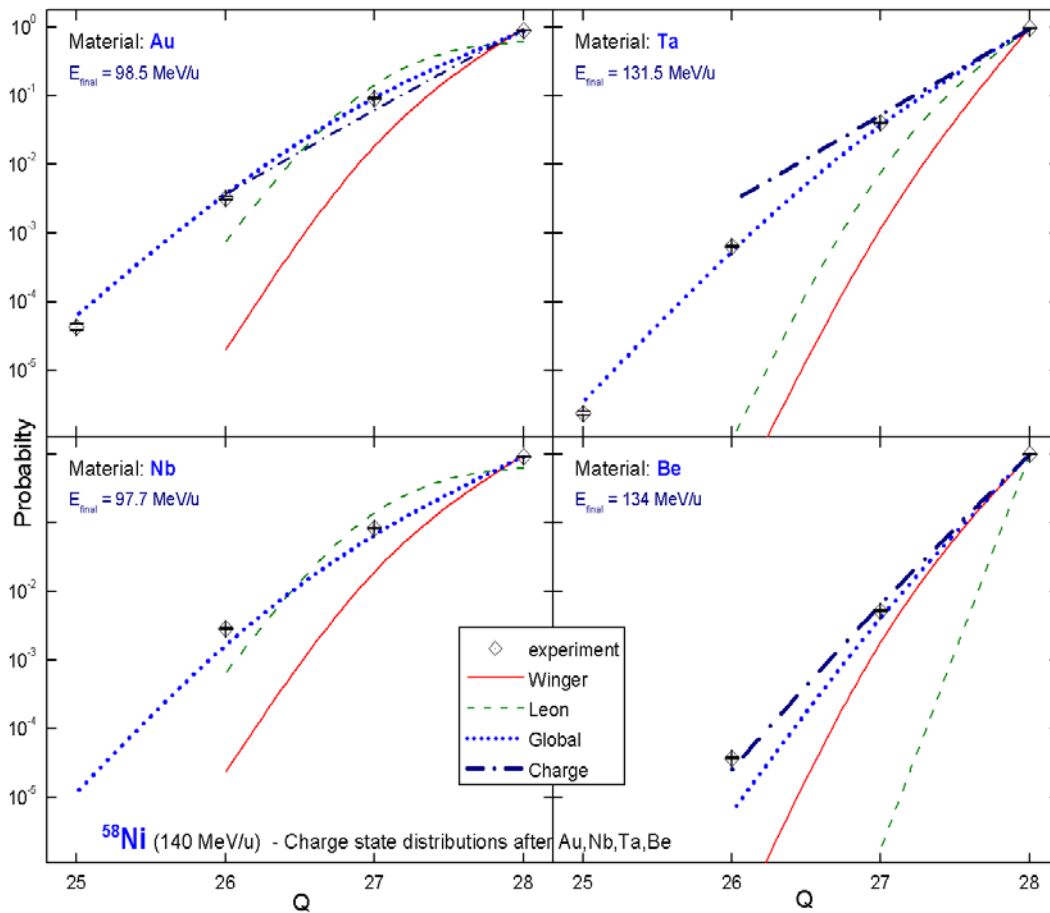
The equilibrium charge states distributions of  $^{136}\text{Xe}^{21+}$  (10.85MeV/u),  $^{124}\text{Xe}^{20+}$  (12.25MeV/u),  $^{86}\text{Kr}^{14+}$  (12.3MeV/u) after a carbon foil [A1903] are shown in Fig.22 (Global and Charge do not calculate at energies lower than 30 MeV/u). The foil thicknesses are shown in the plots.

Looking at these figures it is possible to conclude that in the energy region of 90 to 150 MeV/u the Global model gives the best agreement with the data. The Charge code also gives a quite good agreement but calculates just three charge states ( $Z-Q=0,1,2$ ).

For lower energies Winger and Leon give a good agreement, and Schima calculations are unsuitable for this energy region.



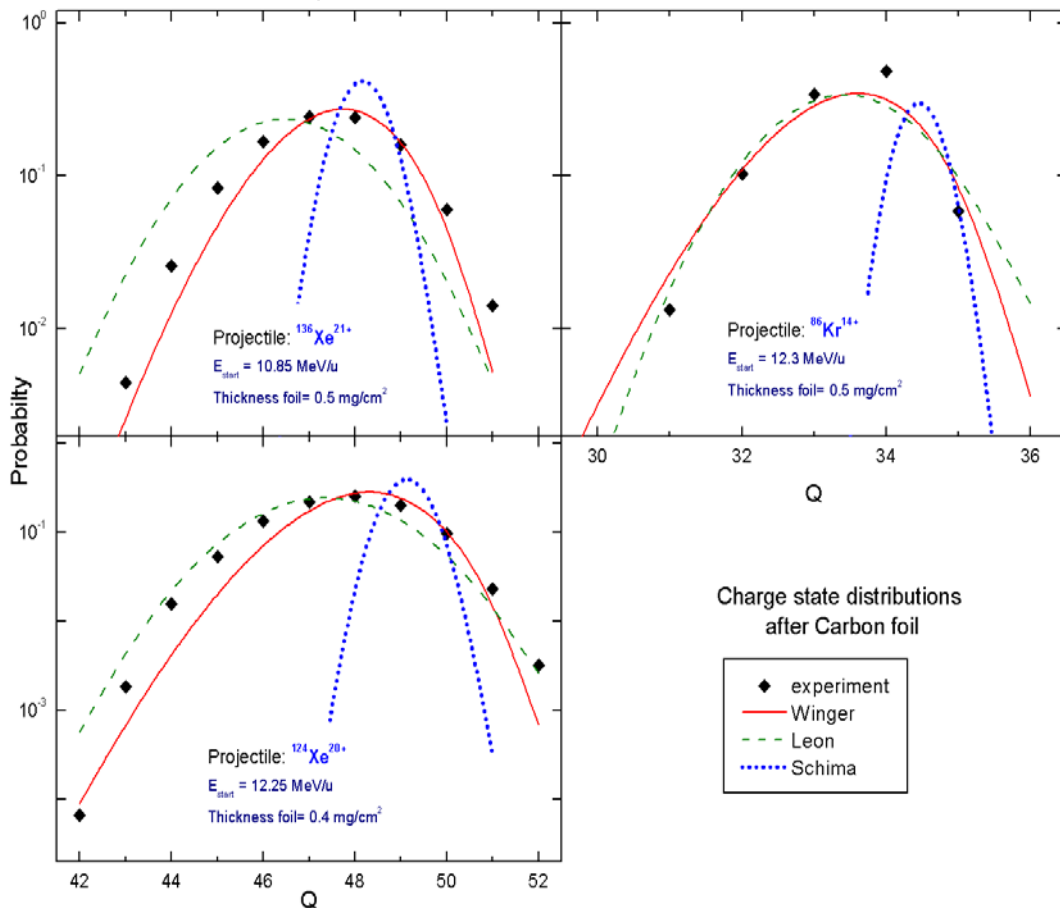
**Fig.20.**  $^{86}\text{Kr}$  equilibrium charge states distributions [Tsa03] after Ta-target (top picture) and Be-target (bottom picture). The energies after the Ta and Be targets are 133.2 MeV/u and 135.9 MeV/u respectively.



**Fig.21.**  
 $^{58}\text{Ni}$  (140 MeV/u)  
 equilibrium charge  
 states distributions  
 [Tsa03] after

Au (top left),  
 Ta (top right),  
 Nb (bottom left),  
 Be (bottom right).

Energies after mate-  
 rials are shown in  
 the plots.



**Fig.22.** Equilibrium  
 charge states  
 distributions of  
 $^{136}\text{Xe}^{21+}$  (10.85MeV/u)  
 (top left),

$^{124}\text{Xe}^{20+}$  (12.25MeV/u)  
 (bottom left),

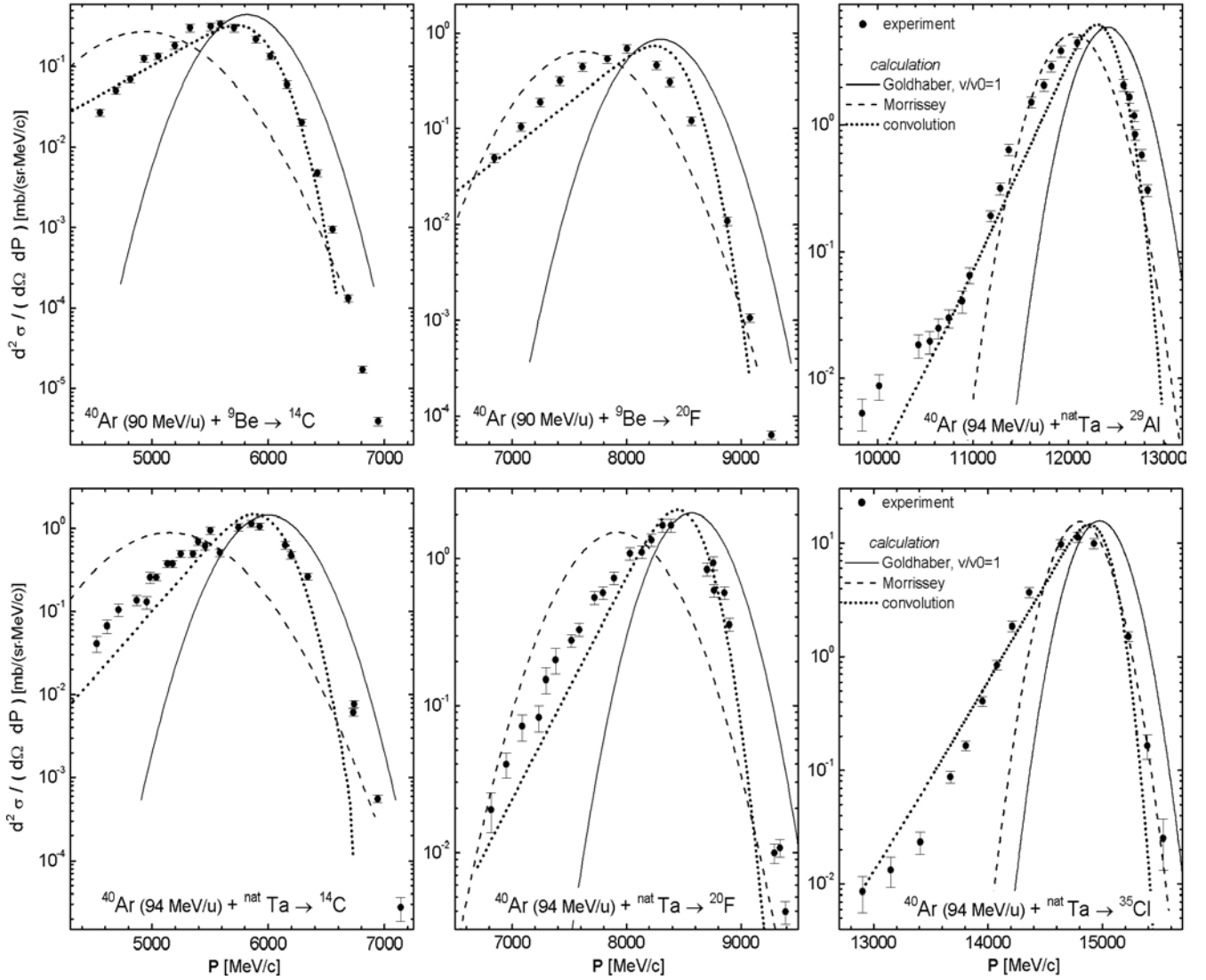
$^{86}\text{Kr}^{14+}$  (12.3MeV/u)  
 (top right)

after a carbon foil  
 [A1903].

Foil thicknesses are  
 shown in the plots.

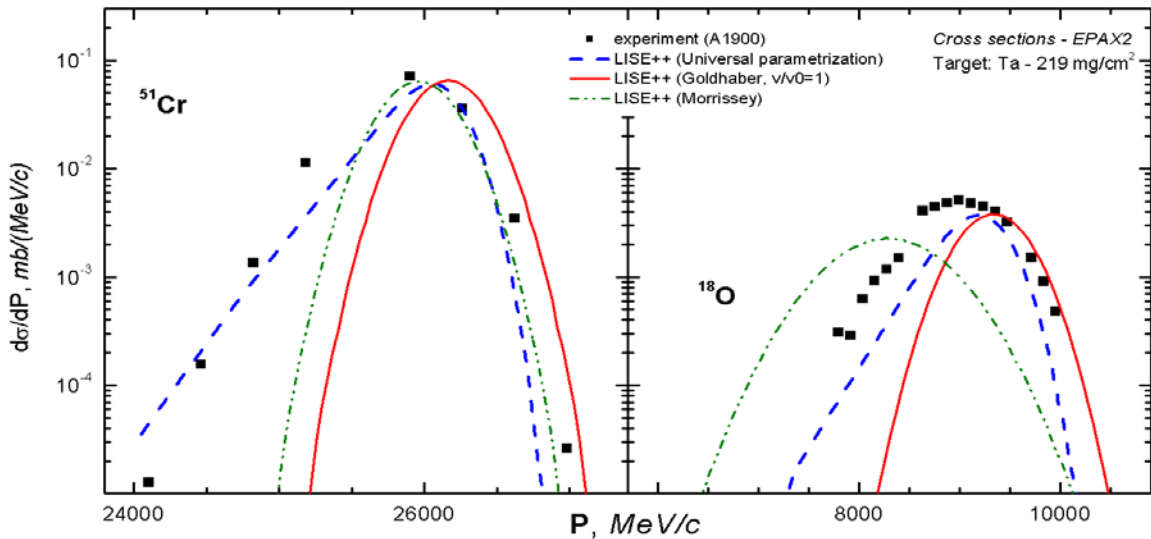
## 4.2. Fragment parallel momentum distributions

Recent experimental results [Mom02] from RIKEN on the study of production cross sections and momentum distribution of projectile fragmentation products in the reactions  $^{40}\text{Ar} + \text{Ta}$  and  $^{40}\text{Ar} + \text{Be}$  at 90 MeV per nucleon are compared to the models in Fig.23. The differential cross section distributions were calculated with LISE++ normalized on the area of the experimental spectra. The sum of surface excess and mass difference was used for the separation energy in the convolution method. Corrections for target thickness have been applied following [Mom02].



**Fig.23.** Experimental spectra of  $^{14}\text{C}$ ,  $^{20}\text{F}$  produced in  $^{40}\text{Ar} + \text{Be}$  [Mom02] and  $^{14}\text{C}$ ,  $^{20}\text{F}$ ,  $^{29}\text{Al}$ ,  $^{35}\text{Cl}$  resulting from  $^{40}\text{Ar} + \text{Ta}$ . The calculated spectra using Goldhaber's model with fragment to projectile velocity ratio equal to 1 are indicated by solid lines. Dashed lines represents the momentum distributions with widths and mean velocity based on Morrissey's systematics and the convolution model calculations are shown by dotted lines.

NSCL experimental results [Tsa03] on the study of production cross sections and the momentum distribution of projectile fragmentation products in the reactions  $^{58}\text{Ni} + \text{Ta}$  at 140 MeV per nucleon are compared to the models in Fig.24. The differential cross section distributions were calculated with LISE++ based on cross section calculations by EPAX 2.15.

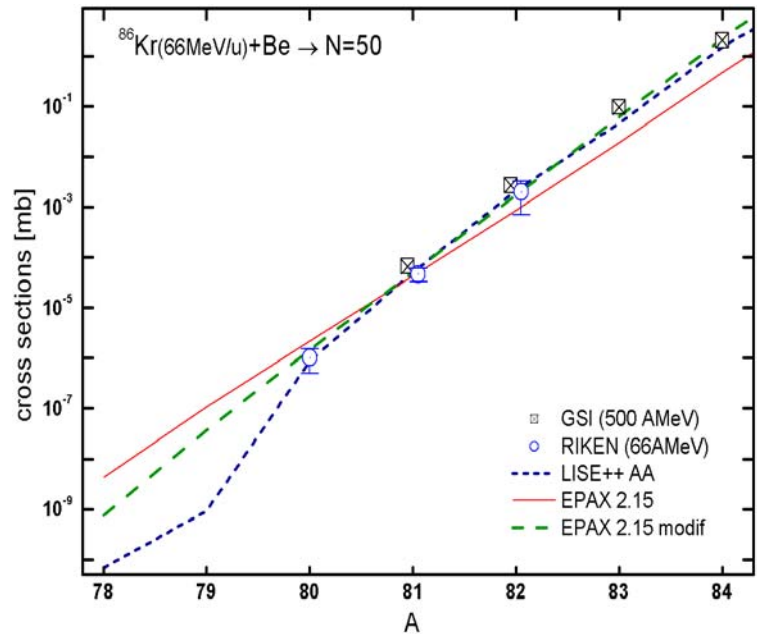


**Fig.24.** Experimental spectra of  $^{18}\text{O}$ ,  $^{51}\text{Cr}$  produced in  $^{58}\text{Ni}(140\text{MeV}/u) + \text{Ta}$  [Tsa03]. The calculated spectra using Goldhaber's model with fragment to projectile velocity ratio equal to 1 are indicated by solid lines. Dashed lines represents the momentum distributions with widths and mean velocity based on Morrissey's systematics and the convolution model calculations are shown by dotted lines.

These figures show that in the energy region of 90 of 150 MeV/u the Universal parameterization based on the 3-step projectile fragmentation model gives a better agreement with the experimental data.

### 4.3. LISE Abrasion-Ablation model

The Abrasion-Ablation model implemented in LISE++ is used to predict production cross sections. However to correctly reproduce experimental cross sections it is necessary to calculate precisely the excitation energy of the prefragment. Some examples of AA calculations and their comparisons with experimental data are given below. The production cross sections of  $N=50$  isotones in the reaction  $^{86}\text{Kr}(66\text{MeV}/u) + \text{Be}$  [Aoi02] as a function of mass number are shown in Fig.25. The parameters of the Abrasion-Ablation model and modified EPAX2.15 are given in Tables 2 and 3 respectively. The LISE file for the example is located on the LISE web-site at: [http://groups.nslc.msu.edu/lise/6\\_3/examples/86kr\\_80zn.lpp](http://groups.nslc.msu.edu/lise/6_3/examples/86kr_80zn.lpp).



**Fig.25.** Production cross sections of  $N=50$  isotones as a function of mass number. See text for details.

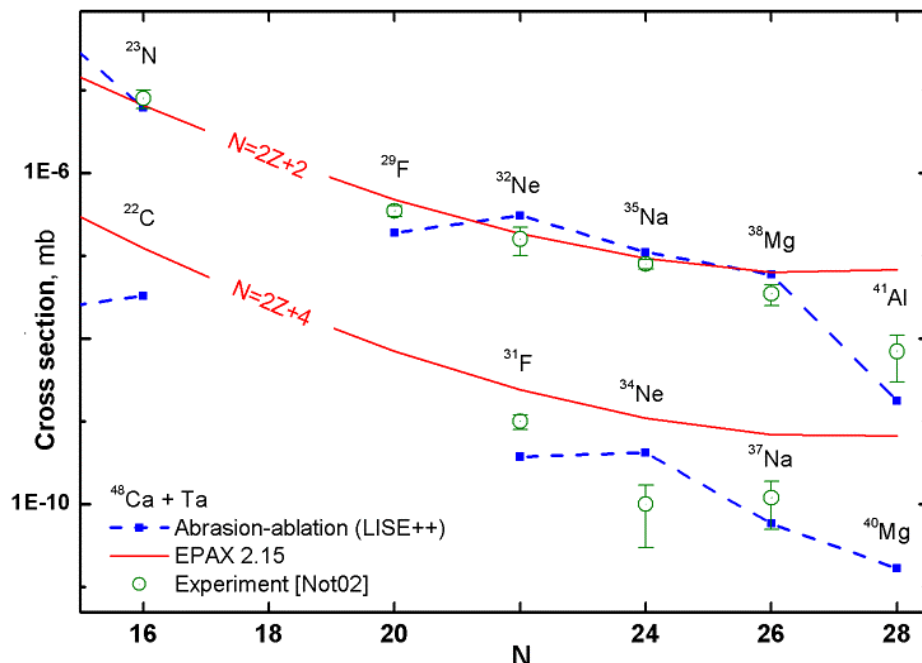
**Table 2.** Parameters of Abrasion-Ablation model used in calculations of Fig.25.

LISE++ version	6.3	State density	Shell+Pairing
Distribution dimension (NP)	64	Option "unbound"	auto
Hole depth (MeV)	48	Decay modes	All (8)
Excitation energy method	1	Tunneling	auto

**Table 3.** Parameters of "EPAX 2.15 modified" in Fig.25.

Changed parameter	New value	EPAX 2.15 value
U_norm	6	1
Un	1.73	1.65

The experimental and calculated production cross sections of various isotopes in the reaction  $^{48}\text{Ca}(90\text{MeV/u})+\text{Be}$  are shown in Fig.26. These results have been already shown in the LISE++ documentation v.6.1. A difference of almost two-orders magnitude is observed between the abrasion-ablation model and the EPAX parameterization for the  $^{40}\text{Mg}$  production cross-section. The parameters used for the Abrasion-Ablation model are given in Table 4.



**Fig.26.** Experimental [Not02,Sak97], calculated by the LISE abrasion-ablation model (blue dash curve) and EPAX parameterization (red solid curve) production cross sections of neutron-rich isotopes in the reaction  $^{48}\text{Ca}+\text{Ta}$  versus neutron number. Binding energies from the database+LDM2 have been used for the Abrasion-Ablation calculations.

**Table 4.** Parameters of Abrasion-Ablation model used in calculations of Fig.26.

LISE++ version	6.1	State density	auto
Excitation energy method	2	Tunneling	auto
Distribution dimension (NP)	64	Option "unbound"	auto
$\langle E^* \rangle$ (MeV)	16.5 dA	Decay modes	All (8)
$\delta E$ (MeV)	9.6		

## 5. Status of the code

### 5.1. LISE tutorial

A tutorial for LISE++ was created for the RIA Summer School at NSCL / Michigan State University on August 2003. This tutorial shows step by step how to prepare for producing a radioactive beam of  $^{22}\text{Al}$  to be used in an implantation experiment where the  $\beta$ -delayed proton decay of this nucleus is to be studied. This tutorial can be loaded using the following links:

<http://groups.nsl.mscl.msu.edu/lise/doc/tutorial.pdf> or <http://dnr080.jinr.ru/lise/doc/tutorial.pdf>.

## 5.2. User statistics

Fig.27 shows in which countries there is interest to LISE++. The statistics corresponds to the past year, and are based on identified visits of sites of the LISE code. Due to temporary problems with the work of dnr080 server (at Dubna) about 40 percents of hits are not registered.

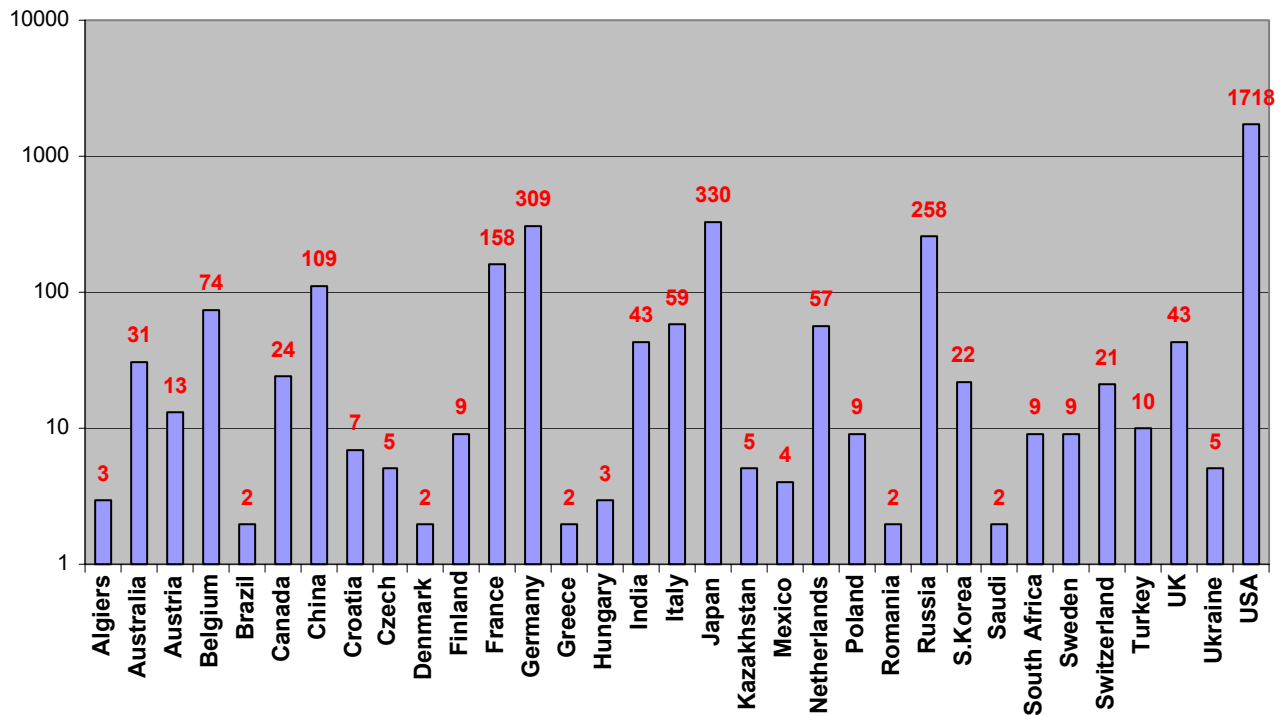


Fig.27. User statistics of the LISE web sites for the past year. Countries with one hit were excluded. More than half the statistics for USA is from NSCL, for Germany GSI, for Japan RIKEN, and for Russia JINR.

## 5.3. Future perspectives for LISE++ (version 6.4)

- Develop fission products kinematics in LISE++.
- Incorporate a new reaction mechanism: **Fission**.

## Acknowledgements

The authors gratefully acknowledge Prof. Carlos Bertulani, Prof. Filomena Nunes, Dr. Helmut Weik and Dr. Ken Yoneda for fruitful help with the development of LISE++.

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