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Production of Fast Rare Ion Beams

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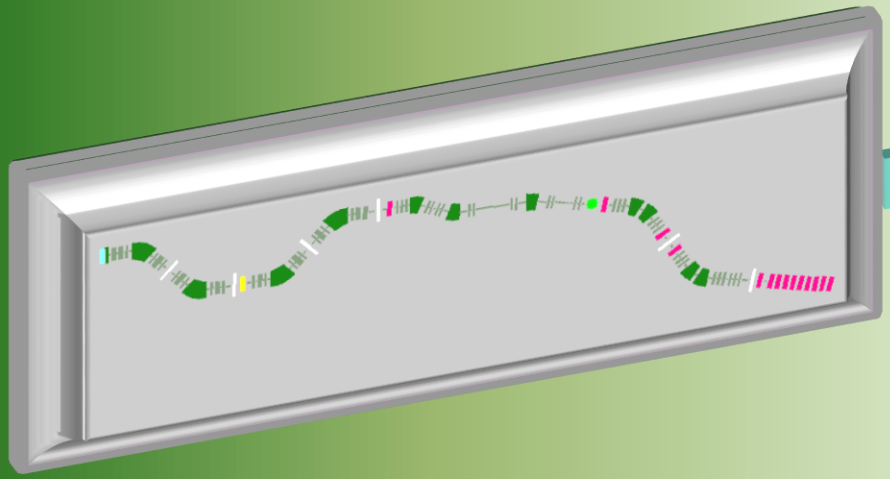


LISE++

LISE++

1. Introduction to production of radioactive ion beams
2. Production Area
3. Separation
4. Identification
5. Production of new isotopes
6. LISE++ : Utilities
7. Radioactive beam physicist task

7. Radioactive beam physicist task

School on Exotic beams 2011 @ East Lansing

- The students attending the School have been divided into 6 groups
- The group structure is for the purpose of giving intense hands-on training on experimental techniques to each group during the afternoon "Working Group" sessions on Monday through Thursday.
- The members of each group will also work together during the 4-hour experiment time allocated to that group on Friday or Saturday.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Beam Optics	Mon. 15:40	Thu 14:25	Wed 16:10	Wed 14:25	Tue 16:10	Tue 14:25
LISE++	Tue 14:25	Mon. 15:40	Thu 14:25	Wed 16:10	Wed 14:25	Tue 16:10
Control systems	Tue 16:10	Tue 14:25	Mon. 15:40	Thu 14:25	Wed 16:10	Wed 14:25
Electronics	Wed 14:25	Tue 16:10	Tue 14:25	Mon. 15:40	Thu 14:25	Wed 16:10
DAQ	Wed 16:10	Wed 14:25	Tue 16:10	Tue 14:25	Mon. 15:40	Thu 14:25
Particle ID	Thu 14:25	Wed 16:10	Wed 14:25	Tue 16:10	Tue 14:25	Mon. 15:40

7. Radioactive beam physicist task

- **Radioactive beam physicist task**
  - Produce an ^{22}Al beam to be used in a ß-delayed proton decay experiment
  - Minimum required intensity: 1000 pps
  - Minimum required purity: 50%
  - Maximum implantation range in silicon: 100µm

- **Tutorial**
  - Walk through steps involved in making right choices to fulfill the radioactive beam requirements
  - Use LISE++ to understand the various possibilities (and impossibilities!) in making these choices

LISE++ tutorial

Created by D. Bazin
Modified by O.Tarasov
NSCL / Michigan State University

In this tutorial you impersonate a "Radioactive beam physicist" who is asked to prepare for producing a radioactive beam of ^{22}Al to be used in an implantation experiment where the β-delayed proton decay of this nucleus is to be studied. The experimentalists would like a minimum intensity of 1000 ^{22}Al ions per second with a purity of at least 50%. The energy of the secondary beam is of no importance. However, they would like to implant these ions in a silicon detector only 100μm thick so that the decaying protons can escape the implantation detector and be detected in surrounding detectors.

The tutorial walks you through the required steps to try to fulfill the experimentalists' requests:

I. Since you plan to use the A1900 fragment separator, you need to first configure LISE++ for this device (do it even though this is the default configuration, to see how it is done). This is done as follows:

   a. Start the program LISE++

   b. Select the menu *File* → *Configuration* → *Load*

   c. Choose the le "A1900_2013.lcn" in the NSCL directory

II. Try to guess the primary beam you intend to use to best produce the ^{22}Al.

   That includes energy as well as intensity. The available NSCL beam list is located at: http://www.nscl.msu.edu/exp/propexp/beamlist.

   You can calculate the yields obtained for several beams and see which gives the best result. For each beam, follow these steps:

   a. Set the projectile characteristics by clicking on the "P" letter of thelabel "Projectile" or alternatively selecting the menu *Settings* → *Projectile*. Notice that the projectile can be entered directly from the displayed table of nuclei by clicking "Table of Nuclides" in the dialog box. The projectile is then marked with a yellow band in the table of nuclei.

   b. Set the desired fragment to ^{22}Al by clicking on the "F" letter of the label "Fragment" or alternatively selecting the menu *Settings* → *Fragment*. Again it can be entered

directly from the table of nucleiby the same method as the projectile. The desired fragment is then marked with a white band.

c. Calculate the optimum target thickness for this combination of primary beam – desired fragment by selecting the menu *Calculations* → *Optimum target*. Click OK in the dialog boxes to select the default options and you should see two new windows, the one on top being the optimal target plot showing the rate of ^{22}Al as a function of target thickness. The green line corresponds to the thickness giving the maximum yield. The label above the curve indicates the conditions for the calculation as well as the results. Write down the maximum yield obtained with this beam as well as the corresponding optimum target thickness. Redo steps a, b and c above for other candidate primary beams.

III. Once the best primary beam is found, determining the optimum target thickness is redundant since it has been done previously for each candidate beam. The target thickness can be entered directly by clicking on the "T" letter of the label "Target" or alternatively selecting the menu *Settings* → *Target*. Another method is to click on  from the optimum target plot window, which automatically set the target thickness to the calculated optimum value. After the new target thickness has been entered, the settings of the fragment separator need to be calculated as follows:

a. Calculate the fragment separator settings by dicking on  or selecting the menu *Calculations* → *Tune spectrometer for setting fragment on beam axis*. The default A1900 configuration comes with a wedge thickness of zero so you should see the same values for the Bρ settings of D1, D2 and D3, D4.

b. Calculate the yield of ^{22}Al for these settings by double right clicking on the corresponding nucleus in the table of nuclei. The top yellow number you see is the yield in particles per second, and the bottom one is the total transmission efficiency of the fragment separator in %. You should see the same yield as the one written down for the chosen primary beam.

IV. At this point you should be able to assess whether or not the intensity request of the experimentalists may be reached at the NSCL. However, the experimentalists have also required stopping all the ^{22}Al fragments inside 100μm of silicon. This means that the momentum width of the secondary beam will be constrained by this requirement. So far the calculations have been performed with a momentum acceptance of the A1900 of 1% (indicated below the dp/p sign in the bottom left pane of the LISE++ main window). To check the implantation width requirement, you need to calculate the range distribution:

a. Determine the average range of the ^{22}Al fragments by clicking on

 or selecting the menu *Calculations* → *Goodies*. By default this window displays results for the chosen desired fragment.

b. In the "AFTER" middle pane, select "after D4" from the drop down menu to select the energy after the last dipole. The window then recalculates all results automatically.

c. The "Range to" button allows you to select in which material the range is calculated. Select silicon if it isn't already set. The program calculates the average range of the ^{22}Al fragments in silicon. Write down or remember the order of magnitude of this value (like 4000µm or 5000µm).

d. Dismiss the "Goodies" window and set the thickness of the "FP_PIN" detector to a value greater than the average range previously calculated (for instance 6000µm). To do this, click on the icon 

on the left list pane of the main window and change the thickness.

e. Plot the range distribution in that detector by selecting the menu *1D-Plot* → *Range distributions* and choosing "FP_PIN" from the drop down menu. You will see a square looking distribution showing the range distribution of ^{22}Al fragments in that detector. You can calculate the full width half maximum (FWHM) of the distribution by clicking on  which opens a new window with the results.

V. Does the implantation profile fulfill the 100µm requirement? Probably not! In that case you need to reduce the momentum acceptance of the fragment separator until it does. This is done by adjusting the horizontal slits at the dispersive focal plane, or Image2 in the case of the A1900. Note the implantation width obtained with the 1% full acceptance. The reduced acceptance should roughly scale with the implantation width. To adjust the momentum acceptance do the following:

a. Click on the slit display underneath the 

"Im2_slits" icon in the list pane. The horizontal slits are set to ±29.5mm (1%) by default. Set them to the desired value using either the cursor or by typing in the value. As you modify this parameter, the program automatically recalculates the corresponding momentum acceptance (see bottom left of window).

b. Repeat step e of last section to check the range width until you are close to 100µm FWHM. Note that the yield and transmission of ^{22}Al fragments have decreased accordingly when you closed the momentum acceptance.

VI. Is the rate of ^{22}Al fragments still above what the experimentalists want? Hopefully yes! If not they would have to make a compromise between the minimum intensity they want and the implantation width they require. Now you need to check the most difficult requirement, which is to obtain a beam purity of at least 50%. Without using any wedge,

many other fragments are transmitted through the A1900 using just the Bρ selection of the first half. In order to visualize all the transmitted fragments, you need to calculate their transmissions. One of the best ways to visualize the fragments selected by a fragment separator is to look at a spectrum of energy loss versus time-of-flight. LISE++ can simulate such a spectrum as well as many others.

a. First you need to reset the thickness of the "FP_PIN" silicon detector so that the fragments no longer stop in it (and it measures energy loss). A value of 300μm should be adequate.

b. Then click on  or select the menu *Calculations* → *Transmission and rate* → *All nuclei* to calculate all transmitted fragments.

c. Be patient! This calculation will take some time to finish. If you get really impatient you can interrupt it by pressing the ESC key.

d. Before generating any plots, you need to setup the correct parameters to be used. Select *2D-Plot* → *Plot Options* and fill in the following parameters if they are not already set to these values:

i. Default Dispersive Block for 'Brho'-plot (Tm): D1

ii. Default Dispersive Block for 'Wedge'-plot (mm): FP_slits

iii. dE – detector: FP_PIN

iv. Stop of TOF calculated: FP_PIN

v. Leave the other options at their default values

e. To generate the so-called ΔE-TOF identification plot, select *2D-Plot* → *dE-TOF*. The program displays the identification plot in a separate window. Each transmitted nucleus is represented by an ellipsis labeled by the nucleus. You should be able to clearly identify the N=Z vertical line of nuclei transmitted with the same time of flight, which clearly illustrates the Bρ selection of the fragment separator (ask yourself why). Notice the gap between ^{6}Li and ^{10}B in this line: ^{8}Be is unbound!

f. One of the great assets of LISE++ is the Monte-Carlo simulation of these 2D plots. Click on the button labeled "Monte Carlo" on the top right of the window. The program starts a live simulation of the spectrum, which shows better the relative intensities of the transmitted nuclei. Click "Stop" to interrupt the simulation. The labels might have been overwritten, but you can turn them on and off by clicking on  . Look for ^{22}Al on the plot. It definitely doesn't look like the most intense transmitted nucleus!

g. An important feature of the 2D plots is the possibility to calibrate them to be directly compared to online spectra. This is of great importance for the particle identification. Here is how to do it: click on  to bring up the calibration window. There you have

many choices to enter the correspondence between the physical units displayed on the plot and the channel numbers displayed on the spectrum. You can either directly enter a pre-calculated calibration, or type in 2 points corresponding to 2 nuclei you have identified from the tree-like pattern on the spectrum. To read the physical values corresponding to these 2 nuclei with LISE++, dismiss the calibration window and hover the mouse on the chosen nuclei: the program displays the locked in values once the nucleus appears in the yellow box on the right hand side of the window. To read the corresponding values on the online spectrum, refer to the lecture by R. Fox on the use of the NSCL data acquisition system. Once the calibrations in energy loss and time of flight have been correctly setup, you can directly compare the channel values displayed in the white box underneath the yellow one with those on the online spectrum. Note that in some cases you may have to invert the x axis (time of flight) to see a direct image of the online spectrum. To do this click on  . Keep this ΔE-TOF identification plot for later comparison by shrinking its window.

VII. Although you are producing enough ^{22}Al fragments for the experimentalists, they cannot use this radioactive beam because of the huge number of contaminants, which will overwhelm their detector setup. Note that some experiments do desire different nuclei in the same beam because they can arrange to study all of them at the same time. In that case the beam is labeled "cocktail radioactive beam". To calculate what fraction of the beam the ^{22}Al fragments make, divide their yield by the total intensity of the radioactive beam found on the bottom of the main window after the label "Sum=". You will find that the ^{22}Al fragments only make up a tiny fraction of the total intensity! To see how these contaminants make it through the fragment separator, follow these steps:

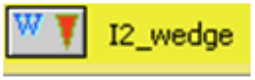
a. Click on  to calculate the Bρ selection plot. By default only the first 10 most intense contaminants are displayed (this can be changed in the options menu).

b. The momentum distributions of the fragments are displayed as a function of Bρ. As you can see, only tails of the contaminants make it through the momentum acceptance indicated by the two vertical green lines, but because their cross sections are so much larger than that of the ^{22}Al fragments, their yield still dominate the composition of the beam.

c. The momentum distribution of the ^{22}Al fragments is drawn in red and centered in the acceptance. To see it, you need to switch to a Log scale by dicking on  .

VIII. To try getting rid of these contaminants, you need to use an achromatic wedge at the dispersive plane of the fragment separator. Because each nucleus will loose a different amount of energy in that wedge, it will be refocused at a different location on the final focal plane of the fragment separator. The reason for using a wedge rather than a uniform piece of material is to preserve the dispersion of the fragment separator at the dispersive

plane, and hence the achromaticity of the whole fragment separator. The thicker the wedge, the greater the separation but also the greater the angular and energy stragglings. A good rule of thumb is to set the wedge thickness to roughly 20% of the total range of the desired fragment.

a. Set the wedge thickness by bringing up its window dicking on 

, after figuring out how thick it needs to be. Remember that the wedge is made of Aluminum when you calculate the total range of ^{22}Al fragments.

b. The A1900 uses a curved profile rather than a real wedge, because it can be made much thinner, and the curve is the same for all thicknesses. This profile is already loaded as an "internal profile" in the A1900 configuration file. Just make sure the "Curved profile" radio button is selected.

c. Dismiss the wedge windows and calculate the new settings of the fragment separator by clicking on  .

d. Calculate all transmitted fragments by clicking on  . You should observe a dramatic reduction of the number of contaminants. The fragments selected by the fragment separator now mostly lie on a vertical line of constant number of neutrons (N=9 isotones).

e. Take a look again at the ΔE-TOF identification plot and compare it to the previous one. The selected isotonic line is a subset of the whole identification tree that you have mostly eliminated, which is nice. However, now that this tree is gone, how can you tell which nucleus is which on your online spectrum? Here is where the calibration you made earlier becomes your life saver. By comparing the results of the LISE++ calculations with the wedge in place to the channels on your spectrum, you will be able to unambiguously identify the nuclei. Remember this during your last session with the A1900!

IX. The quality of your radioactive beam has tremendously improved, but it is still not up to the specifications of the experimentalists. If you calculate the fraction of ^{22}Al fragments in your beam, you should find something on the order of 1 to 2% only. Moreover, two of the main contaminants ^{21}Mg and ^{20}Na are β-delayed proton and alpha emitters respectively, which will swamp the detector setup with radioactivity, making it very difficult to extract the spectrum for ^{22}Al. To better understand the selection performed with the achromatic wedge, and try to improve it, it is useful to take a look at the wedge selection plot:

a. Click on  to calculate the wedge selection plot. You will see a plot of the beam spot images for each of the selected fragments, together with the current setting of the focal plane slits drawn in green.

b. Close the slits around the image of the ^{22}Al fragments to eliminate the contaminants located on the far sides of the focal plane, by clicking on 

below the "FP_slit" button to bring up their setting window.

c. Recalculate all transmitted fragments by clicking on  . Now only the N=9 isotones are transmitted. Recall the wedge selection plot to see the location of the contaminants' images. Clearly you cannot close the slits further without cutting into the ^{22}Al. Keep this plot for later comparison.

d. Try increasing the wedge thickness by a factor of 2 to further separate the contaminants. You need to recalculate the settings after the wedge as well as the achromatic wedge angle. Does increasing the thickness help?

e. Calculate another wedge selection plot and compare it to the previous one. You should see that you have indeed increased the separation between the ^{22}Al and its contaminants, but at the expense of the width of the images because of the additional straggling you have introduced by increasing the wedge thickness. The rate of ^{22}Al has therefore decreased and you would have to open the focal plane slits to recover all the ^{22}Al fragments, bringing the purity of your beam roughly back to the same as before. f. Reset the wedge thickness to its original value and redo the calculations.

X. You have reached the limit of purity you can achieve using both Bρ and wedge selections on a fragment separator. The N=9 isotones cannot be separated because their combination of A, Z and energy loss make the Bρ and wedge selections just about cancel each other. Can you think of a different selection criterion to purify the beam? Take a look again at the last ΔE-TOF identification plot. In which parameter do these isotones really differ?

XI. You got it! Their time of flights and therefore their velocities are very different. The best way to further clean the beam is to use a velocity filter, also called Wien filter, which is a device made of perpendicular magnetic and electric fields. Another method also using the differences in velocities of the fragments is to use an RF Separator, also called "RF Kicker" which takes advantage of the relationship between the phase and the velocity of the particles accelerated in a cyclotron. You probably know that particles accelerated in a cyclotron (or linac) are bunched in packets because they have to follow the phase of the RF electric fields that accelerate them. After the nuclear reaction which produces the radioactive isotopes, these particles keep this bunched structure, but only for a given velocity. Different velocities mean different time bunches, therefore an RF field locked on the cyclotrons will deflect these bunches differently. The NSCL RF Fragment Separator located in the S1 vault does just that, and can easily be added in LISE++. To add it to the A1900 configuration you have been using so far, do the following:

a. Open the setup window by clicking on 

. Select the "FP_PIN" material block in the block list, make sure the Insert Mode is on "before", and insert an RF separator. If you have made a mistake, you can either delete and re-insert the blocks, or move the selected one up or down in the list using the "Up" and "Down" buttons.

b. The program sets default values for the various parameters of the new blocks. You can use those for now. Click OK and the diagram as well as the block list on the left of the main window will show the new inserted block you have just added. Note that the default bending plane for RF separators is vertical.

c. Click on 

to open the control window of the RF separator. Most parameters are set to default values which are fine for our example, except for the "Tuning on Position" which should be set on "Maximum" rather than 0. This will set the RF phase so that the selected fragment will experience the maximum deflection from the RF cavity. Click OK and recalculate all settings, which will calculate the correct phase.

d. Recalculate all transmissions. Then select *2D-Plot → Plot TOF-Y*. This plot shows the vertical position of the various nuclei as a function of their time-of-flight. You can see the effect of the RF Separator as their position follows a sine wave. Do a quick Monte-Carlo simulation to see better the vertical size of the beam for the ^{22}Al isotopes and note the values you would like to close the slits to get rid of the contaminants.

e. You can now close the slits at the RF Separator to effectively apply the new selection. Like for the wedge, click on the slit indication located just below the RF Separator button in the list of blocks, and set the vertical slits to the chosen values. Do not forget to select the "Use in Calculations" box for the "Vertical plane" if it isn't already. f. Recalculate all transmissions once more. You should now see the effect of closing the slits after the RF Separator. You can also plot the vertical position as a function of time-of-flight again to see why there are still some contaminants in the beam.

g. The main contaminant should be ^{18}F, because it undergoes the same deflection as ^{22}Al in the RF Separator. This in turns happens because the phase difference between those two nuclei is just about 360°. Can you think of a way to alter this difference and hence eliminate ^{18}F? What consequences this might have on the transmission of other contaminants?

XII. **Congratulations**! You are done! You can recalculate the fraction of ^{22}Al fragments in the beam, which should be at least 50% while still keeping the minimum yield of 1000 particles per second. You will need to contact the experimentalists and tell them that the only way to achieve their radioactive beam objectives is by using an RF Separator in combination with the fragment separator.

The program LISE++ contains many more features and options than those described in this tutorial. You are strongly encouraged to experiment with them and see the effects they have on the results. A very large amount of physics is incorporated in this program, from projectile fragmentation models, cross section systematics, electron stripping models, energy loss models to beam optics, just to list a few. All the references of the works the calculations are based on are directly accessible within the program itself (see the various option windows) and you are encouraged to consult them for further understanding.

The LISE++ name is obviously borrowed from the well known evolution of the C programming language, and is meant to indicate that the program is no longer limited to a fixed configuration like it was in LISE, but can be configured to match any type of device or add to an existing device using the concept of blocks, as is demonstrated in this tutorial by adding a Wien filter and compensating dipole to the A1900 fragment separator.

The program is constantly expending and evolving using the feedback of users around the world. At the time of this writing, many "satellite" tools have been incorporated into the LISE++ framework, which are accessible with buttons on the main toolbar and include:

1. Physical calculator
2. Kinematics calculator
3. Evaporation calculator
4. Units converter
5. Stripper foil lifetime
6. The program PACE4 (fusion-evaporation code)
7. Spectrometric calculator by J. Kantele
8. The program CHARGE (charge state distributions)
9. The program GLOBAL (charge state distributions)
10. The program BI (search for 2-dimentional peaks)

A few references:

LISE++ web site: http://lise.nscl.msu.edu

LISE publications :

1. The program LISE: a simulation of fragment separators, D. Bazin, O.Tarasov, M. Lewitowicz, O. Sorlin, Nuclear Instruments and Methods in Physics Research A 482 (2002) 307-327

2. LISE++: Design your own spectrometer, O. B. Tarasov, D. Bazin, NSCL preprint MSUCL-1248, November 2002

3. Development of the program LISE: application to fusion-evaporation, O.B. Tarasov, D. Bazin, Nuclear Instruments and Methods in Physics Research B 204 (2003) 174-178

4. The code LISE: a new version for "Windows", O. Tarasov, D. Bazin, M. Lewitowicz, O. Sorlin, Nuclear Physics A 701 (2002) 661c-665c

5. Transport Integral: a method to calculate the time evolution of phase space distributions, D. Bazin, B. M. Sherrill, Physical Review E 50 (1994) 4017

*** The latest official publication on the LISE++ program is:**
"LISE++ : Radioactive beam production with in-flight separators",
O. B. Tarasov and D. Bazin, NIM B 266, (2008) 4657-4664.