BEAM PURITY STUDIES FOR A FACILITY FOR RARE ISOTOPE BEAMS*

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Abstract

An exotic beam facility for the production of rare isotopes such as the Facility for Rare Isotope Beams (FRIB) [1] at Michigan State University will require a high resolution fragment separator to separate isotopes of varying mass and charge. The goal of the fragment separator is to produce a high-purity beam of one rare isotope. Sources of contamination in a beam such as this are isotopes with a similar magnetic rigidity to the separated isotope and those which are produced by fragmentation in the energy degrader. This can be particularly detrimental when a contaminating isotope has a large cross section. Here we investigate beam purity as a function of the separated isotope and the type of fragment separator setup used, i.e. one stage, two stage, or one stage with gas cell branch.

SEPARATION PURITY

The separation purity is perhaps the most important quantity that describes the fragment separator since it describes separator's ability to select one isotope from all others. The separation purity P of the system is given by the ratio of the number of particles of the selected isotope to the number of particles of all other isotope types at the end of a separation stage:

$$P = \frac{\#\text{ of Particles of Selected Isotope}}{\#\text{ of Particles (All Isotope Types)}}. \qquad (1)$$

This quantity depends on many things which are not explicit in this expression. First, the optics of a fragment separator system must be optimal to focus the separated isotope in as small of a region in x as possible [2,3]. The ability to do this differs according to the isotope and the reaction mechanism by which it is produced. The primary beam also plays a role in producing the background impurities (type and quantity) that exist. If the primary beam is of a low Z (nuclear charge), the background impurities produced must have Z lower than this and the resulting impurities will only be within a small region of the N-Z plane. Here, N is the number of neutrons in the nucleus. If, however, a high Z beam such as uranium is used the range of contaminating isotopes produced is vast. Also, a radioactive beam such as this will produce background that would not otherwise be seen with a fragmentation-only beam. The addition of fission as a production mechanism leads to an even broader range of isotopes produced and, in addition, these production rates are dependent on the energy of the primary beam

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There are four general reaction mechanisms that take place in the production target. Each of these, because of the energy and mass of the isotope to be separated, has different beam dynamics and background that either complicate or make the separation easier. These mechanisms represent the extremes of the dynamics in the separator. All other isotope production mechanisms fall between these extremes in beam dynamics. For each of these four reaction mechanisms, one isotope was selected to be studied in detail. Each is a rare isotope that is of interest to nuclear physicists that will be studied when a FRIB comes online. In these cases, the energy of the beam is limited by the parameters of the FRIB linear accelerator. The maximum energy that a primary beam attains is a ^{238}U beam at 200 MeV/u. Lighter primary beams can be accelerated to a higher energy. The optimal target and wedge thicknesses in each case are computed using the program LISE++ [4]. The optimization is done for a one stage setup with the second stage having the same wedge thickness as the first in terms of fraction of range of the rare isotope beam. Also, since a thick wedge is used in the gas cell branch of the fragment separator, secondary fragmentations occur and alter the separation purity. The gas cell branch is a difficult problem because any contamination that is produced in the wedge can end up in the gas cell along with the separated isotope. There is no additional rigidity selection by a dipole after the monochromatic wedge. Only range selection in the He gas cell can be used for separation. All gas cell branch calculations are for a wedge that is 70% of the rare isotope's range in aluminum.

RESULTS

A hybrid map- Monte Carlo code developed within COSY INFINITY [5] has been used to calculate the separation purity of various isotopes. The separation purity results from the four rare isotope production mechanisms are presented here. These are light fragmentation, where light products are emitted from the target in a relatively small phase space cone, fitting well within the acceptance of the fragment separator. Heavy fragmentation products are emitted in an even smaller cone. All fission products are emitted in a large phase space cone due the extra energy release. This release leads to a wide range of δ and angular coordinates that can be quite large for light isotopes and smaller for heavy isotopes. As the energy of the primary decreases, the size of the cone increases. The purity for each case is computed for a one and two stage separator. Also, results for a one stage separator with gas cell branch are presented.

Light Fragmentation

^{14}Be is one isotope that is produced by light fragmentation. The primary beam is ^{18}O beam at 305 MeV/u that fragments on a 5000 mg/cm² Li target. The wedge was 10,000 mg/cm² thick, which is 21% of the range of the rare isotope beam in aluminum. Of the rare isotopes used as test cases, ^{14}Be is the easiest to separate. Since it is of low Z, the number of background contaminants produced is small. Also, it has a relatively large cross section. The separation purity after one stage is 100%, so only one separation stage is needed. The transmission after one stage is 91%. The slit setting in *x* at the end of the first stage is 2.5 cm.

When the gas cell branch of the separator is added, the separation purity is slightly decreased due to fragmentation of ^{14}Be in the thick monochromatic wedge. There is only one contaminant that is produced, which is ^{11}Li. This brings the separation purity down to 96.77% in this case.

Heavy Fragmentation

^{100}Sn is produced by a 245 MeV/u ^{124}Xe primary beam. For the described studies a 450 mg/cm² target and 700 mg/cm² wedge (44% of range) were used. The separation of ^{100}Sn should not be difficult if only the dynamics are considered. A fragmentation product that is heavy emerges from the target with very small angular and energy divergence. For this reason, any aberrations at the end of one stage will be very small, which corresponds to a small beam spot. Since the beam is small at the end, the slit needed to capture the maximum number of ^{100}Sn should also be small. Unfortunately, there is another isotope, also a heavy fragmentation product that has almost the exact rigidity of ^{100}Sn, namely ^{99}In. This means that the two isotopes essentially are overlapping at the end of the separation stage. To add to the difficulties, ^{99}In has a much larger cross section than ^{100}Sn by two orders of magnitude. So, while the dynamics of a ^{100}Sn beam alone would make for a good separation, the identical rigidities and large cross section of the contaminant make it impossible to separate at the energies of the proposed FRIB. This case could be improved at higher energies because the separation cut angles [3] after each separation stage could be rotated so that the intersection chooses mainly ^{100}Sn.

The first stage separation purity for ^{100}Sn (Figure 1) is 7.73×10^{-7}. This corresponds to a slit setting in *x* of 4 mm. In order to rotate the separation cut angle as much as possible at the specified energy, a very thick wedge (80% of range) is used in the second separation stage. The separation purity and slit settings are 7.5% and 2.3 cm, respectively. While having a thick wedge in the second stage does not solve the separation problem entirely, it does improve the separation purity by one order of magnitude compared to the case where a thickness of 44% of the range in the second stage is used. The transmission is 40.5% after the first stage and 11.6% after the second.

The separation purity is not good in the case of the gas cell branch, 1.48×10^{-5}%, mainly because a significant fraction of the ^{99}In is let through. This isotope fragments in the monochromatic wedge and since there is only one and a half separation stages, this leads to much contamination at the end.

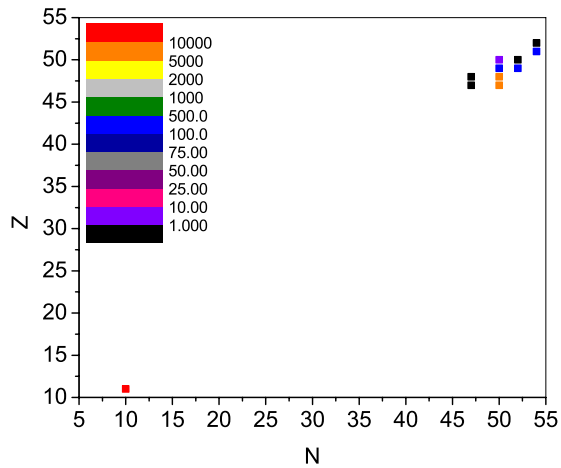

Figure 1: Distribution of isotopes that remain after the one stage separation of ^{100}Sn. Remaining isotopes are plotted in the N-Z plane. The quantities of the isotopes at the end of the system are indicated by the color of the box with all isotope quantities scaled such that one ^{100}Sn particle is at the end of the separation stage.

Light Fission

^{78}Ni is a light fission product that is produced by a 200 MeV/u ^{238}U primary beam. Due to the fact that ^{78}Ni is produced by fission and is light, it is very difficult to separate. In the optimized setup, a 125 mg/cm² Li target and 800 mg/cm² Al wedge were used. Despite the optimization performed to increase the separation purity, it is only a dismal 2.79×10^{-4}% after the first separation stage. The transmission was 13.1%. For this stage a slit setting of 1 cm in *x* was used. For the second stage, a wedge equal to 80% of the range was used with a slit setting in x of 5 cm. This resulted in a separation purity of 3.64×10^{-3}% after two separation stages. The second stage transmission was 6.1%.

While a thick wedge directly results in better mass and charge resolution, it has the downside of added straggling. For this reason, a thinner wedge (40% of the range) was

used to try to improve the separation purity, however, this endeavor was not successful. The separation purity after two stages is just 5.89×10^{-4}%. It is necessary to keep a thick wedge in the second stage to keep close to maximum resolution. The gas cell branch yielded a separation purity of 2.94×10^{-4}% and a transmission of 24.8%.

Heavy Fission

^{132}Sn is a heavy fission product that is produced by the fission of a 200 MeV/u ^{238}U beam. To produce this beam, a 125 mg/cm² target and 800 mg/cm² wedge in the first stage were used. The slit setting in *x* at the end of the first stage was 2 cm to capture the bulk of the ^{132}Sn going into the second stage. The second stage contained an Al wedge equal to 49% of the range and had a slit setting in *x* of 2 cm. The separation purity at the end of the first stage was 1.15% with a transmission of 19.18%. The second stage improves the separation purity to 4.04% (Figure 2). This also translates into greater transmission losses with a decrease to 3.2%. The gas cell branch has a separation purity that is almost identical to a fist stage separation at 1.52%. The transmission in this case is 17.6%.

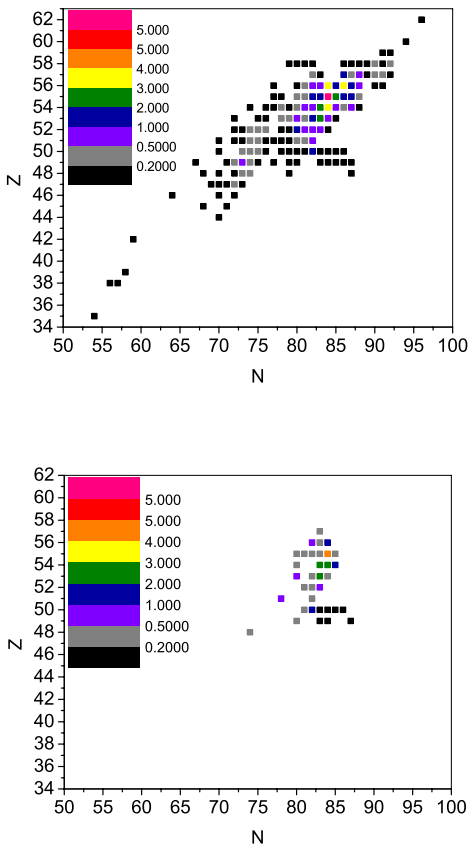

Figure 2: Distribution of isotopes that remain after the one stage (above) and two stage (below) separation of ^{132}Sn. Remaining isotopes are plotted in the N-Z plane.

^{199}Ta is also a heavy fission product of great interest. This isotope was produced by the fission of a 200 MeV/u ^{238}U beam incident on a 850 mg/cm² target. The first stage wedge was 350 mg/cm², which corresponds to 70% of the range. In this case it was advantageous to increase the thickness of the wedge in the second stage to 80%. After a one stage separation, the separation purity is 8.35×10^{-3}% with a transmission of 18.8 %. The second stage increases the separation purity significantly to 10.8% and the transmission is decreased to 7.9%. The gas cell branch has a separation purity of 6×10^{-2}% and a transmission of 30.34%.

CONCLUSION

Using the recently developed hybrid map-Monte Carlo code within COSY INFINITY, the separation purity of many rare isotopes has been calculated for four types of production mechanisms representing the extremes in beam dynamics. The results yielded 100% purity for a one stage separation of ^{14}Be, a light fragmentation product. For ^{100}Sn, the separation purity is 7.5% after two separation stages, with only one contaminant. The heavy fission product, ^{132}Sn, has a separation purity of 4.04% after two stages. The light fission product, 78Ni is challenging to separate with a separation purity of only 0.003% after two separation stages. Separation purity with the gas cell branch has also been computed with each of these isotopes. Future work will focus on more detailed optimization to find the best fragment separator settings for rare isotopes to be captured for experiment.

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