Nuclear Astrophysics with Radioactive Beams

Big Bang Nucleosynthesis.

Most of the reactions which are of importance to the nucleosynthesis in the BB involve stable nuclei and have been studied extensively in the past. In some models describing the transition from the quark-gluon to the hadronic phase density inhomogeneities are predicted which might lead to the production of heavier elements up to about C. The reaction path in this network proceeds through short-lived nuclei (e.g. ^{8}Li, ^{8}B) which have been studied at some laboratories. The temperatures involved are sufficiently high so that the reactions can be studied in the relevant energy range. Although the first data are sometimes contradictory it can be assumed that during the next few years the reaction rates will be studied at existing facilities.

Quiescent Hydrogen Burning.

The reactions during the quiescent burning phase occur on such a slow rate that unstable nuclei have sufficient time to decay into their stable isobars. One of the critical reaction is ^{7}Be(p,γ)^{8}B which is actively studied at various places worldwide. It can be expected that this reaction rate will be known with sufficient accuracy when RIA will be operational.

Explosive Nucleosynthesis.

The network of nuclear reactions occurring in stellar explosions proceeds to a large extent through regions of unstable, short-lived nuclei that have long since decayed in our galaxy. A considerable fraction of the elements and isotopes that make up the variety of every-day life on earth are therefore daughters and granddaughter of the nuclei that existed for a brief period in the history of our galaxy. In that sense the amount of the stable elements and isotopes present on earth depends on the properties of many unstable nuclei through which the reaction network proceeded. This process is still ongoing, as shown by the observation of several isotopes with relatively long half-lives (e.g. ^{22}Na, ^{26}Al, ^{44}Ti, ^{60}Fe..) which have been detected recently in gamma-ray surveys of the sky. These radioactive elements provide important 'markers' in the reaction network and thus can give a detailed information of the reactions processes which occur at the end of a star's life. Next-generation satellite-based telescopes will push the detection limits to stars at even larger distances and to shorter-lived nuclei.

Hundreds of nuclei are involved in this process and therefore it is not possible to single out one dominating nuclear reaction which can only be studied at a future RIA facility. There are a some reactions that play a larger role in the production of a particular nucleus (as seen e.g. for ^{44}Ti) but in general it is the whole network of reactions that needs to be considered. The reactions occurring in quiescent burning have (with one exception) been measured at higher energies and are then extrapolated into the energy range of interest. In explosive nucleosythesis on the other hand the temperatures are in most cases high enough that the relevant reactions can be studied at the appropriate energies which eliminates the problems associated with extrapolations.

Among these hundreds of reactions a good fraction can probably be estimated on theoretical grounds. Experience has shown, however, that there are always surprises even for cases that were thought to be well understood.

Presently very few of the reactions producing these short-lived are accessible to studies in the laboratory. Only during the last ten years experiments with radioactive beams performed at first generation facilities have put some of the rates occurring in the reaction network on more solid ground. In many cases these new data have changed the reaction rates by orders of magnitude, when compared to previous, pure theoretical estimates.

Proton-rich Nuclei.

The majority of the reactions in a given network involves radiative capture reactions, e.g. (p,γ), (α,γ) and (n,γ) which generally have only very small cross sections. Thus, measurements of excitation functions with high precision beams, which were crucial in the early days of nuclear astrophysics and have provided important information for the understanding of nuclear burning in younger stars, can not be performed with the first generation radioactive beams. Only for very special systems where the nuclear structure was well understood (e.g. ^{14}O or ^{8}B) has astrophysical relevant information be obtained.

Measurements of excitation functions for reactions with cross sections below $\sim$ 1μb can only be performed with high quality beams with intensities above $\sim 10^9$ particles/sec. Present-day experiments due to their low intensities were only able to give upper limits for the (p,γ) cross sections. Thus it is in this area where a next generation rare isotope accelerator can provide improvements by many orders of magnitude.

Fig.1 gives the yields expected at the RIA facility for nuclei which are of interest to the rapid-proton capture process. Superimposed on the color-coded yields is the rp-process path expected for a nova event, i.e. reactions occurring when proton-rich material from a companion star falls onto the surface of a white dwarf. It is clear that for the first time we will have beams with excellent qualities (spot size, energy definition and emittance) and with sufficient intensities so that detailed excitation functions for important radiative capture reactions can be measured.

Of particular interest are proton capture reactions on ^{23}Mg, ^{27}Si, ^{31}S, ^{35}Ar and ^{39}Ca. (p,γ) reactions on these nuclei control the breakout from the various cyclic reaction (e.g. NeNa cycle, MgAl cycle, SiP cycle..) and due to the small Q-values they strongly depend on the nuclear structure of the compound nucleus. RIA will produce beams of these nuclei with intensities between 10^{10}–10^{12} particles/s. Together with the high detection efficiencies which can be achieved by detecting the heavy reaction product in a high acceptance recoil separator improvements by about a factor of 10^6 compared to present capabilities can be expected.

(in here we could add a page describing one experiment of XX(p,γ)XX+1 using numbers obtained at the FMA. I estimate that with a 1 pnA beam one can measure resonance strengths down to a few hundred μeV) which are values that are done today in experiments with stable beams.

Other examples where the underlying nuclear structure has hindered the progress in this field are the reactions ^{21}Na(p,γ)^{22}Mg and ^{25}Al(p,γ)^{26}Si. Because of the ground state spins of the target nuclei these capture reactions populate states of unnatural parity in the final nuclei which are difficult to identify in reactions with stable beams. (^{3}He,d) or (d,n) reactions measured with particle-nA beams for these systems will provide this information within running times of hours. Presently these experiments require weeks of running time.

A good example of this situation is the recent measurement of the location of the 3^+ state in ^{18}Ne performed at ORNL. This state which had been searched for in several experiments could only be located via the ^{17}F + p reaction and has lead to a modification of the reaction rate by xx orders of magnitude, compared to earlier estimates.

Another example is the $^{15}O(\alpha,\gamma)^{19}$Ne reaction that controls the breakout from the (hot) CNO cycle into heavier nuclei which are produced by the rapid proton capture process. Measurements of this reaction have been attempted, so far unsuccessfully, in at least seven different laboratories worldwide, using direct and indirect approaches. The parameters of this reaction and the resulting cross sections are so small that even beams of 1 particle nA are not sufficient. The high intensities for ^{15}O beams expected at the next generation RIA facility ($\sim$ 100 pnA) will perhaps for the first time provide the possibility for a direct measurement of this reaction which is crucial for the formation of elements heavier than Z=8.

Because of their long half-lives ^{44}Ti($T_{1/2}$=59y), ^{56}Ni($T_{1/2}$=6.1d) and ^{56}Co(78d), play a central role in supernova explosions. The amount of ^{44}Ti and ^{56}Ni produced in these events depends strongly on cross sections of the reactions that produce and those that destroy it. Because of the lower absorption of the gamma rays emitted by these nuclei (and their daughters) young supernovae remnants can be observed even if the optical observation is obscured by interstellar dust. Among the many reactions that control e.g. the production of ^{44}Ti is the $^{45}V(p,\gamma)^{46}$Cr reaction which depends on resonant states in ^{46}Cr. Presently no information exists about excited states in ^{46}Cr and high-quality beams with sufficient intensity (e.g. ^{45}V) for a spectroscopic study of this T_z=-2 nucleus are not available. The beam intensity for ^{45}V and other beams in this mass region at a future RIA facility would be of the order of 10^9 enabling for the first time a detailed study of astrophysical reaction rates in the critical region between the ^{28}Si and the ^{56}Ni 'islands'.

Nuclei in the vicinity of the proton drip-line above ^{56}Ni play an important role in the rapid-proton capture process at higher temperatures which occurs e.g. on so-called X-ray bursters or X-ray pulsars. The reaction path in such a network is shown in Fig.2 superimposed on the production yields predicted by a 400 MeV/u facility. Due to the structure of the proton drip-line in this mass region the reaction flow at the even N=Z nuclei (e.g. ^{72}Kr, ^{76}Sr, ^{80}Zr,..) has to wait for a

β decay, unless the transition through the next (odd-Z) proton unstable nucleus can be bridged by a two-proton capture reaction. This requires studies of proton-unbound nuclei e.g. ^{69}Br, ^{73}Rb,..which have predicted half-lifes below 100 ns. As shown by the dashed line which represents the production yields of 1 particle/min. mass measurements with accuracies of 10^{-6} can be obtained for all relevant nuclei in this mass region.

Traditional experiments of proton-radioactivity are limited by the time of flight ($\sim$xx ns) through the spectrometer used to separate the reaction products from the primary beam. Recently, experiments have been performed with Si detectors in a much closer geometry which reduced the flight time of the reaction products to xx ns. The availability of proton-rich beams of ^{34}Ar at RIA would allow to produce and study e.g. ^{73}Rb via the strong 1p channel (cross sections of $\sim$ xx mb) with a ^{40}Ca target and a ^{34}Ar beam at intensities of 1 particle nA. (we might use another reaction)

Another route to study the structure of the proton-unbound ^{73}Rb would be via the (^{3}He,d) reaction on ^{72}Kr at energies of about 5 MeV/u. This beam should be available at RIA with intensities of several 10^{7} particles/s which is about 2-3 orders of magnitude more than what was used in a recent (^{3}He,d) experiment with a radioactive ^{56}Ni beam at ATLAS. Similar experiments can be performed for other odd-Z nuclei in this mass region.

(in here example for ^{72}Kr(^{3}He,d)^{73}Rb with count rates based on our ^{56}Ni experiment).

These measurements will give crucial information on the energy production during a X-ray burst and on the thermal structure of the surface of a neutron star.

Neutron-rich Nuclei.

About one half of the nuclei heavier than ^{56}Fe is produced through the so-called r-process, a rapid sequence of neutron capture reactions followed by beta decays which is thought to occur in a type II supernova in the neutron-rich shell outside the central proto-neutron star. The path of this process proceeds through a region of neutron-rich, exotic nuclei that to a large extent have never been produced in the laboratory. Only in the vicinity of the closed neutron shells (N=50,82,126) the reaction flow approaches the valley of stability sufficiently far that some nuclear structure information could be obtained at ISOLDE. A better understanding of the r-process would allow to determine the age of a star from a measurement of the optical lines of the heavy elements (Th,U), relative to the strength of e.g. the stable rare earth lines.

For most nuclei involved in the r-process the information that is needed are half-lives and masses with accuracies of better that 10^{-6}. This accuracy can (only?) be achieved with a Penning trap using stopped beams with intensities down to 1 particle/min. Because practically no experimental information is available for these exotic nuclei the ability of RIA accelerating U up to 400 MeV/u will bring orders of magnitude improvements.

A 100 MeV/u machine limited to beams with A<40 can produce neutron-rich isotopes of non-refractory elements only through fission of U. Since the secondary exotic nuclei have to effuse from the production target only certain elements (Rb, Kr, Cs, Xe, Sn..) with half-lives longer than ∼1s can be produced with good efficiencies. The ability to use in-flight fission of U and separating the fragments in a mass separator followed by a gas stopper results in much higher yields, especially for exotic, short-lived isotopes, independent of their chemical properties.

Fig.3 shows the stable nuclei (squares), the limits of production yields (1 particle/sec) estimated for a 100 MeV/u facility limited to masses up to A=40 (dotted line) and the yields (1 count/min) using in-flight-fission of a 400 MeV/u U beam (dashed line). The solid line is the limit for nuclei expected to be produced with intensities of 5×10^3 particles/s which are needed to study neutron-adding reactions (e.g. (d,p)) (see below). The green line gives the estimated path of the r-process taken from Ref.xx

There are several important points that can be observed from Fig.3.

- Compared to the yields achievable at a 100 MeV/u facility which is limited to non-refractory elements and isotopes with half-lifes of ∼1s (see dotted line), a 400 MeV/u facility extends the range of neutron-rich isotopes by about 10 units, covering all the elements.
- There is a large overlap between the r-process region and the limits up to which accurate mass and half-life measurements will be possible (dashed line)at a

400 MeV/u facility. This includes for the first time the nuclei along the N=126 neutron shell which produce the A=195 mass peak in the abundance curves, as well as the nuclei that ultimately decay into the doubly magic nucleus ^{208}Pb.

Even for nuclei where the r-process path can not be reached RIA will extend mass measurements towards the neutron drip-line by about 10(??) neutrons. These new data can then be put into theoretical extrapolations which are still needed for very heavy nuclei.

In addition to masses and half-lives there is also some need to measure radiative neutron capture cross sections which play a role towards the end of the event during the freeze-out. Because of the short lifetimes of these nuclei these rates can not be measured at a spallation neutron source. However, because of the relationship between the (n,γ) yields and the low-spin level structure measured e.g. in neutron-adding reactions such as (d,p) which has been studied extensively in the early days of (d,p) transfer reactions, inverse reactions induced by heavy nuclei incident on a deuterium target can be used to obtain information about the neutron capture yields. The signature of a low angular momentum transfer in this case is a large cross section for the protons emitted at backward angles (small angles in the c.m. system). These measurements require a beam with good qualities (emittance, beam spot size and energy definition) and with intensities of at least 5x10^3 particles/sec.

Fig.4 shows production rates for nuclei at the N=50, 82 and 126 neutron shells. The rates of 5×10^3/sec and 1/min are indicated by the horizontal lines. From this figure one can see that practically all the N=50 r-process waiting point nuclei $\geq$Cu are accessible to neutron transfer measurements. Along the N=82 line mass measurements down to Ru should be possible while neutron transfer can be studied for nuclei $\geq$Ag. For the yet unexplored neutron-rich N=126 line mass measurements above Z=70 (^{196}Yb) should become possible.

(For the r-process we could elaborate on 2 experiments: i) mass measurements on ^{126}Ru (production yield 10/sec) or another case, ii) (d,p) on ^{130}Cd (yield 10^5/s) to get information on the (n,γ) cross section.) a similar example might be used in connection with the structure around ^{132}Sn.

Equation of State.

I haven't found a good example where low energy reactions can contribute to the EOS. The fragmentation people talk in length how they will get the EOS from the sideward flow, but I guess this is very model dependent and probably not well accepted in the community. Monopole excitations are probably the best way of studying that, but they require higher energies and higher intensities.

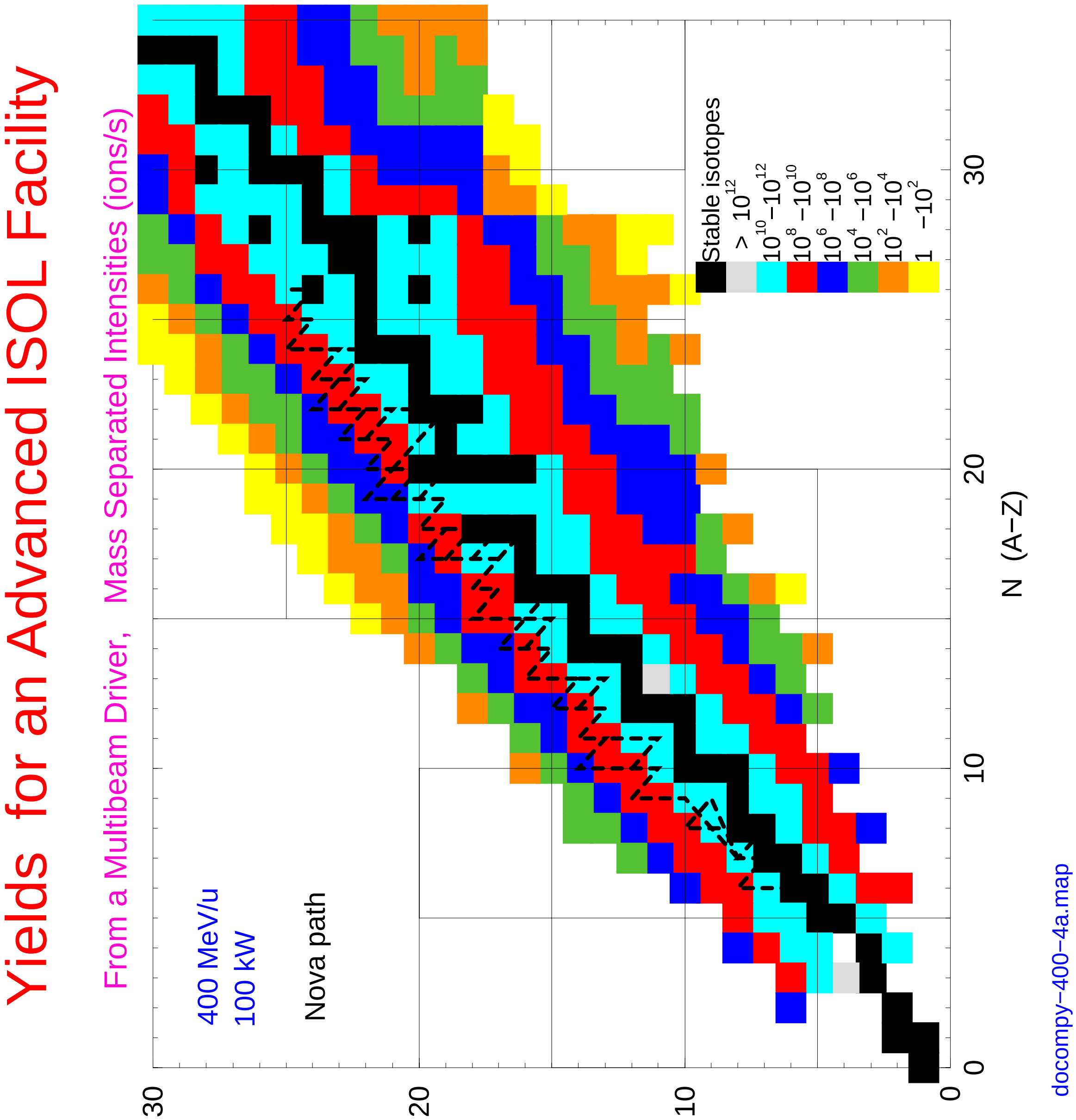
Yields for an Advanced ISOL Facility
From a Multibeam Driver, Mass Separated Intensities (ions/s)
400 MeV/u
100 kW
Nova path
Stable isotopes
> 10^12
10^10–10^12
10^8 –10^10
10^6 –10^8
10^4 –10^6
10^2 –10^4
1 –10^2
N (A–Z)
Z
0
10
20
30
docompy-400-4a.map

Figure 1:

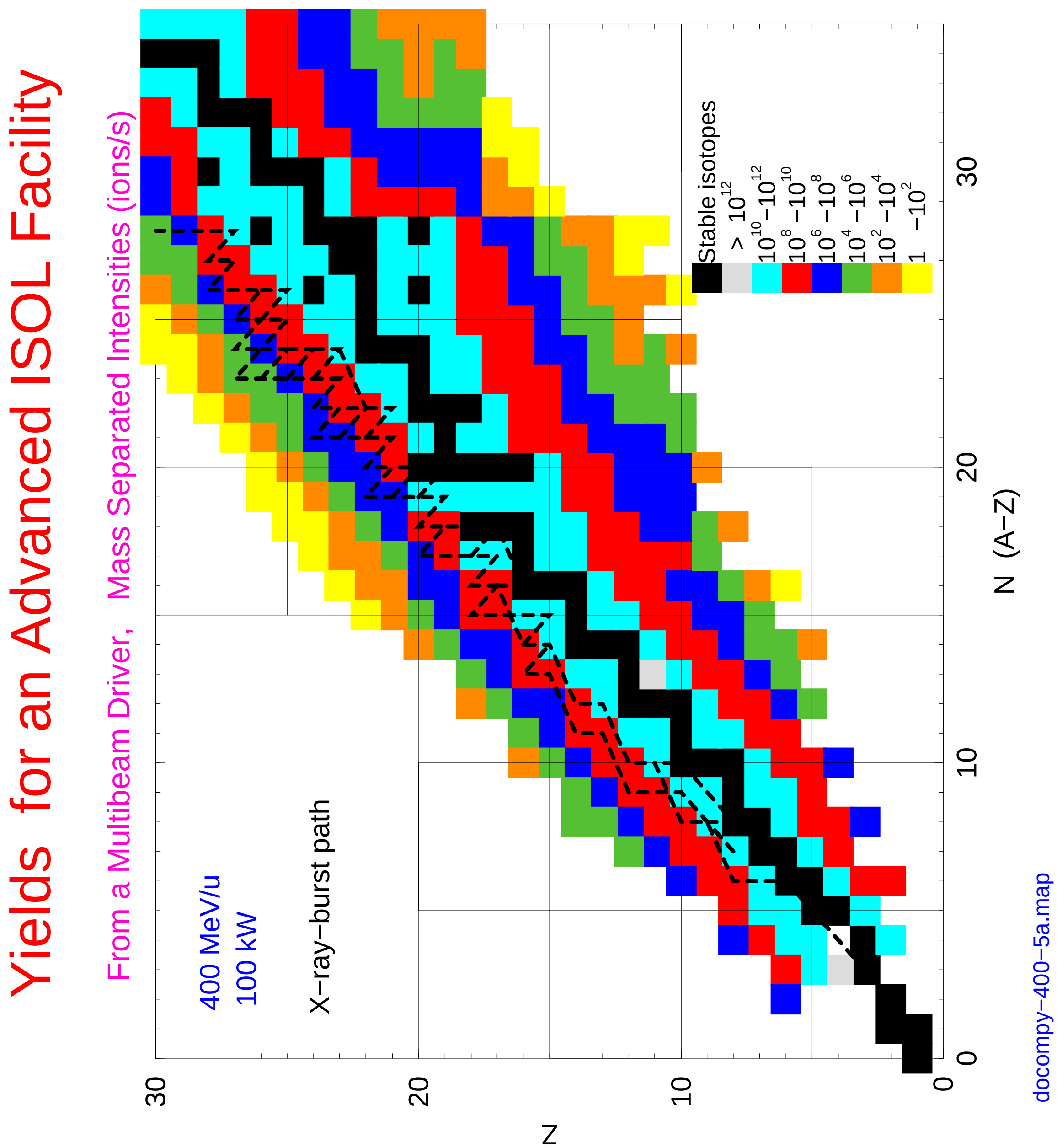
Yields for an Advanced ISOL Facility
From a Multibeam Driver, Mass Separated Intensities (ions/s)
400 MeV/u
100 kW
X−ray−burst path
Stable isotopes
> 10^12
10^10−10^12
10^8 −10^10
10^6 −10^8
10^4 −10^6
10^2 −10^4
1 −10^2
N (A−Z)
Z
docompy−400−5a.map

Figure 2:

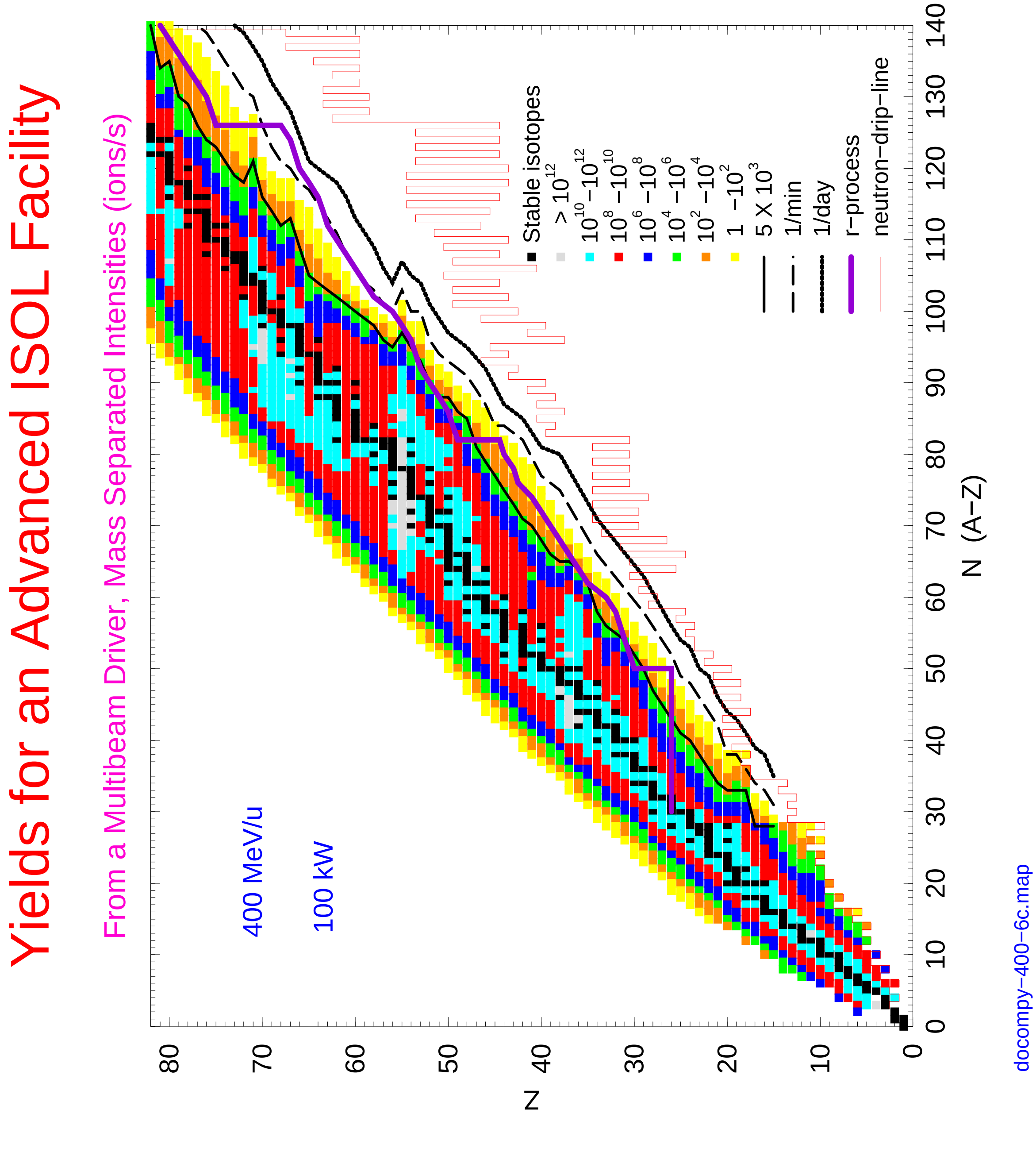
Yields for an Advanced ISOL Facility
From a Multibeam Driver, Mass Separated Intensities (ions/s)
400 MeV/u
100 kW
Stable isotopes
$> 10^{12}$
$10^{10} - 10^{12}$
$10^{8} - 10^{10}$
$10^{6} - 10^{8}$
$10^{4} - 10^{6}$
$10^{2} - 10^{4}$
$1 - 10^{2}$
5×10^{3}
1/min
1/day
r−process
neutron−drip−line
N (A−Z)
Z
docompy−400−6c.map

Figure 3:

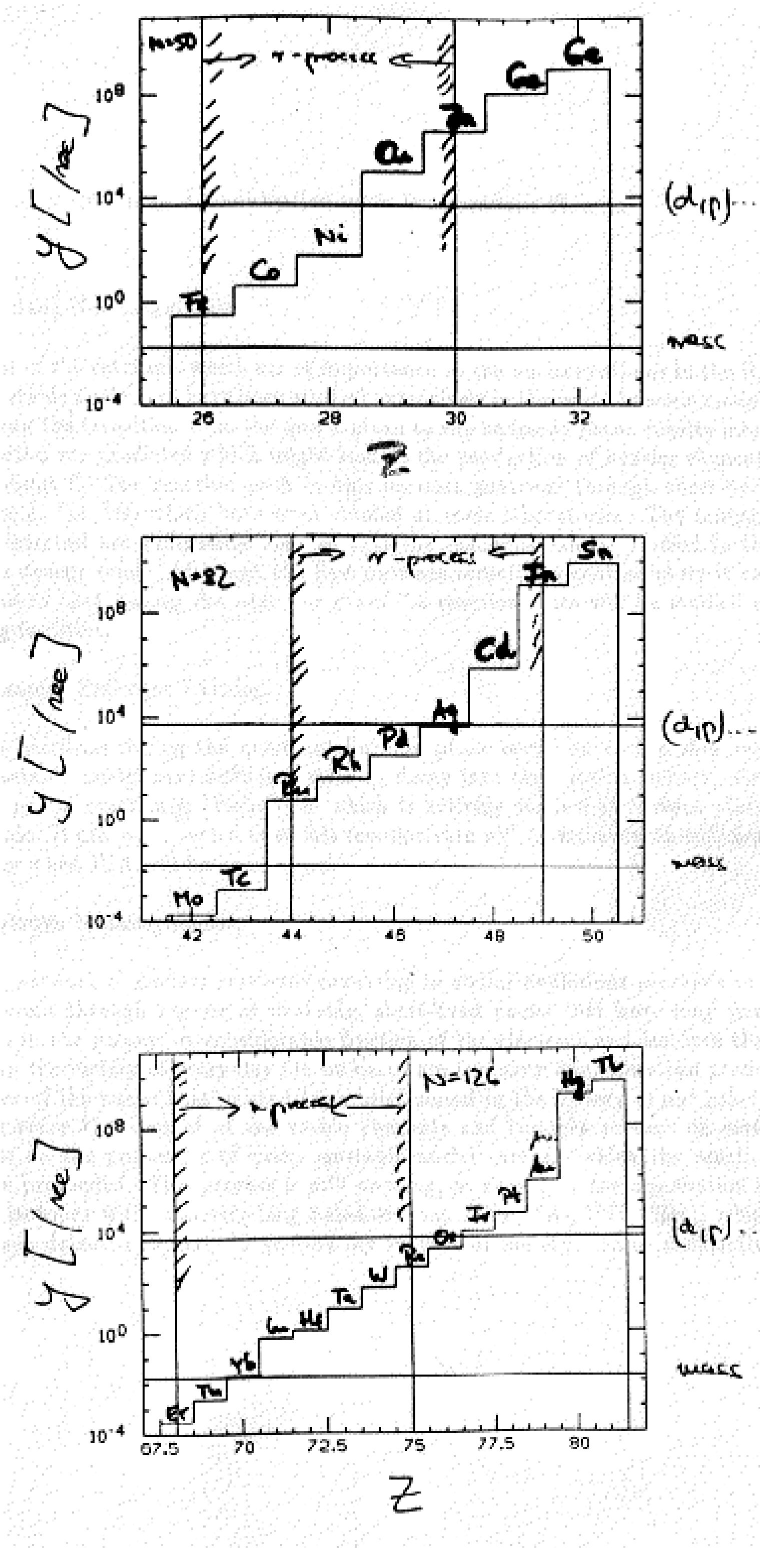
N=50
r-process
Fe
Co
Ni
Cu
Zn
Ga
Ge
(d,p)...
mass
26
28
30
32
Z
N=82
r-process
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
42
44
46
48
50
N=126
r-process
Er
Tm
Yb
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
67.5
70
72.5
75
77.5
80
Z

Figure 4: