Projectile Fragmentation of ^{86}Kr -- Comprehensive cross-section measurements including the proton-removal chain up to ^{79}Cu

Betty Tsang	NSCL	Professor	517-333-6386
Michal Mocko	NSCL	Graduate Student	517-333-6469
Bill Lynch	NSCL	Professor	517-333-6319
Mike Famiano	NSCL	Research Associate	517-333-6427
Oleg Tarasov	NSCL/Dubna	Visiting Scholar, NSCL	517-333-6320
Hui Hua	Peking University	Associate Professor	
Hiroyoshi Sukarai	University of Tokyo	Professor	
Nori Aoi	Riken		
Motobayashi	Riken		

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SUMMARY

We propose to measure the cross-sections of fragment products produced in the projectile fragmentation of ^{86}Kr beam on ^{9}Be and ^{64}Ni targets at E/A=63 MeV. ^{86}Kr is one of the most neutron rich naturally occurring stable isotopes. Due to its noble gas chemical properties and that it can be easily ionized in ECR source, ^{86}Kr has been widely used to produce rare isotopes in radioactive beam facilities around the world. We propose to study the fragmentation with two targets with different N/Z in order to understand the role of the target asymmetry. Our goal is to obtain a comprehensive set of cross-sections so that comparisons of fragmentation reaction mechanisms can be made for energy ranging from E/A=25 to 500 MeV. Such extensive sets of data will provide more accurate predictions of rare isotope production rates at Riken and MSU and extrapolations to higher energies. Since all isotope rates predicted in the next generation rare isotope accelerator such as the Rare Isotope Accelerator (RIA) at USA and the Riken Radioactive Ion Beam Factory in Japan, rely on EPAX2 calculations, accurate measurements of selected nuclei such as the one proposed here are very important for the technical development of intense rare isotope beams in future accelerators.

The proposed comprehensive set of data will include cross-sections of ^{84}Se, ^{83}As, ^{82}Ge, ^{81}Ga, ^{80}Zn and ^{79}Cu isotopes, which form the "proton-removal chain" or "multiple proton knock outs" from the ^{86}Kr projectile. The proposed measurements will greatly assist in the development of a theoretical understanding of fragmentation of highly excited nuclei and the production mechanisms in creating neutron-rich nuclei.

DESCRIPTION OF EXPERIMENT

Physics justification

Fragmentation is the fundamental decay mode of highly excited nuclear systems [1]. While there are many puzzling aspects to this phenomenon, it does display some simplifying characteristics at high incident energies. For example, many of the experimental observables in peripheral collisions at high incident energies (E/A > 200 MeV), such as charge or multiplicity distributions, approach "limiting fragmentation" values that vary little with incident energy and target mass [2]. This "limiting fragmentation" behavior forms the basis for the EPAX2 parameterization [3] used to calculate the rates in the proposals for many radioactive beam facilities, and even the rates for the next generation rare isotope facility [4]. This parameterization assumes that the isotopic distributions and their dependence on the isospin of the projectile and target are consistent with limiting fragmentation. However, EPAX2 derives its results from a careful empirical fit to a limited data set of production cross sections measured under a wide variety of experimental conditions. Very little data exist to examine whether isotopic distributions are independent of target and beam energy. As the parameterization is not based upon a specific theory for projectile fragmentation; EPAX2 is better at interpolating between measured data points taken under similar conditions than at predicting the production of an isotope further away from the valley of stability [4, 5].

Some indication of the failure of EPAX2 in predicting isotopes with extreme asymmetry is shown in Figure 1. The data (blue solid points) are fragmentation cross-sections obtained by bombarding 140 MeV ^{58}Ni beam on ^{9}Be target measured with the A1900 fragment separator at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). The cross-sections are plotted as a function of the neutron excess, N-Z, of the emitted fragments where N and Z are the neutron and proton numbers of the isotopes. Data are closed circles and the EPAX2 predictions are open points, offset in the x-axis by 0.3 for clarity in presentation. For reference, the neutron excess of the projectile ^{58}Ni is 2. While most of the data around N-Z=2 agree with EPAX2 predictions within a factor of 2, production of the isotopes with large neutron excess, N-Z>7 is more than a factor of 10 lower than the predictions of EPAX2. Incidentally, the parameters in EPAX2 have been adjusted taking into account the cross-sections of fragments, mostly proton-rich ones, obtained from the fragmentation of ^{58}Ni beam at 650 MeV/u [6]. The lack of neutron-rich fragments from the previous ^{58}Ni data set used in the EPAX2 fits may explain the observed discrepancy in the production of neutron-rich nuclei. It is therefore important to examine a system with neutron rich projectile.

Some preliminary measurements have been obtained using the ^{86}Kr beam at MSU. Figure 2 shows the N=50 isotopes obtained in the fragmentation of ^{86}Kr on ^{9}Be target. The red points are preliminary data obtained at the NSCL while the open points are the data obtained at GSI [7]. The red line is the predictions from EPAX2. At Z=30, the production of ^{80}Zn is an order of magnitude below the EPAX2 prediction. Similar disagreements in cross-sections have also been observed for six proton removal cross-sections measured in the projectile fragmentation of ^{58}Ni and ^{40}Ca [8]. Accurate rate predictions are paramount in designing experiments using rare isotope beams. Comprehensive measurements like those shown in Figure 1 are the most efficient ways to establish the relationship between predictions and actual rates and provide the most reliable extrapolations to isotopes with very low cross-sections, which may not be measured.

The discrepancy shown in Figure 1 suggests that it is possible that “limiting fragmentation” is not reached at energy below 150 MeV/u where MSU and Riken currently operate. This apparent sensitivity to details of the initial stage provides a strong motivation for new measurements in which the projectile energy, the projectile and target N/Z are varied. A proposal has been submitted to the NSCL program advisory committee to conduct a parallel measurement with ^{86}Kr beam at MSU. By comparing the data at Riken and MSU, one may be able to disentangle the energy dependence of the fragmentation process. The ^{86}Kr beam is chosen because of the existence of such data in previous measurements at GSI. This previous set of data contributes significantly to the final selection of the EPAX2 parameterizations [3]. In addition, recent measurements at Texas A& M using 25 MeV/u ^{86}Kr beam show that production of n-rich isotopes is enhanced in inelastic scattering suggesting an alternate route to produce rare isotopes at lower energy. Thus, a comprehensive set of cross-section measurements from 25 MeV/u to 500 MeV/u for the fragmentation of ^{86}Kr nuclei would aide in the development and provide a rigorous test to models for rare isotope production mechanisms. *We stress that the confrontation of good quality data with theory, not a blind fitting of a random assortment of data, is essential to disentangling the various effects.*

Initial investigations both at Riken and MSU suggest that there is a target effect in the fragmentation process. Such effect is beyond predictions of EPAX2 and the Abrasion-ablation model suggesting that other mechanisms of fragment productions may be present. Thus we propose to measure the fragment cross-sections with neutron-rich

^{64}Ni targets and a more symmetric light target such as ^{9}Be. The asymmetry term of the nuclear equation of state may also play a significant role in the dynamical transport of nucleons between projectile and target, in their non-equilibrium emission during the collision and therefore, in the isotopic composition of the fragments produced at the end of the non-equilibrium initial stage [9,10].

Recent calculations using Abrasion-Ablation (A-A) model suggests that "cold fragmentation" mechanism may be responsible for producing extremely rare neutron-rich nuclei [5]. Such nuclei cannot be produced at high excitation energy because this would likely lead to the emission of neutrons leaving the nucleus more neutron-deficient. Exploring this issue has the additional simplicity that within the A-A model, such nuclei can only be produced with high probability if the protons are removed in the dynamical first stage in such a way that the excitation of the fragment is small and secondary decay does not occur. Here we refer to such a production mechanism as a ``p-removal chain'' or "multi-proton knock-out" [11]. Due to the Coulomb barrier for the proton, nuclei in this region decay preferentially by neutron emission. For nuclei on the p-removal chain where only protons are removed, this implies an upper limit on the excitation energy equal to the neutron separation-energy, S_n. These considerations imply a strong and calculable relation between binding energy of the fragment and its production cross-section.

It is interesting to test this idea with experimental data [11]. In particular, we believe it is important to check this technique for nuclei with known n-separation energies and also for nuclei where this information is currently unknown but may be determined by measurements. Only in this way, can the accuracy of the relationship between n-separation energy and p-removal cross section be determined. At GSI, the p-removal chain for ^{86}Kr up to ^{81}Ga (5 protons removed) has been observed and the data agree well with the p-removal A-A model [7,11] using the relatively well-known separation energy of ^{84}Se, ^{83}As, ^{82}Ge and ^{81}Ga, (2, 3, 4, 5 protons removed). Here, we propose to test the predictive power of the A-A model by measuring the p-removal chain of ^{86}Kr beam up to ^{79}Cu (7 protons removed). The neutron separation energy of ^{79}Cu is not known better than 1.2 MeV from extrapolation [12]. The theoretical uncertainty of the p-removal calculations depends on the fitting of the single proton-removal excitation energy using the proton removal chain with known neutron separation energy. The fitting parameter obtained in ref [11] using the data of ref [7] is rather large. The situation may be improved with more data available include data from the current proposal.

Experimental details and Beam time request

The experiment will be performed with the Riken isotope separator, RIPS. The count rate estimate of the experiment is calculated with EPAX2. The cross-sections for the nuclei of interest are plotted in the bottom panel of Figure 3 in a 2d plot with the y axis being the Z and x axis, neutron excess (N-Z). For clarity the cross-sections plotted in Figure 3 are color coded and represent 4 regions,

1. Red: σ_{EPAX}>0.01 mb,
2. Mageta: σ_{EPAX} =1.e^{-2}-1.e^{-4} mb,
3. Dark blue: σ_{EPAX} =1.e^{-4}-1.e^{-6} mb
4. Light blue σ_{EPAX} =1.e^{-6}-1.e^{-8} mb.

The most efficient mode to do cross-section measurement is to scan across the magnetic field of interest with small momentum slits (typically $\Delta p/p$=0.2%). The range Bρ values for the corresponding nuclei are plotted on the top panel of Figure 3 with the same color code. Since the cross-sections range from mb to pb, we have to change the method of measurements depending on the range of cross-sections.

1. For the isotopes with cross-sections above 0.01 mb (about 200 isotopes), we will scan between Bρ=3.2 Tm - 4.2 Tm with low beam intensity (<5 nA). Typically, the count rate is limited by the data acquisition, not the beam intensity. This requires of the order 40 settings per beam target combination allowing full momentum distributions of most of the isotopes measured. Additional time (about 10 min) must be allowed for changing magnetic settings. Thus for each setting, we will take data for both targets. These isotopes are not statistically limited. (show some calc). Typically we take 20 min data per setting equivalent. This amounts to about 1 hour per setting. 40 hr is needed for both target-beam combination for these nuclei with high cross-sections.
2. For the 2nd and 3rd groups of isotopes with cross-sections between 1.e^{-2}-1.e^{-4} mb and 1.e^{-4}-1.e^{-6} mb we will need to use thin wedges (?? mg/cm2

Al foil) to deflect the light particles so that the beam intensity can be increase to >10 nA. As shown in the top panel of Figure 3, the required range of Bρ=3.8 Tm - 4.9 Tm (these values will be slightly modified due to the wedge. For simplicity in the discussion here, the shift can be ignored.) This region is not beam intensity limited and will require 40 hour per beam target combination as in group 1.

3. For region 4 containing nuclei with cross-section in the order of 1pb, we can probably continue the previous technique of using thicker wedge to deflect the undesired nuclei. However, with thicker wedge (?? Mg/cm2), less isotopes are detected with full transmission efficiencies. Most likely only about 10 isotopes will be detected at one time. Thus this will require 30 settings to detect most of the isotopes in this region.

4. Our challenge is the nuclei with cross-sections for the most neutron rich nuclei with neutron excess of $N-Z\geq 6$, figure 1 and 2 suggest that there may be an additional two order of magnitude decrease in cross-sections for this region. We will use thicker wedges so that maximum beam intensity will be utilized by deflecting most of the undesired nuclei away. Using the extracted cross-sections of ^{79}Cu from Fig. 2 (10^{-9} mb instead of 10^{-7} mb as given by EPAX) as an example. With 100 mg/cm2 Be target and beam intensity of 80 nb, the count rate is 3.5e-3 per sec. In one hour, we will get 13 counts if the transmission is 100% and the momentum slits are wide open. Assuming a transmission efficiency of 50%, about 100 counts (10% uncertainties) will be produced in 15 hours. This will require 30 hours to measure both targets. 10% uncertainties in cross-section measurements correspond to about 500 keV in the neutron separation energy determination using the parameters given in ref. 11. However the uncertainty may improve as the proton-removal chain is also measured in the current experiment. Even a 500 keV uncertainty in the neutron separation energy

determination is better than the current situation of 1.2, MeV which is an extrapolated value.

Based on our past experience at MSU and Riken, the experiment setup requires 24 hours to debug, to measure the charge state distributions with different targets and to calibrate different beam monitors to provide dynamical range to measure cross-sections with span of 10 orders of magnitude and to check out the transmission efficiencies of different wedges. Use of ^{64}Ni target complicates the measurement a little due to the charge state distributions. Calculations with GLOBAL in LISE [13] suggest that only about 50% of the fragments similar in mass to the projectile with the charge Q=Z-1 will be detected. However, the high intensity beam may compensate such loss in the comprehensive measurements except for the Cu79 measurement. In the latter cases, there is experimental indication that ^{64}Ni beam will enhance the production of n-rich nuclei and may compensate the reduction in detection efficiency and effective thickness of the target material. The total beam time requested is 7 days and is itemized below:

Debug time and miscellaneous measurements	24 hours
^{96}Kr+^{9}Be, ^{64}Ni (region 1)	40 hours
^{96}Kr+^{9}Be, ^{64}Ni (region 2 & 3)	40 hours
^{96}Kr+^{9}Be, ^{64}Ni (region 4)	30 hours
^{79}Cu	30 hours
Total	164 hours~7 days.

References:

1. W.G. Lynch, Ann. Rev. Nucl. Part. Sci. 37, 493 (1987).
2. A. Schuttauf, et al., Nucl. Phys. A607, 457 (1996).
3. K. Sümmerer and B. Blank, Phys. Rev. C 61, 034607 (2000)
4. http://www.phy.anl.gov/ria/ria_yields/yields_home.html
5. W. A. Friedman et. al. Phys. Rev. C 62, 064609 (2000).
6. B. Blank, Phys. Rev. C 50 2398 (1994).
7. M. Weber et al., Nucl. Phys. A578, 659 (1994).
8. M.B. Tsang, NSCL user-workshop, September 27-28, 2003, E. Lansing, USA http://meetings.nscl.msu.edu/userworkshop2003/Presentation%20files/tsang.pdf
9. M.B. Tsang, et al., submitted to Phys. Rev. Lett. and nucl-ex/0310024 (2003)
10. G. A. Souliotis, et al., Phys. Rev. Lett. **91**, 022701 (2003).
11. A. Friedman and M. B. Tsang; Phys. Rev. **C 67**, 051601 (2003).
12. http://www-csnsm.in2p3.fr/amdc/jvnubase/jvNubase_en.html
13. O.Tarasov, http://groups.nscl.msu.edu/lise/lise.html

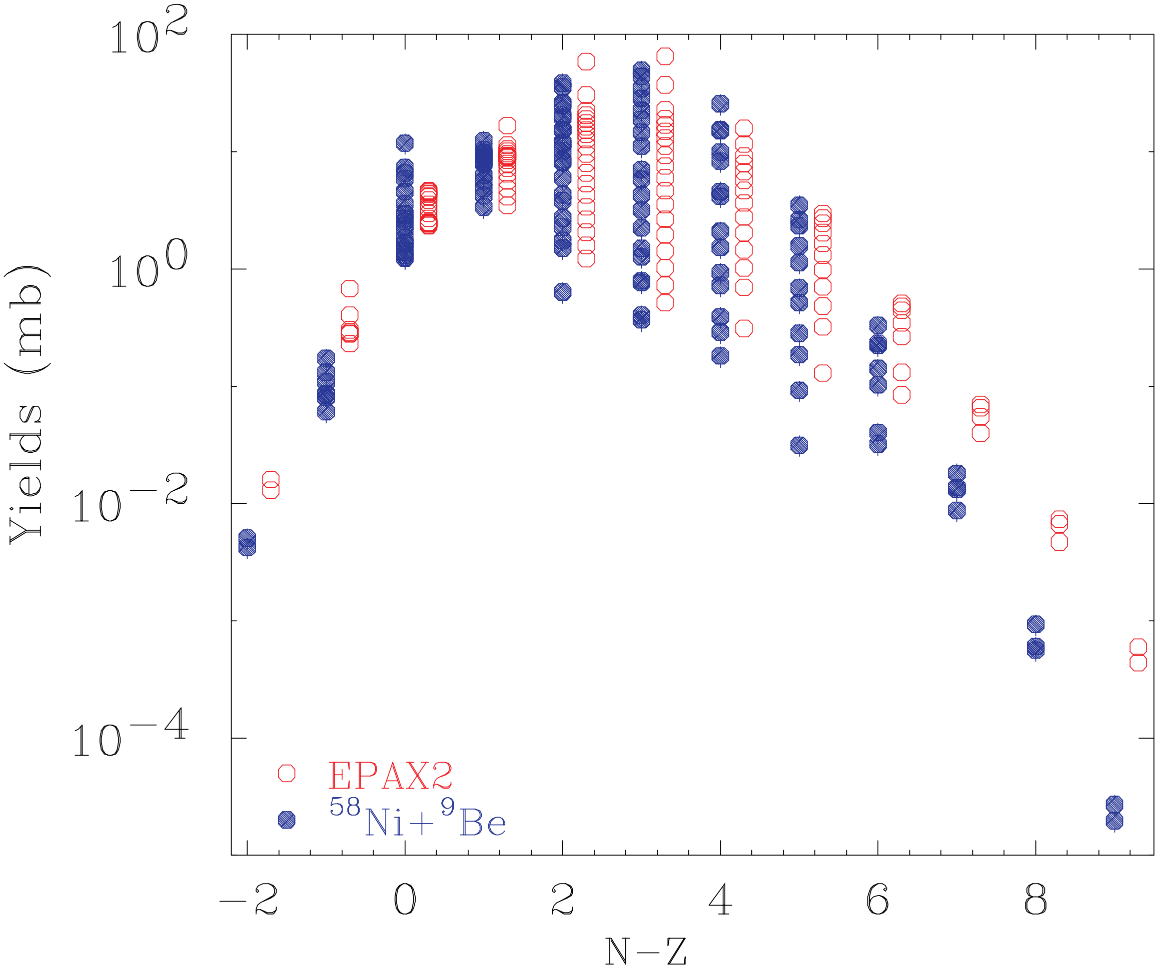

Figure 1: Comparison of measured cross-sections (solid blue points) with EPAX2 (open red points) as a function of neutron excess. The data is obtained from the projectile fragmentation of ^{58}Ni on ^{9}Be target at MSU. The EPAX2 predictions are offset by 0.3 unit in the x axis for clarity in the presentation.

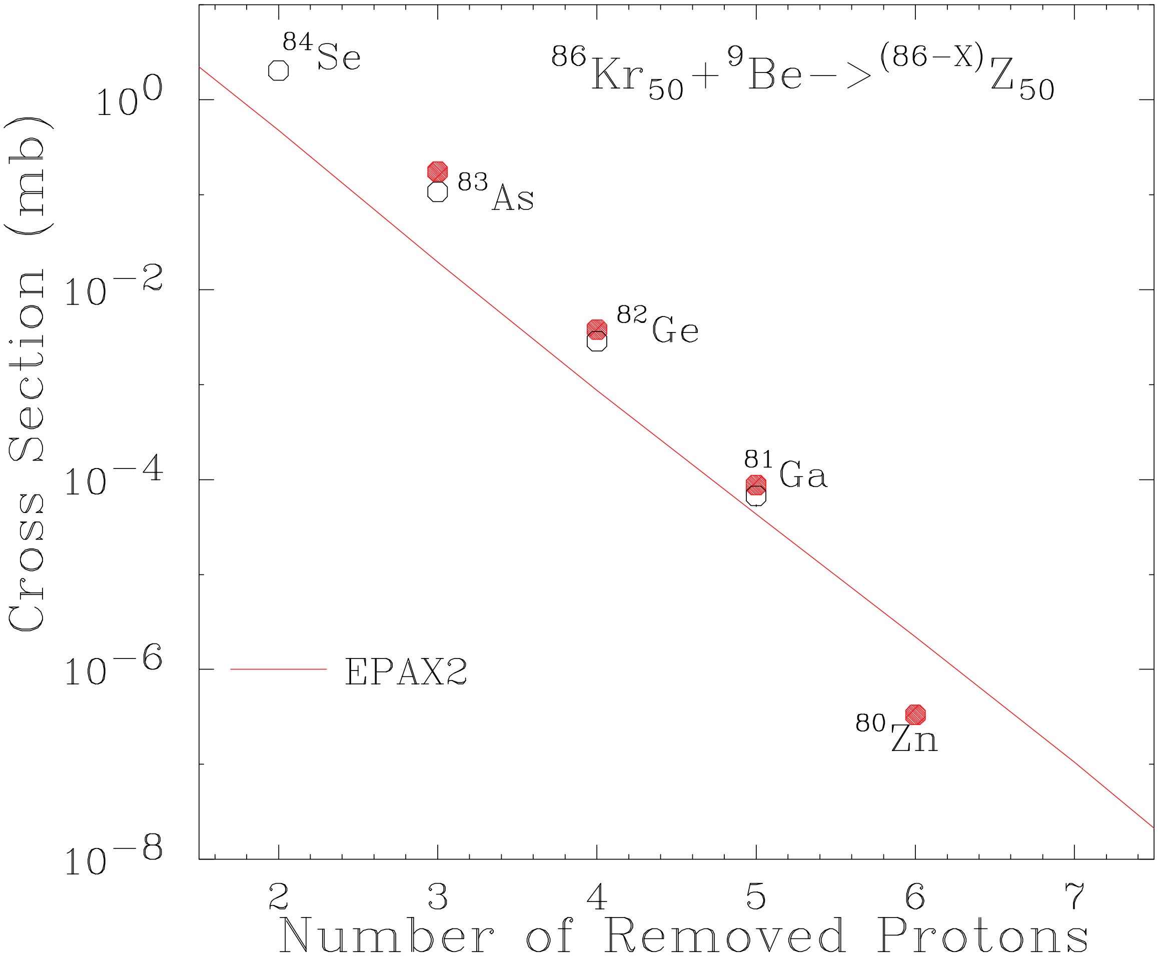

Figure 2: Proton removal chain from the fragmentation of 86Kr + 9Be. The solid points are preliminary data from MSU. Open points are data from ref. [7] and the solid line is the prediction from EPAX2.

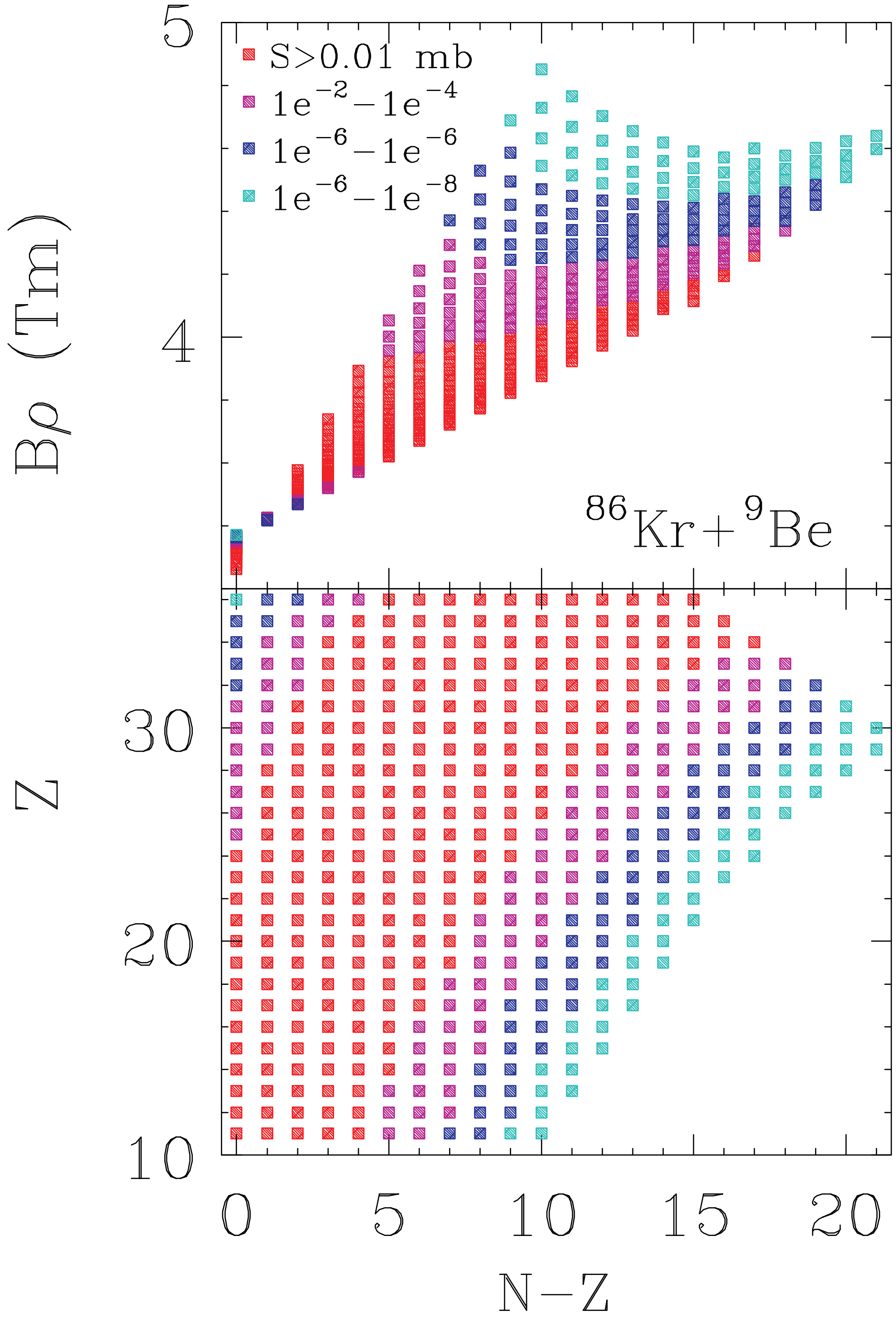

Figure 3: Bottom panel: Four regions of cross-sections predicted by EPAX2 for the fragmentation of ^{86}Kr+^{9}Be represented by 4 different color. Top panel: the range of magnetic regidity associated with the four different regions of cross-sections assuming.