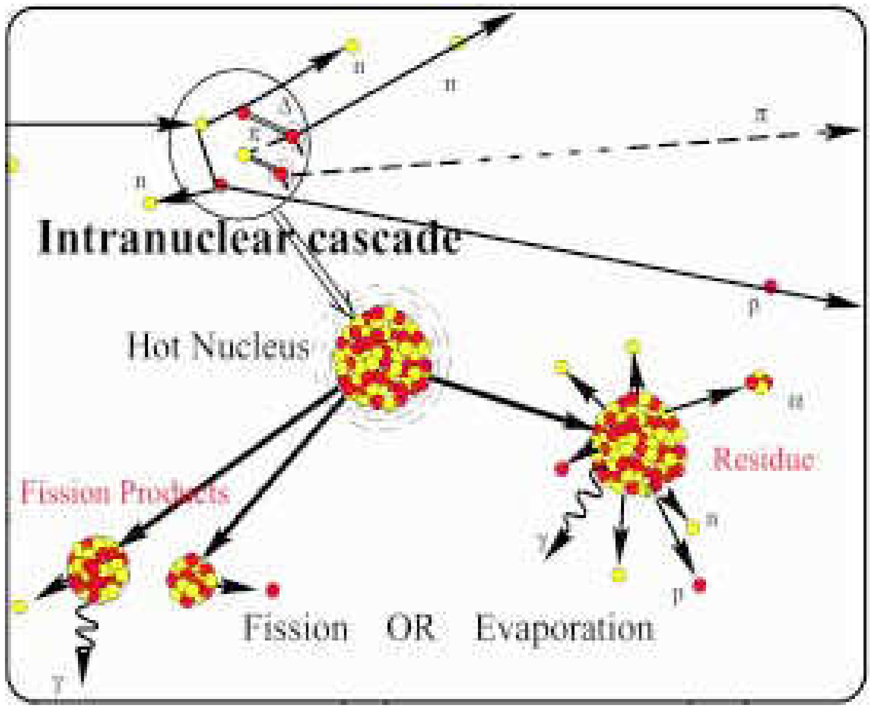
Paper Review

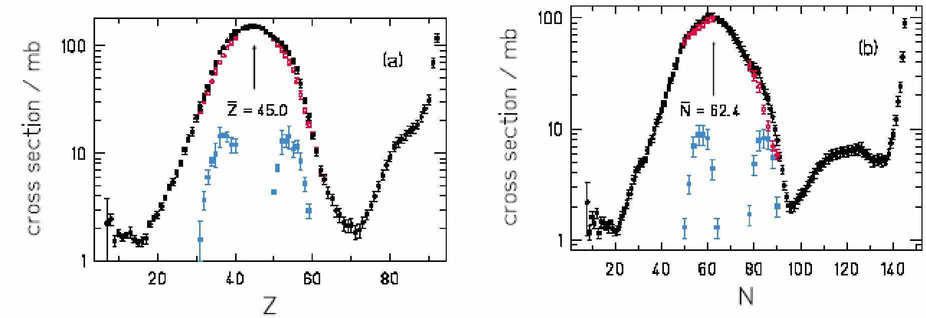
- Proton-induced *spallation* of ^{238}U (1A GeV) by *inverse kinematics* has been studied in [1].
    - ✓ ***Spallation***: Incoming beam reacts with the target and breaks it up in several fragments, emitting light and heavy nuclides, protons, neutrons and energetic radiation.



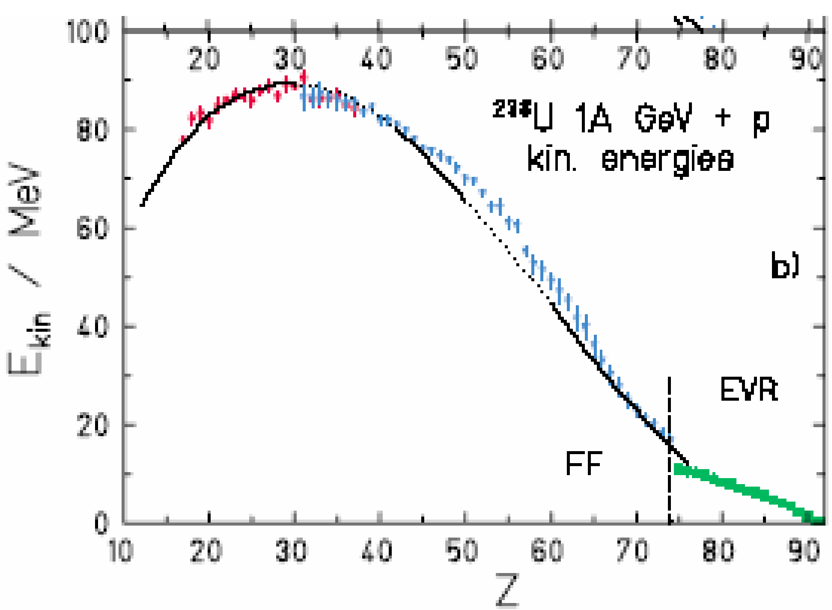
- ✓ ***Inverse kinematics***: The beam is of the heavier nuclide (^{238}U)and target is the lighter one (proton), which is the reverse of the usual situation, which is called direct kinematics.

- Some important features of the experiment,
    - ✓ It was carried out at *Gesellschraft fīr Schwerionenforschung* (GSI), Darmstadt, Germany.
    - ✓ The fragments emitted in spallation were emitted in a small cone at forward angels.
    - ✓ The fragment separator was used for detection of spallation fragments, with techniques like Ray-tracing (optical method) , Energy-loss and TOF.
    - ✓ The fragments (nuclides) emitted were completely stripped of their electrons, which made it easier to detect them by fragment separator.
    - ✓ The formation cross-sections and kinetic energies were measured.

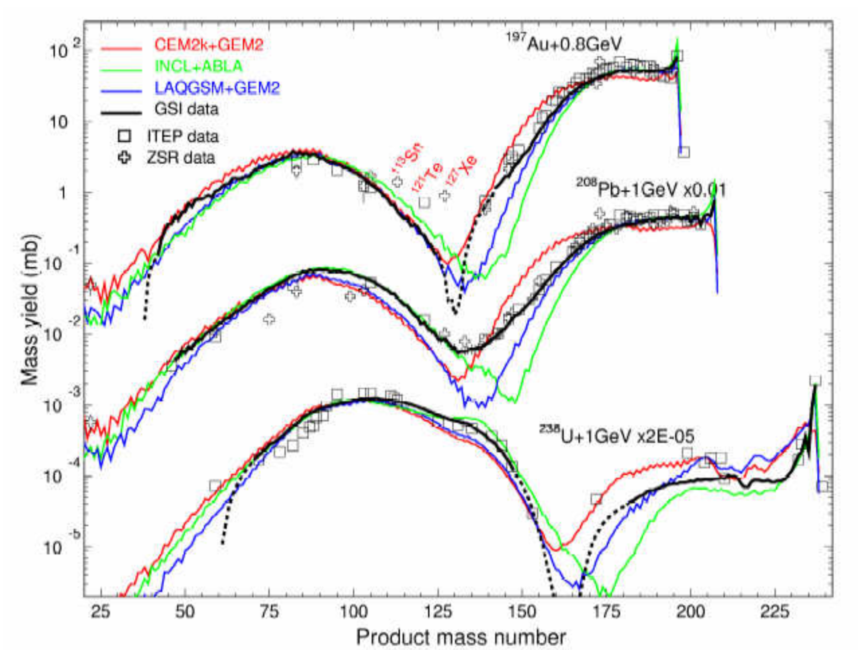
- Observations and results put forth,
  - ✓ 1385 nuclides produced and studied in one reaction, which is a very unique feature of this particular experiment.
  - ✓ Nuclides ranging from Nitrogen to Uranium, with many isotopes of each one. The cross-sections measured down to 1μb for some nuclides.
  - ✓ 78% of fragments come from the fission process (FF) to which only a 5% contribution is that of the low-energy asymmetric fission. The evaporation process (EVR) dominates after Z=74. The minima in cross-section at Z=71 and N=97 separate the FF from EVR events.



  - ✓ The 220-Th is the mean parent nuclide for fission and the 107-Rh is the mean daughter formed.
  - ✓ Nuclides beyond Z=68 show a tendency to lose neutrons and therefore are all proton-rich species. The neutron-rich species come mostly from the low-energy asymmetric fission.
  - ✓ The kinetic energy (KE) vs. Z plot shows that KE for the EVR fragments, which are all heavier nuclides, are very small. This is because they slow down considerably by elastic collisions. Also, for symmetric fission, maximum KE is expected for Z= 1/3 (Z of parent). 220-Th mean parent, therefore maximum expected at Z=30, which is true from the plot.



- Comparison with some other similar studies,
  - ✓ The GSI values are compared with the values calculated at *Institute for Theoretical and experimental Physics* (ITEP), Moscow, Russia and with some theoretical codes developed by different labs like LANL and Liege in [2].
  - ✓ Some fundamental differences between the two experiments,
    - ITEP used direct kinematics (1GeV proton and ^{238}U target).
    - Only about 400 nuclides were produced (or at least studied).
    - Detection using γ-spectrometry.
    - The yields measured at ITEP were cumulative yields whereas the ones measured at GSI were individual yields.
    - There was no separation between metastable and ground states in GSI measurements which was possible at ITEP.
  - ✓ The mean cross-section ratio $<\sigma_{GSI}/\sigma_{ITEP}> = 0.77$
  - ✓ Results at ITEP are typically 10-20% higher than that at GSI.
  - ✓ Cross-sections in the region A=160-170, the region between FF and EVR, differ by an order of magnitude. For other regions the difference is not so serious.



  - ✓ Comparison with data calculated by theoretical codes shows that GSI data is in better agreement with the theory, however the theoretical values are lower than experimental.

Data set	<σ$_{calc,i}$/ σ$_{exp,i}$>			<F>		
	LAQGSM	CEM2k + GEM2	INCL + ABLA	LAQGSM	CEM2k + GEM2	INCL + ABLA
	^{197}Au + p 0.8GeV					
ITEP	0.69	0.85	0.63	1.83	1.63	2.07
ZSR	0.49	0.73	0.45	2.53	2.45	2.94
GSI	0.75	0.99	0.79	1.96	2.17	1.89
	^{208}Pb + p 1.0GeV					
ITEP	0.66	0.87	0.63	1.86	1.90	2.07
ZSR	0.55	0.71	0.57	2.26	1.94	2.30
GSI	0.68	0.83	0.84	2.10	2.58	1.88
	^{nat}U + p 1.0GeV					
ITEP	0.58	0.64	0.63	2.45	2.50	2.04
GSI	0.89	0.99	0.84	2.11	2.67	1.90

- ✓ The residual nuclides produced by proton-induced reactions on U for energies between 20-70 MeV are studied in [3].
    - Direct kinematics, γ-spectrometry for detection.
    - 460 cross-sections measured. Nuclides produced were isotopes of Y, Zr, Nb, Mo, Ru, Pd, Cd, Sb, Te, I, Xe, Cs, Ba, Ce, Nd and Np (mostly from 5th and 6th periods).
    - Except Np all are fission products and all yields except Np are cumulative.
- ✓ Fission of U with 0.1-6.2 GeV protons is studied in [4].
    - Predominant products were Cs and Rb with some isotopes of Ba and La also being formed.
    - The cross-sections of n-rich nuclides decreased with increasing energies and cross-sections of p-rich nuclides went though a maximum with increasing energies.
    - This is a very old study, done in 1963. Therefore separation and detection techniques used were radiochemical and mass spectroscopic.
- ✓ A comparison of both [3] and [4] with GSI results is given in a form of a table on the next page,

Isotope	HINDAS (20-70 MeV)	GSI (1GeV/A)	BNL (1GeV)
84Rb	---	1-5	6.9
86 Rb	---	5-25	10.8
95 Zr	50-60	25	---
115 Cd	20-60	25	---
125 Cs	---	5-25	1.1
127 Cs	---	5-25	3.0-4.4
129 Cs	---	5-25	6.45-9.45
130 Cs	---	5-25	5.55(+/-0.05)
132 Cs	---	5-25	3.5-4.2
134 Cs	1-15	5-25	3.0(+/-0.05)
136 Cs	8-25	5-25	4.4(+/-0.3)
137 Cs	40-60	1-5	9.6(+/-1.5)
127 Ba	---	1-5	1.4
129 Ba	---	1-5	3.6
131 Ba	---	1-5	4.4-5.7
140 Ba	---	1-5	9.3(+/-0.6)
131 La	---	1-5	2.4(+/-0.1)
147 Nd	15-25	1	---

✓ If we go by the fact given in [4] that cross-sections of n-rich nuclides decreased with increasing energies, almost none of the data give the same results.

- The kinematics as well as detection techniques used in the experiment at GSI are totally different from any previous experiment. Hence the comparison cannot be done with confidence.
- These in fact could be important factors contributing to the difference in the data and calculation results of different experiments.
- However, GSI data are in better agreement with the theory hence, there is a good reason to do further research in this area.
- Also, in direct kinematics experiments, 1GeV proton bombarded on 238 U target whereas at GSI, 1GeV/A, that is, 238 U beam accelerated to 238GeV is bombarded on liquid H_2 target. So energy of the system is much higher.
- In all, another experiment with exactly the same conditions should be carried out to enable one to reach some conclusions.

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References:

[1] Measurement of a complete set of nuclides, cross sections, and kinetic energies in Spallation of 238 U 1A GeV with Protons, P. Armbruster et al., Physical Review Letters, Vol. 93, number 21, 212701-1, 2004.

[2] Nuclide production in 197 Au, 208 Pb, and ^{nat} U irradiated with 0.8-1 GeV protons: comparison with other experiments and with theoretical predictions, Yu.E. Titarenko et al., http://arxiv.org/ftp/nucl-ex/papers/0401/0401034.pdf

[3] Residual nuclide production by proton-induced reactions on Uranium for energies between 20MeV and 70MeV, M.A.M. Uosif et al., http://www.zsr.uni-hannover.de/veroeff/nd04uran.pdf

[4] excitation functions and nuclear charge dispersion in the fission of Uranium by 0.1- to 6.2-GeV Protons, G. Friendlander et al., Physical Review, Vol. 129, number 4, 1809, 1963.