



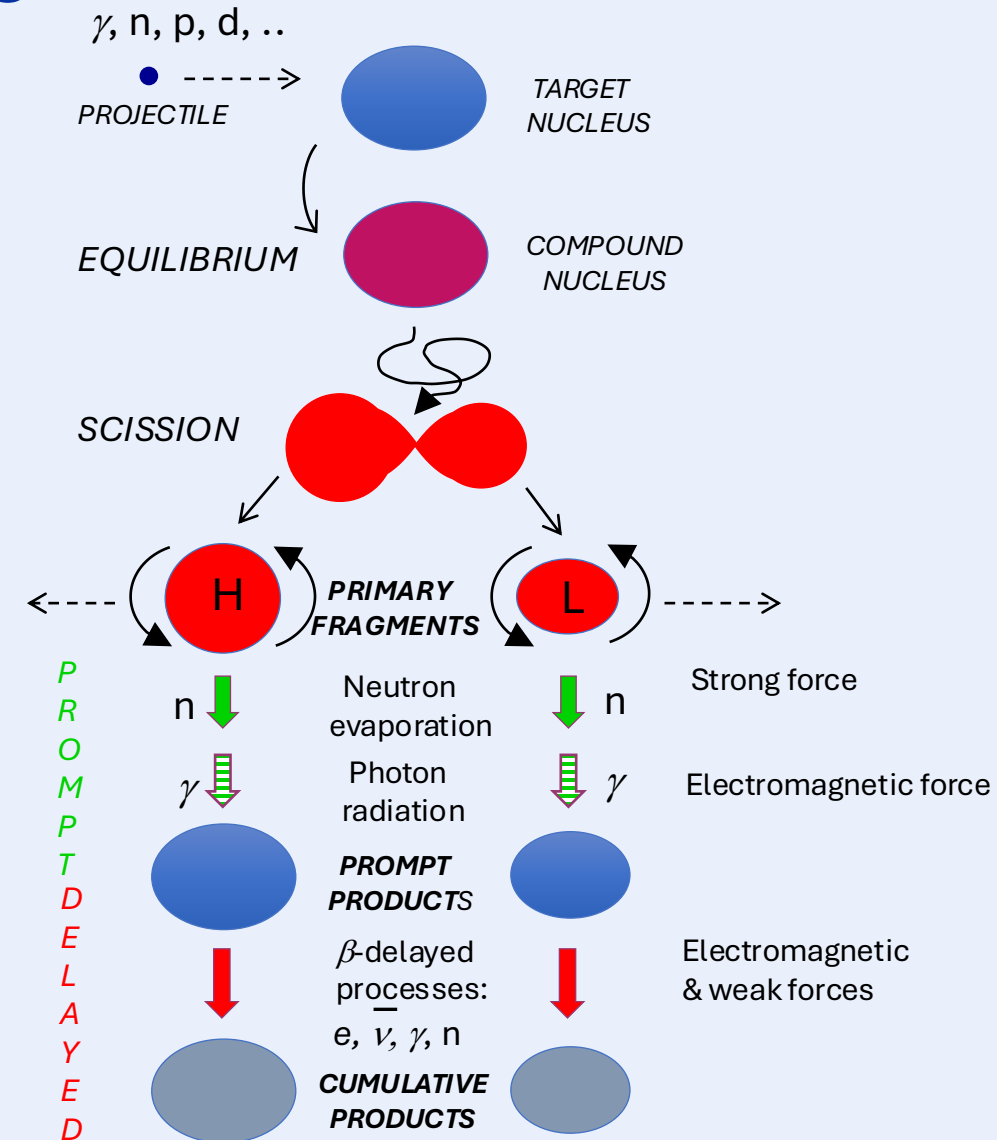
Fission in ultraperipheral heavy-ion collisions

Ramona Vogt (LLNL and UC Davis)

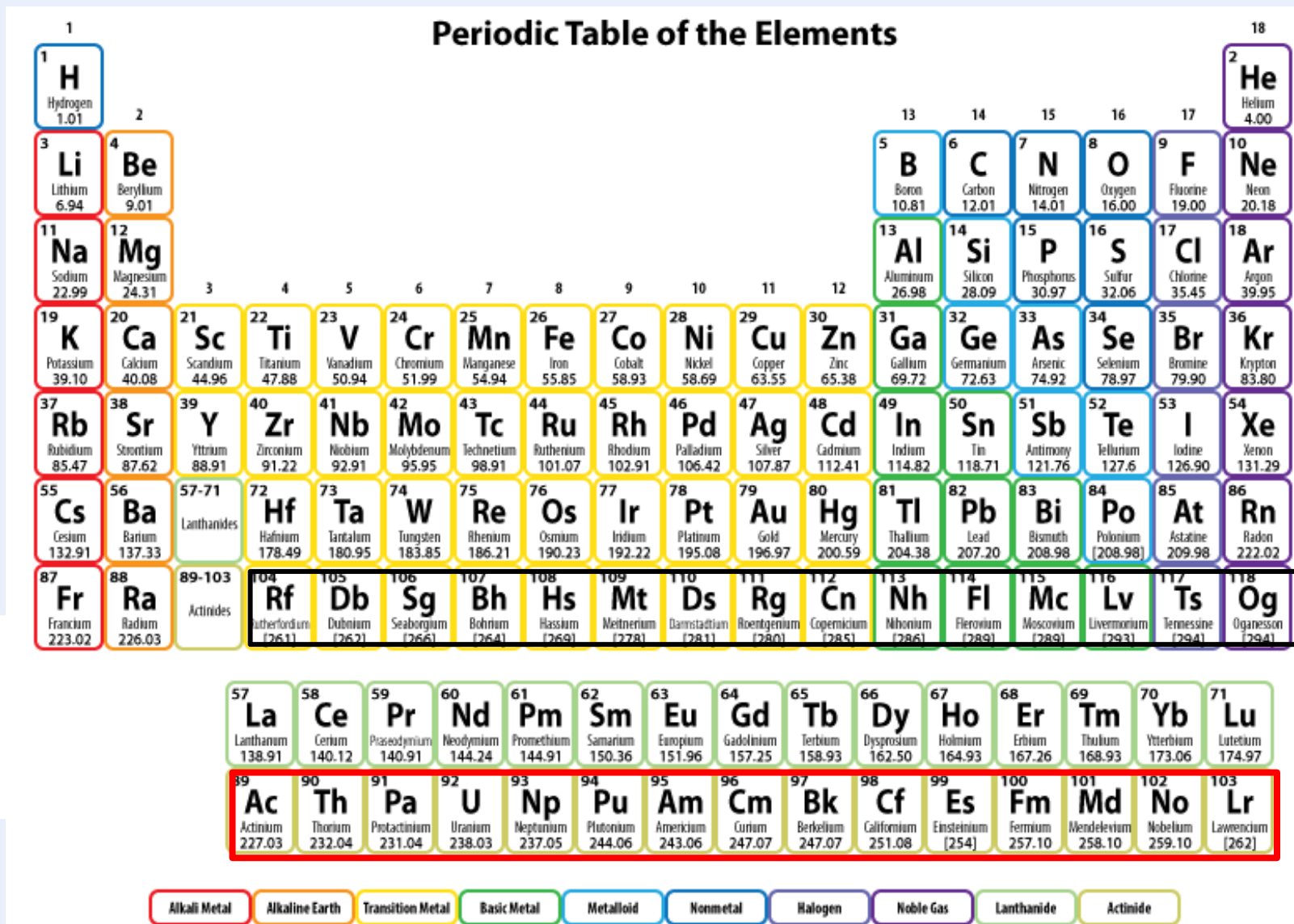
Prepared by LLNL under Contract DE-AC52-07NA27344.

Fission is a complex physics process

- The characteristics of fission fragments and their subsequent neutron and photon emission are dependent on nuclear structure and decays
- Fission involves three of the four forces of nature and the entire process occurs over a range of time scales
- Most applications are at low energies and many studies are directed at neutron-induced fission in the thermal (0.0253 eV) to few MeV energy range



Only the heaviest elements on the periodic table fission

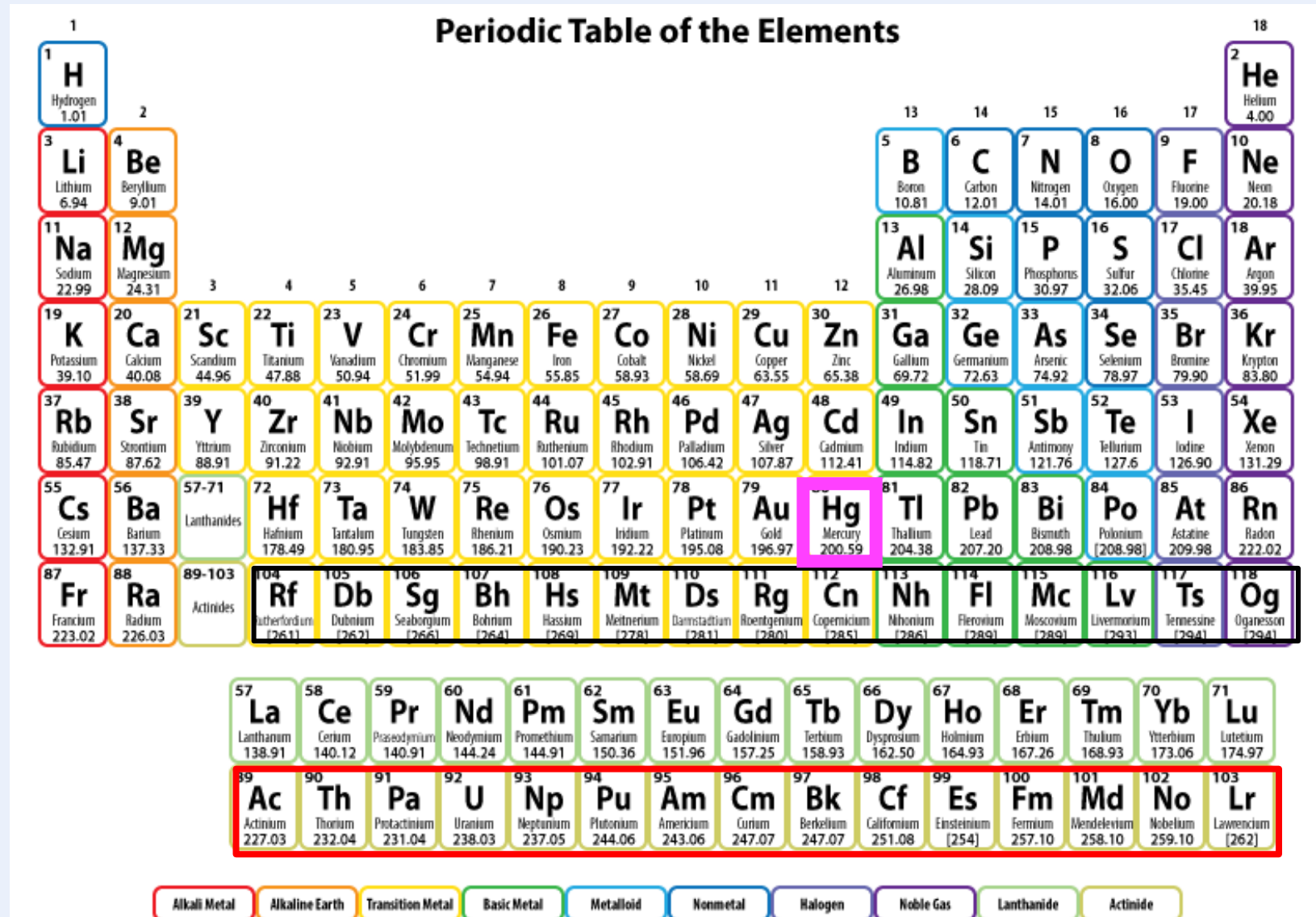


**Actinides
and more
massive
elements**

Only the heaviest elements on the periodic table fission?

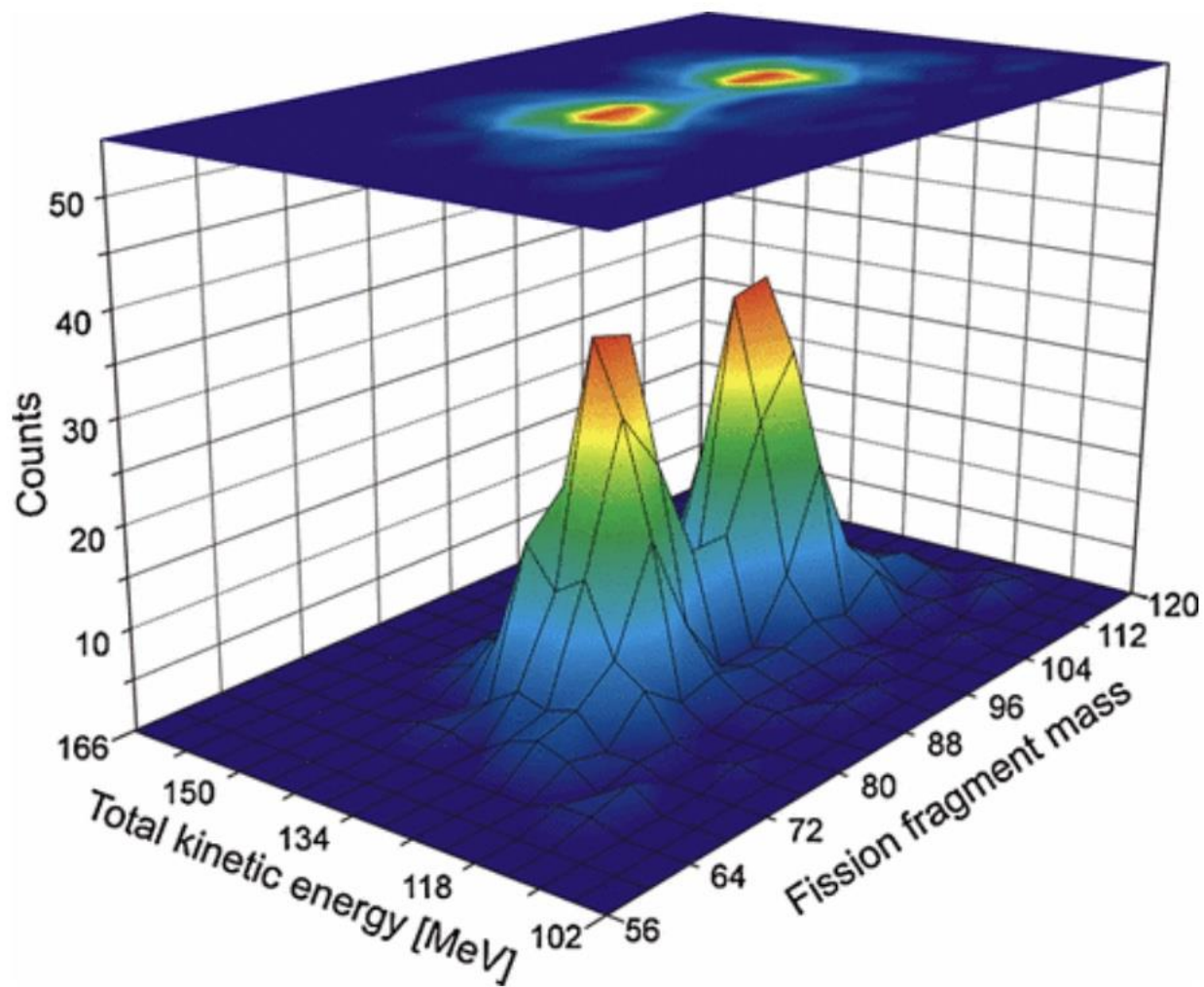
^{180}Hg produced from beta decay of ^{180}Tl , the ^{180}Hg then fissions (Andreyev et al., PRL **105** 252502 (2010))

Surprise was that the low mass ^{180}Hg nucleus fissioned asymmetrically



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Only the heaviest elements on the periodic table fission?



Periodic Table of the Elements

																18		
																2		
																He		
																Helium		
																4.00		
													13	14	15	16	17	18
													5	6	7	8	9	10
													B	C	N	O	F	Ne
													Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
													10.81	12.01	14.01	16.00	19.00	20.18
													13	14	15	16	17	18
													Al	Si	P	S	Cl	Ar
													Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon
													26.98	28.09	30.97	32.06	35.45	39.95
4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19			
26	27	28	29	30	31	32	33	34	35	36	37	38	39	40				
Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Y	Zr				
Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton	Rubidium	Strontium	Yttrium	Zirconium				
55.85	58.93	58.69	63.55	65.38	69.72	72.63	74.92	78.97	79.90	83.80	85.47	87.62	88.91	91.22				
44	45	46	47	48	49	50	51	52	53	54	55	56	57	58				
Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Ba	La	Ce	Pr				
Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon	Barium	Lanthanum	Cerium	Praseodymium				
101.07	102.91	106.42	107.87	112.41	114.82	118.71	121.76	127.60	126.90	131.29	137.33	138.91	140.12	140.91				
76	77	78	79	80	81	82	83	84	85	86	87	88	89	90				
Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Th				
Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon	Francium	Radium	Actinium	Thorium				
190.23	192.22	195.08	196.97	200.59	204.38	207.20	208.98	[208.98]	209.98	222.02	223.02	226.02	227.03	232.04				
108	109	110	111	112	113	114	115	116	117	118	119	120	121	122				
Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og	Uu	Uub	Uut	Uuq				
Hassium	Mitlerium	Darmstadtium	Roentgenium	Copernicium	Nihonium	Flerovium	Moscovium	Livermorium	Tennesseium	Oganesson	Ununseptium	Ununseptium	Ununseptium	Ununseptium				
[269]	[278]	[281]	[280]	[285]	[286]	[289]	[289]	[293]	[294]	[294]	[294]	[294]	[294]	[294]				
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75				
Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re				
Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium	Hafnium	Tantalum	Tungsten	Rhenium				
144.91	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.06	174.97	178.49	180.95	183.84	186.21				
93	94	95	96	97	98	99	100	101	102	103	104	105	106	107				
Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	Rf	Db	Sg	Bh				
Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium	Rutherfordium	Dubnium	Seaborgium	Bohrium				
237.05	244.06	243.06	247.07	247.07	251.08	[254]	257.10	258.10	259.10	[262]	[261]	[262]	[263]	[264]				

PRL 105 252502 (2010)

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Metalloid
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

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Lots of low energy ($E_n < 20$ MeV) fission data on actinides – what about higher energies and lower masses?

- It turns out that there is a lot of fission data at the GeV scale
 - JLab
 - CERN SPS
 - More?
- I'll only talk about some of it because a large-scale literature search was a bit beyond my capacity for this talk
- However, this brief survey suggests that one could look for fission at the EIC as well -- as has already been suggested!



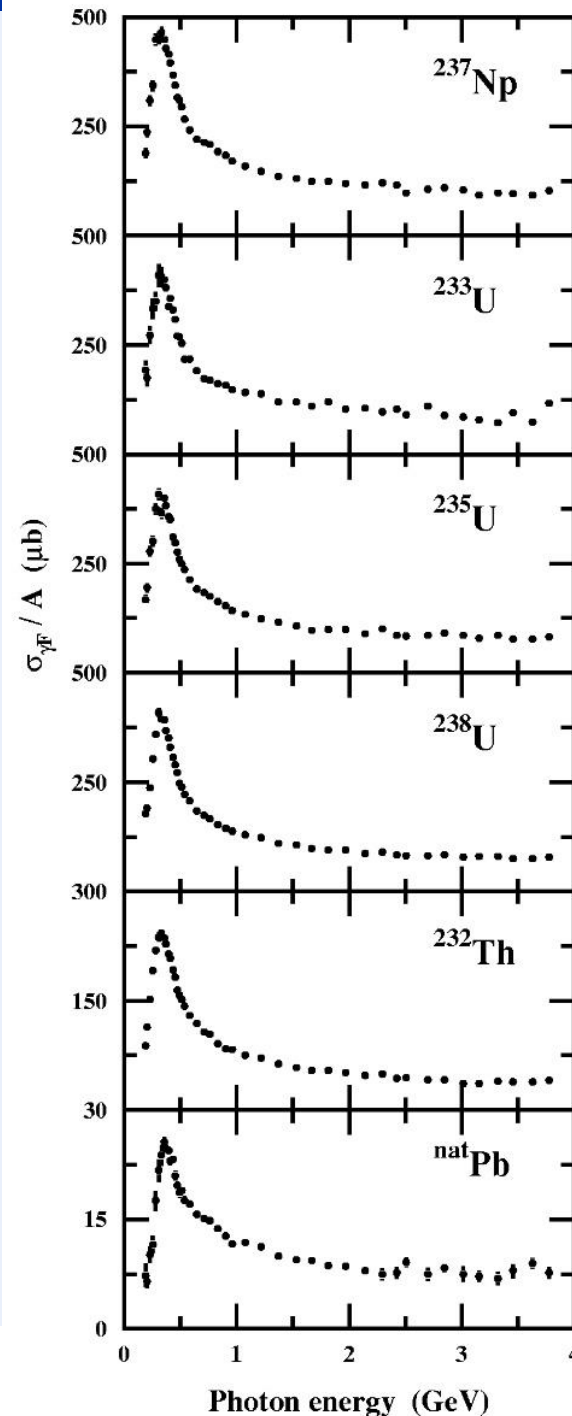
Photofission at JLab

^{237}Np , $^{233,235,238}\text{U}$, ^{232}Th , and $^{\text{nat}}\text{Pb}$ photofission measured at Jefferson Lab

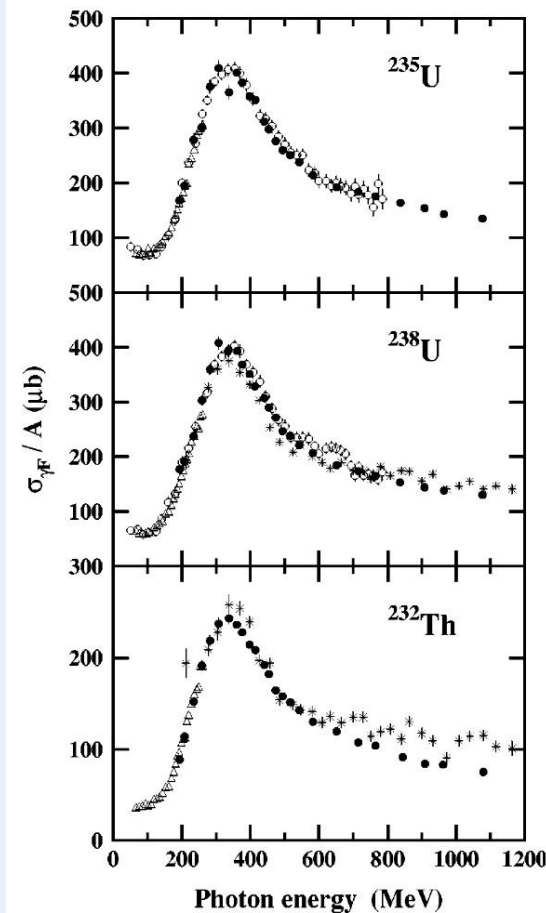
- The experiment in Hall B utilized tagged photons over at least two electron energies in the photon energy range $0.17 < E_{\gamma} < 3.84$ GeV
- This paper noted that there were also photofission data for Ba (PRC **36**, 1027 (1987)) and Au (PRC **39**, 911 (1989)) for a few hundred MeV photons
- They wanted to test the assumption that the photofission cross section, $\sigma_{\gamma F}$, and the photoabsorption cross section, $\sigma_{\gamma A}$, were equivalent
- Also studied the energy dependence of the fissility (Z^2/A)

Photofission cross sections

- ^{237}Np has highest photofission cross section, $^{\text{nat}}\text{Pb}$ is the lowest
- The peak on the left-hand side is from the Δ resonance
 - At $E_\gamma \sim 300\text{-}400\text{ MeV}$, the photon can excite a nucleon into a Δ , resulting in a high probability of fission
- Fissility, Z^2/A , is highest for ^{237}Np , lower for all other cases, giving ^{237}Np the largest cross section

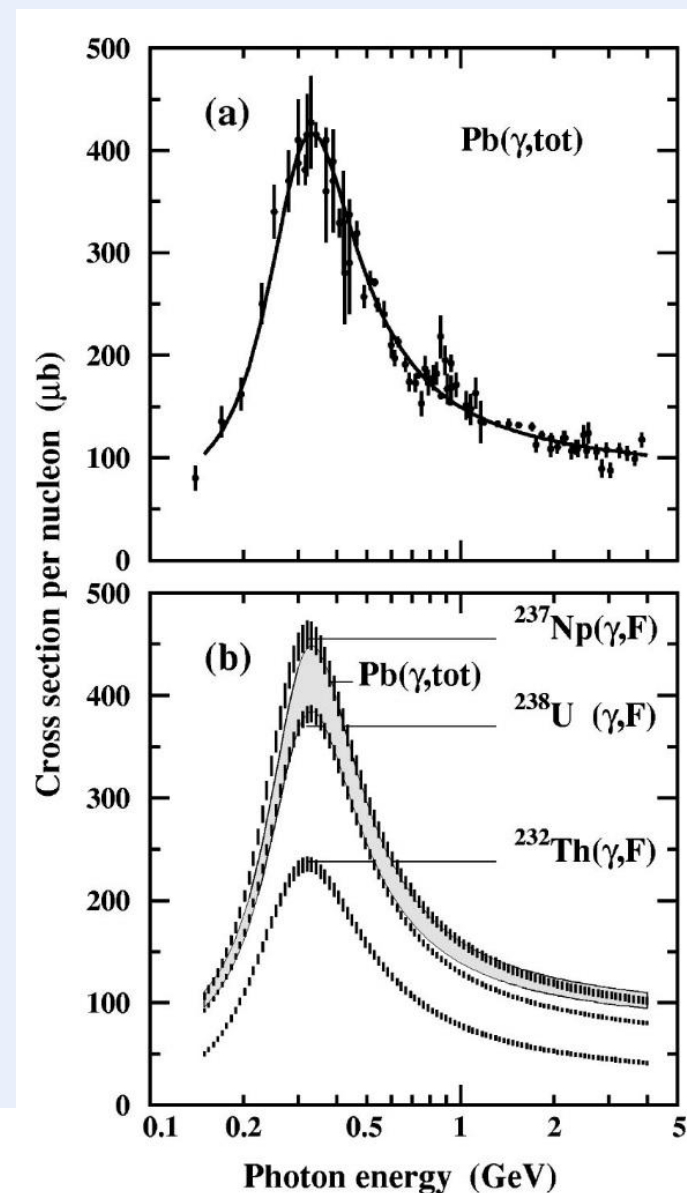


Good agreement with previous measurements



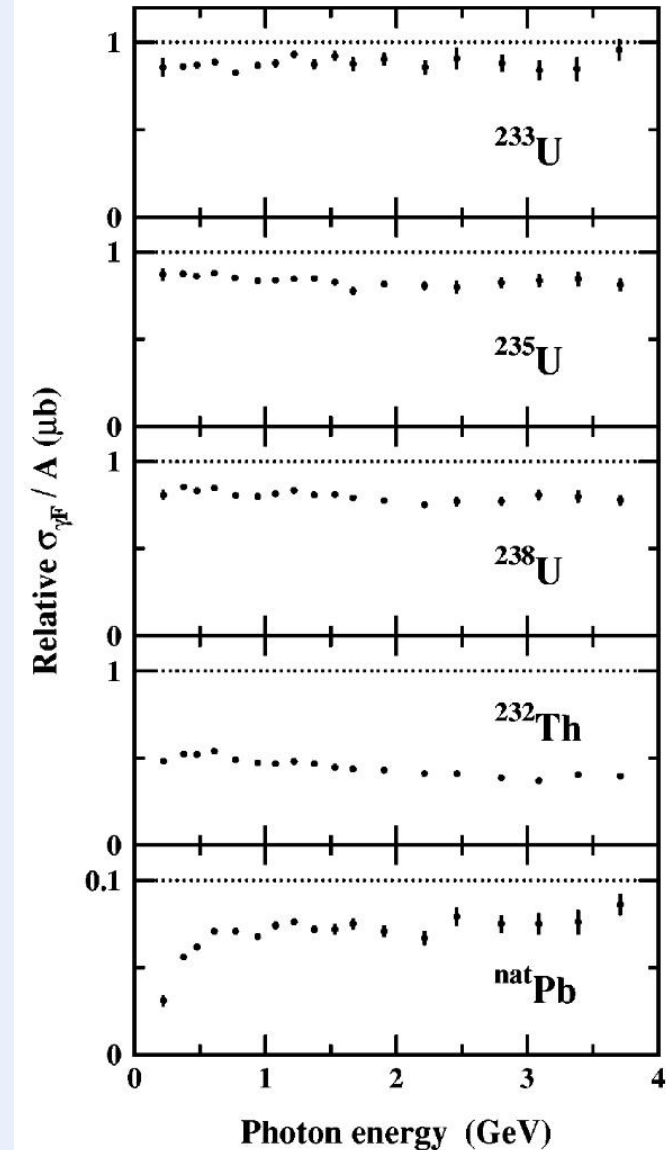
Photofission vs. photoabsorption

- Top plot shows the Pb photoabsorption total cross section
- Bottom result shows the measured ^{237}Np , ^{238}U , and ^{232}Th photofission cross sections per nucleon in comparison
- $\sigma_{\gamma F} = \sigma_{\gamma A}$ for ^{237}Np but clear differences for U and Th, showing that photofission does not saturate the total cross section for these isotopes



Photofission cross sections relative to ^{237}Np (measure of relative fissility)

- Using the liquid drop model, Bohr and Wheeler estimated fissility to be $\sim Z^2/A$
- There is almost no energy dependence of the relative cross sections
- The U isotopes have about a 20% lower fissility than Np while ^{232}Th is about half that of Np
- Note the significantly lower fissility of $^{\text{nat}}\text{Pb}$, about 8%
- Results suggest similar fission mechanism over all energies





Lead fission in ultraperipheral heavy ion collisions at the CERN SPS

Fission of Pb at the CERN SPS

NA50 primarily studied J/ψ and Drell-Yan production on nuclear targets but they also measured Pb fission

Two types of fission in reactions:

nuclear ($b < R_A + R_B$, s scales like $A^{1/3}$, $E_{\text{proj}} \sim 158 \text{ GeV/nucleon}$)

electromagnetic ($b > R_A + R_B$, s scales like Z^2 , $E_\gamma \sim 2 \text{ GeV}$)

To make this measurement, they added a new detector in front of the ZDC
To measure the charge of the lead projectile fragments

This was a “proof of principle” measurement due to thickness of Pb target

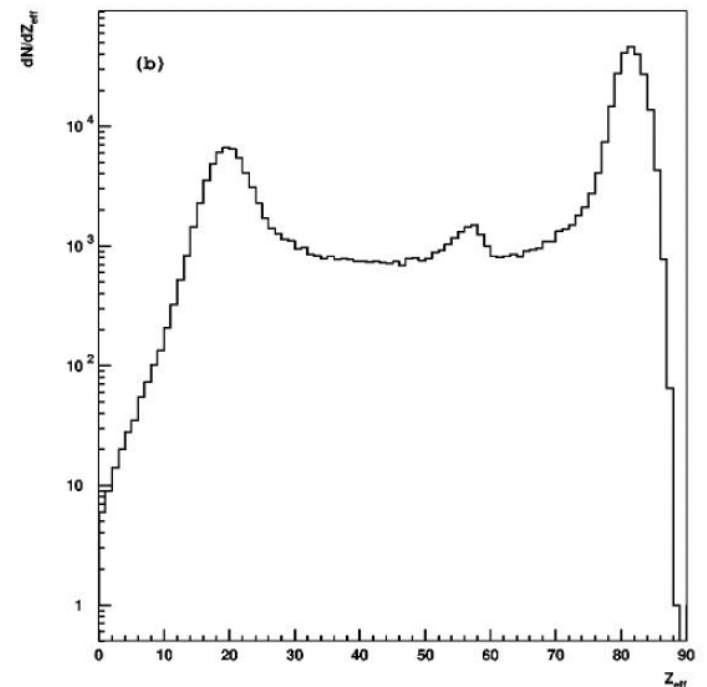
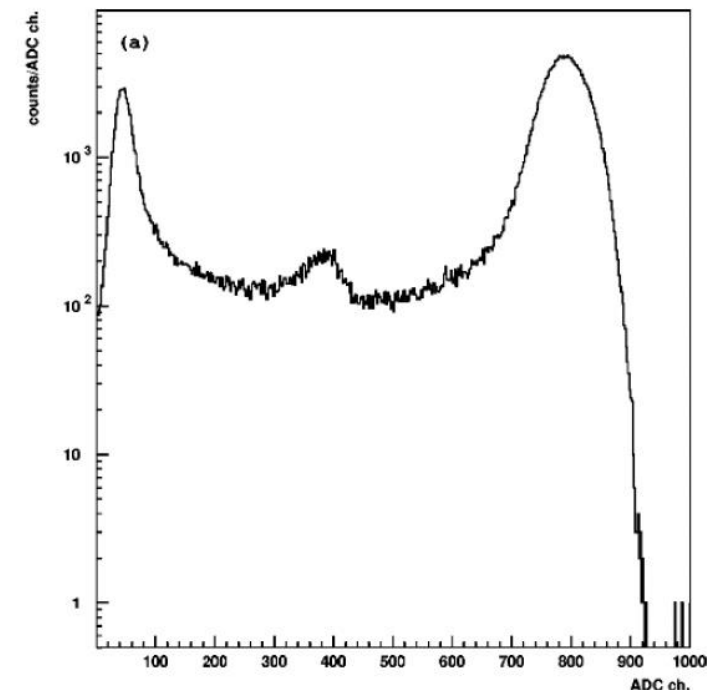
The figure has 3 peaks in the top and bottom:

right – no Pb interaction, maybe few neutrons emitted

left – effective Pb breakup into small fragments

middle – approximately symmetric Pb fission

Top figure shows light output, bottom converted to effective charge



NA50 followed up with dedicated runs at 40 and 158 GeV/nucleon on more targets

The beam intensity was lowered and thinner targets were used for these runs

The fragment detector was used as an additional trigger to increase fission sample

Targets and energies:

40 GeV/nucleon – C, Ca, Ag, and Pb

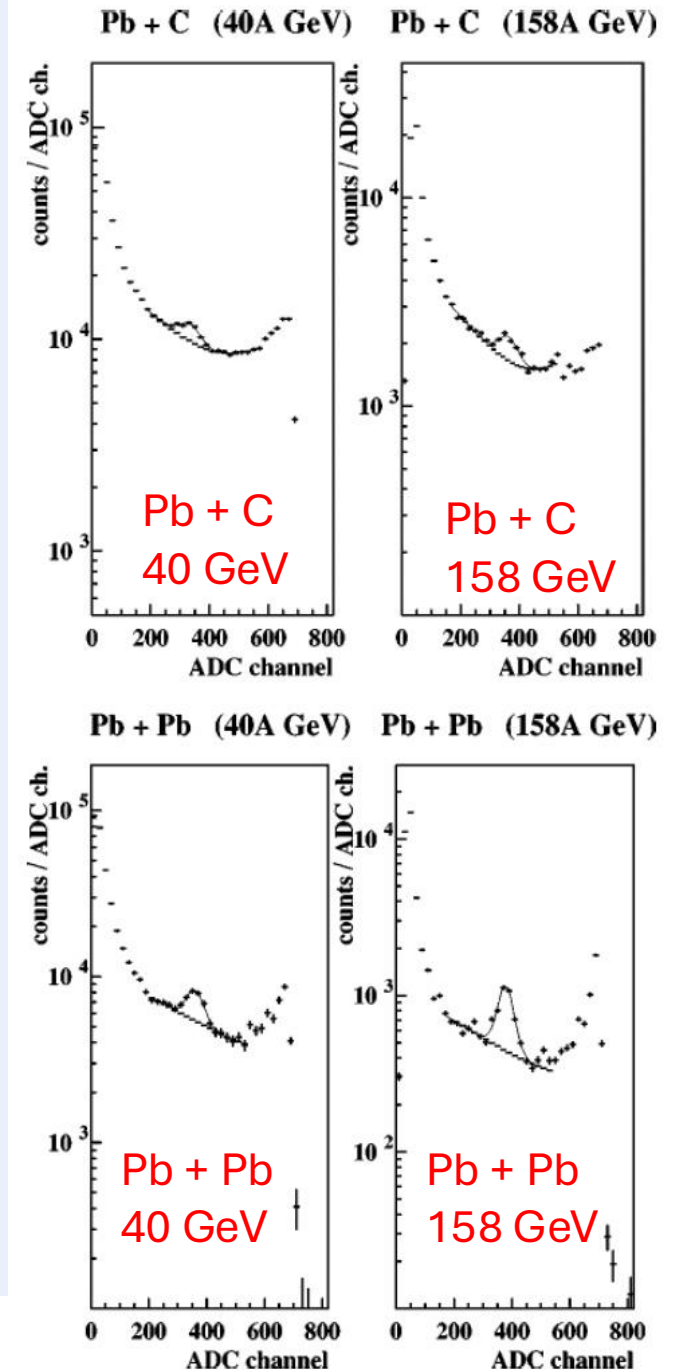
158 GeV/nucleon – C, Al, Ca, Ag, and Pb

About 1M events collected on each target and at each energy

Different from previous measurement, an empty target setup was used to reduce backgrounds

Goal was to separate nuclear and electromagnetic contributions to fission and Study the cross section dependence on energy and target mass

NB: for the Pb projectile energies, $28 \text{ MeV} < E_\gamma < 2 \text{ GeV}$

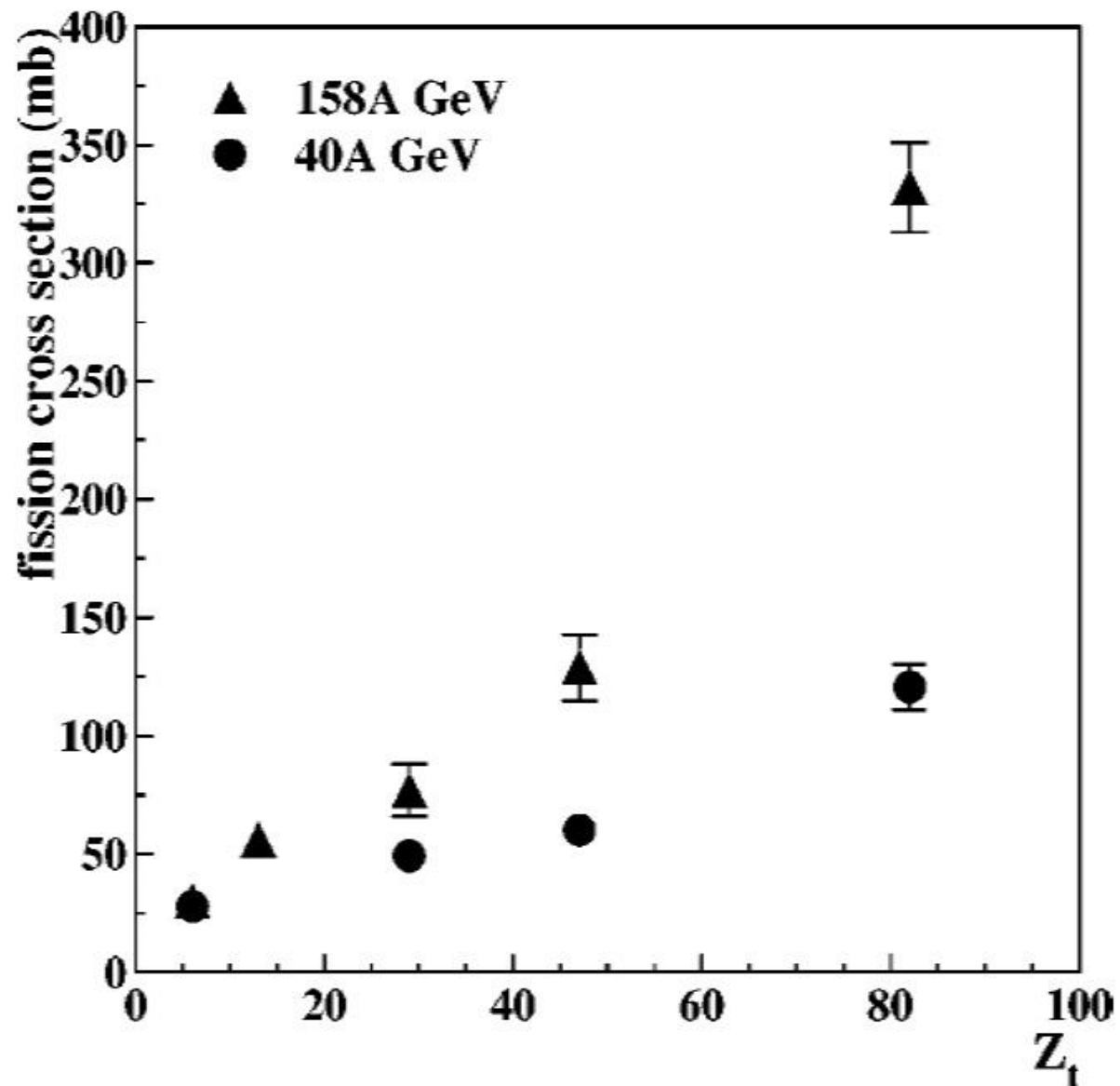


Total fission cross sections measured by NA50

There is a much stronger increase in the cross section with target mass at 158 GeV than at 40 GeV

The cross section was separated into the two Contributions to determine their relative importance

$$\sigma_f = \sigma_f^C + \sigma_f^N$$



Electromagnetic contribution to fission

- The cross section is calculated a la ultraperipheral collisions:

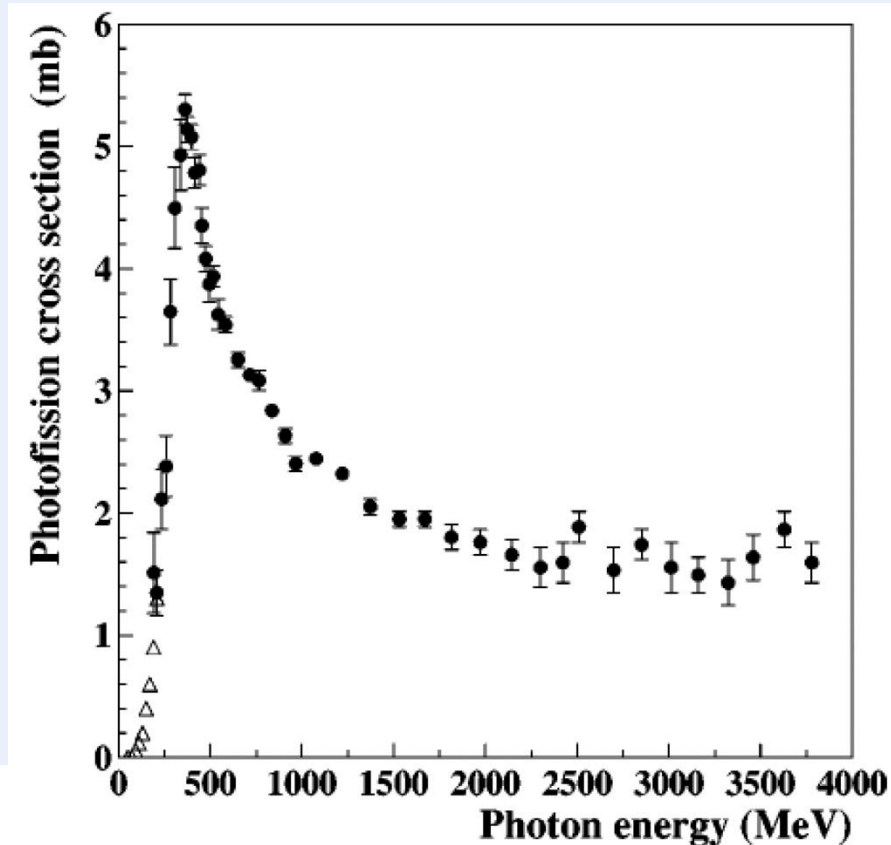
$$\sigma_f^C = \int n_t(\omega) \sigma_{\gamma f}(\omega) d\omega$$

$$n_t(\omega) = \frac{2Z_t^2 \alpha}{\pi \omega \beta^2} \left(\xi K_0(\xi) K_1(\xi) - \frac{\beta^2 \xi^2}{2} [K_1^2(\xi) - K_0^2(\xi)] \right)$$

- The photon flux $n_\gamma(\omega)$ is convoluted with the photofission cross section measured at JLab (PRC **65**, 044622 (2022)) and PR **179**, 1176 (1969) below 0.17 GeV

- $\xi = \omega b_{\min} / \beta \gamma$ with $b_{\min}^{BCV} = r_0 [A_p^{1/3} + A_t^{1/3} - x(A_p^{-1/3} + A_t^{-1/3})]$
 $r_0 = 1.34$ fm and $x = 0.75$

- $\sigma_f^C = \sigma_0 Z_t^\delta$ with $\delta = 1.72$ at 40 GeV and 1.86 at 158 GeV, less than the Z_t^2 in $n_\gamma(\omega)$



Nuclear contribution to fission

- The nuclear contribution only contributes in the impact parameter region $b_{\min} - \Delta b < b < b_{\min}$ with $\Delta b = 0.8$ fm

$$\sigma_f^N = 2\pi \times \Delta b \left(b_{\min} - a - \frac{\Delta b}{2} \right)$$

$$a = \frac{Z_p Z_t e^2}{\mu \beta^2 \gamma}$$

- Here a is small because γ is large, it and $\Delta b/2$ can be neglected
- There is also a correction factor f applied because lead has a low fissility (low probability of fission)
- $\sigma_f^N = 2\pi f b_{\min} \Delta b$

Total contribution to fission

- Putting the two contributions together with 2 free parameters to determine electromagnetic and nuclear contributions to fission:

$$\sigma_f = \sigma_f^C + \sigma_f^N = c_1 Z_t^\delta + 2\pi c_2 b_{min}$$

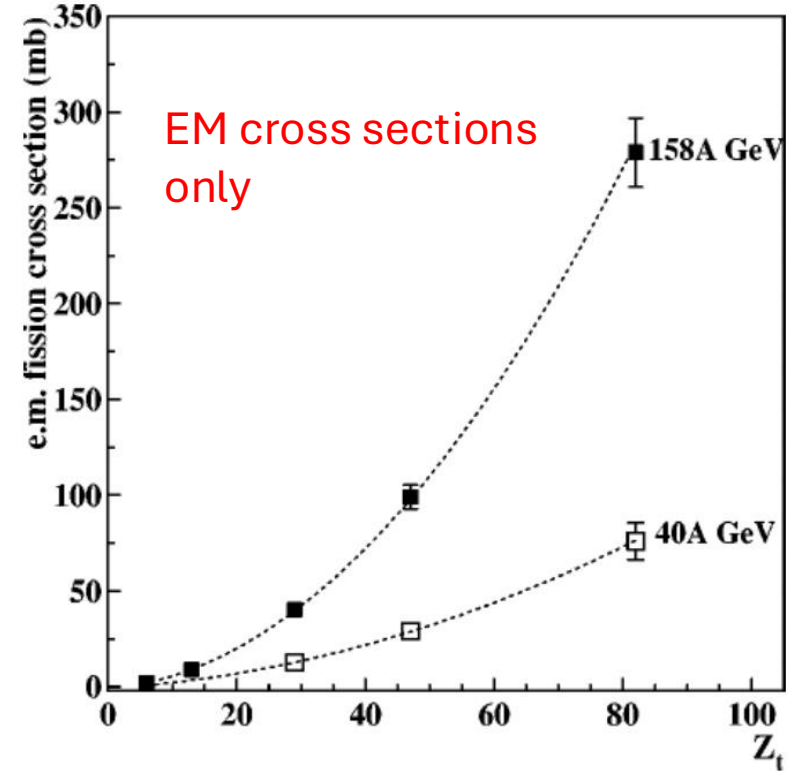
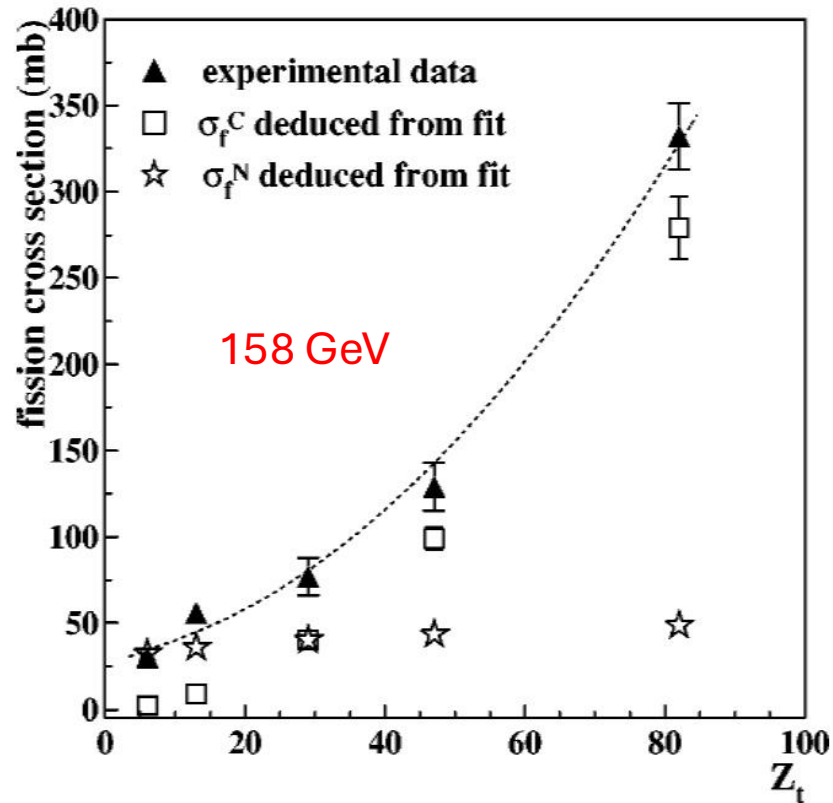
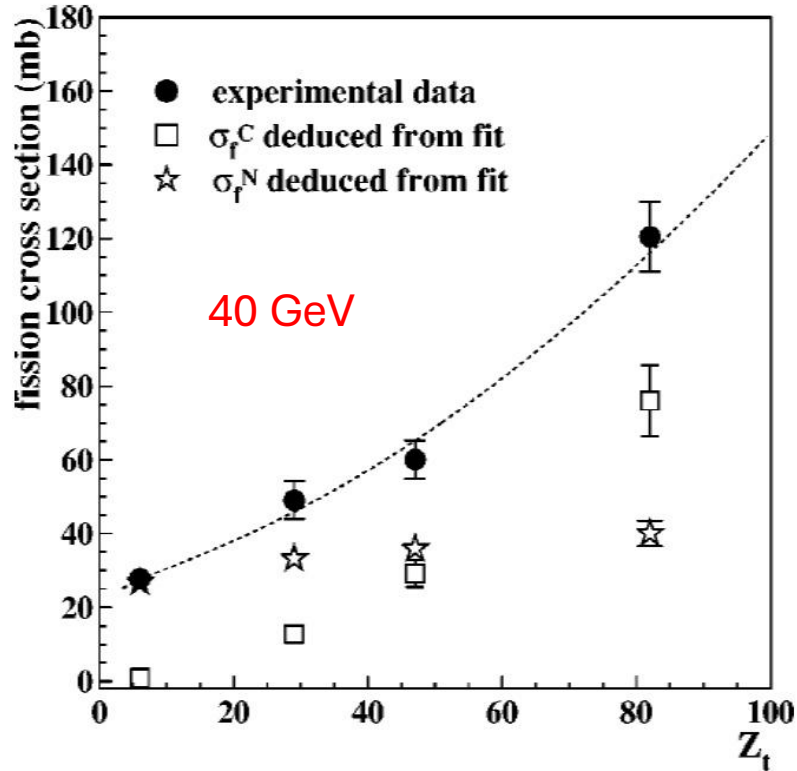
- Here $c_1 = \sigma_0$ and $c_2 = f \Delta b$

Energy	c_1 (mb)	c_2 (fm)
40 GeV	0.0388 ± 0.0049	0.0411 ± 0.0035
158 GeV	0.0768 ± 0.0049	0.0497 ± 0.0040

- It is possible to deduce the fissility of lead from the extracted c_2 , $f = c_2/\Delta b$, giving $f \sim 0.05 - 0.06$, similar to $f = 0.08 \pm 0.01$ for ^{nat}Pb

Charge dependence of the EM fission cross section

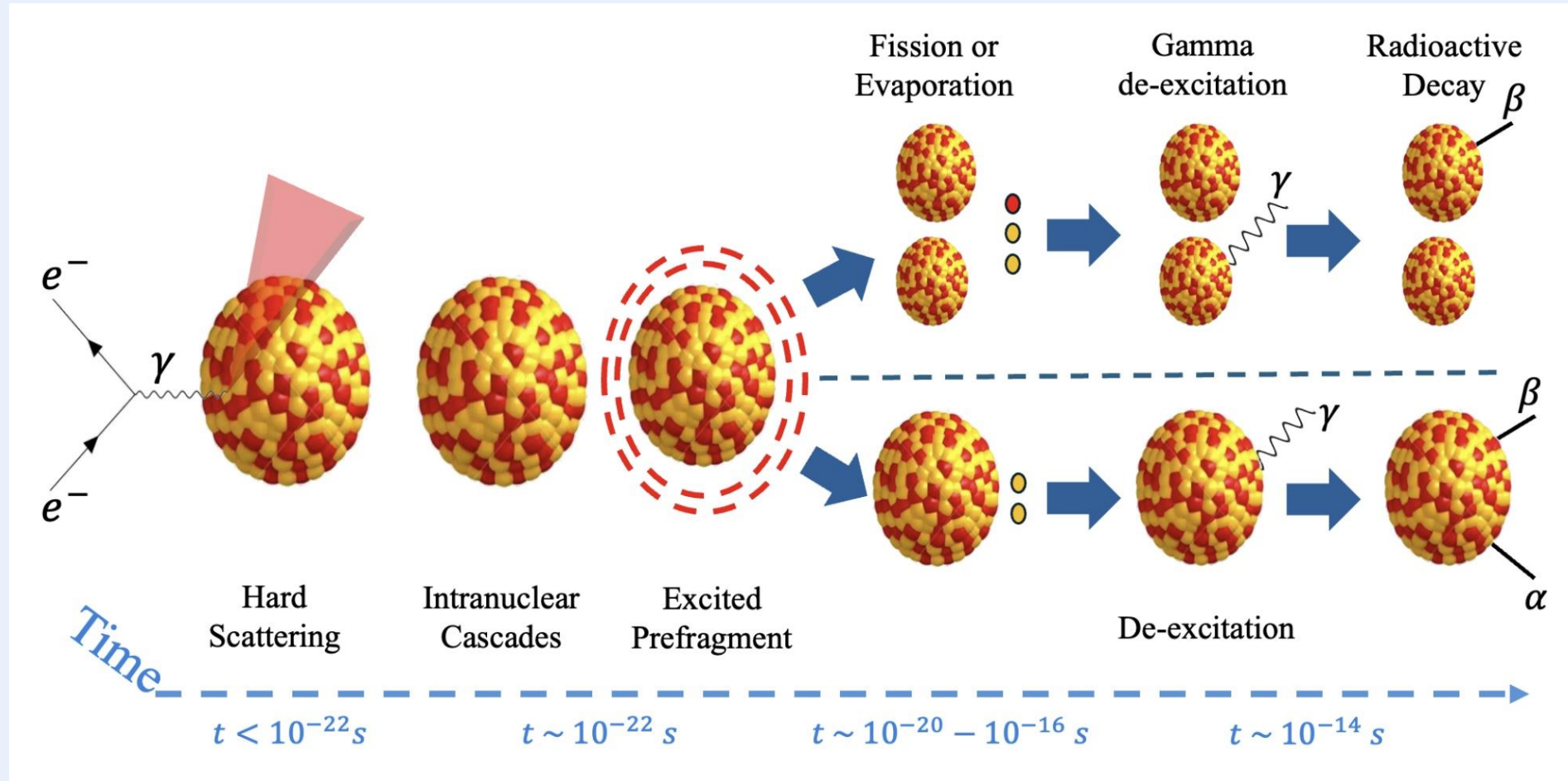
- σ_f^N is independent of target charge
- σ_f^C is negligible for light (low Z) targets and dominates for heavy ones



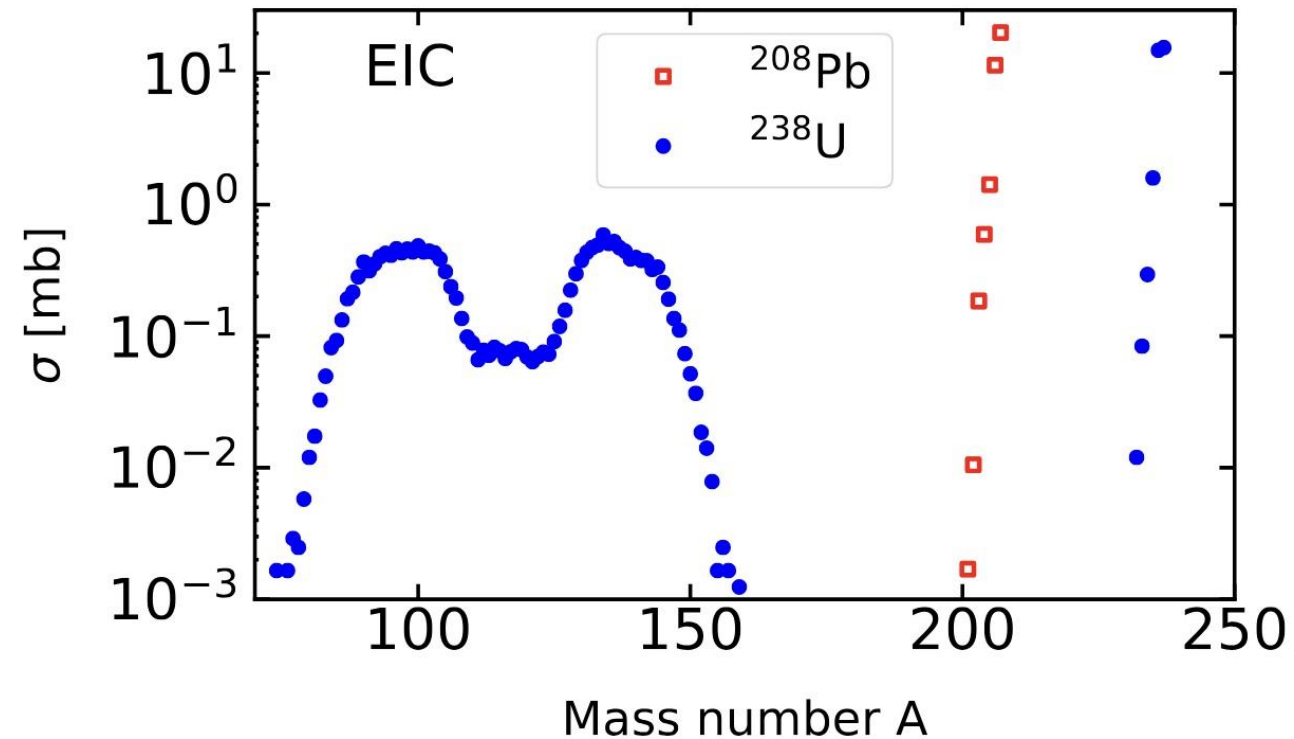
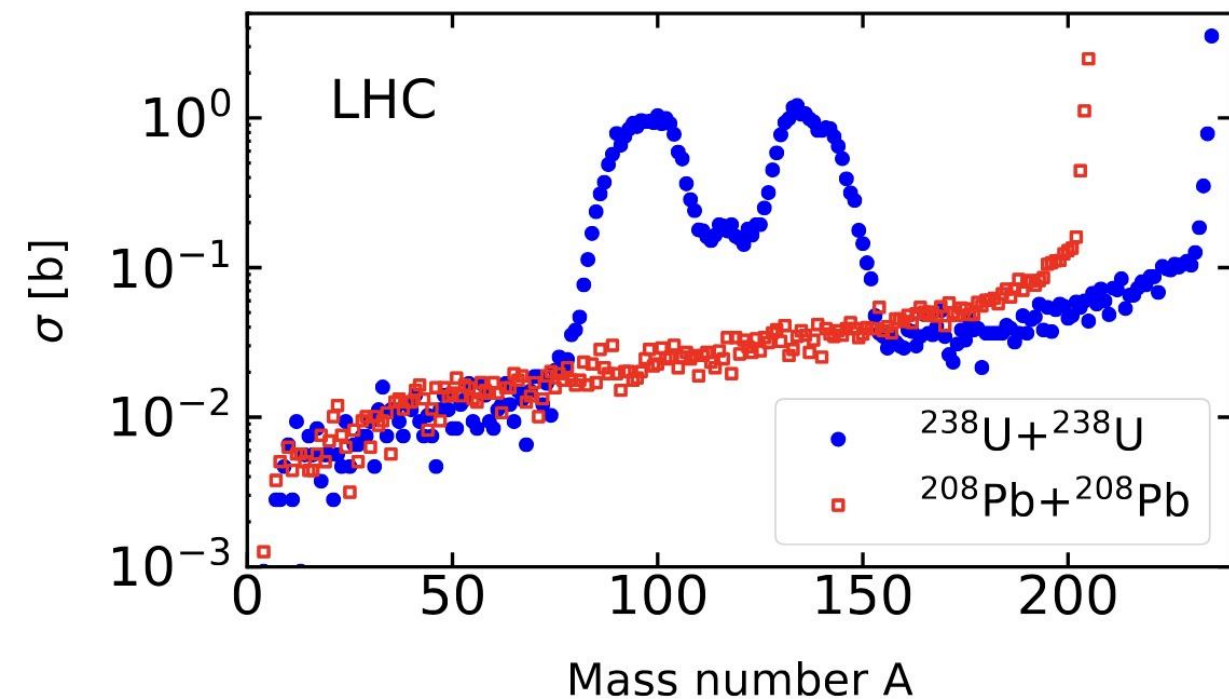


What about fission at the EIC?

Electron induced nuclear excitation can lead to nuclear fragmentation or fission



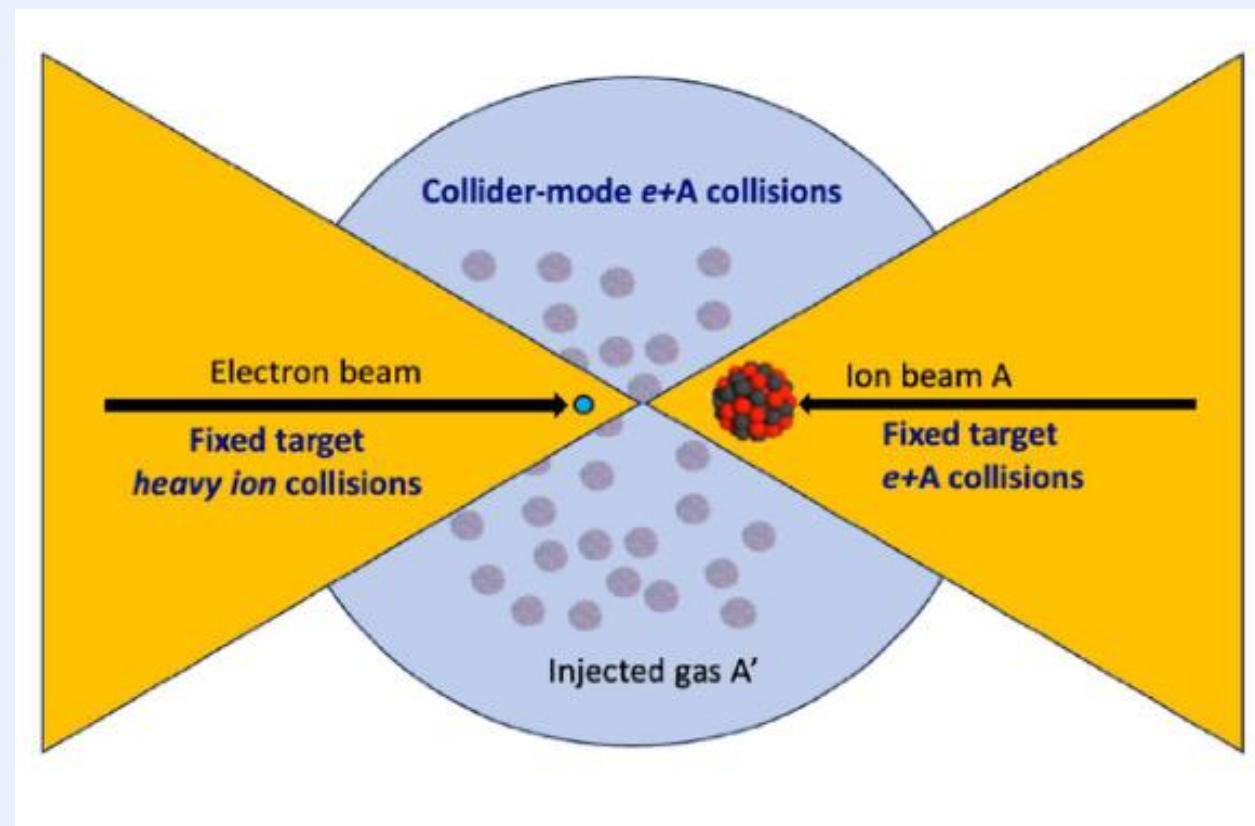
Bertulani et al calculated U+U and Pb+Pb UPC interactions at the LHC and e+U and e+Pb at the EIC



They seem to assume that Pb does not fission, missed a memo?

A fixed-target setup at the EIC could present further opportunities for UPC fission

- Installing target wires in ePIC and/or as part of a second detector would allow for the possibility of UPC fission at the EIC
- Energy region for A+A collisions would be similar to the NA50 setup at the CERN SPS albeit lower than their top energy
- For more physics opportunities in this case, see [arXiv:2603.00265](https://arxiv.org/abs/2603.00265) (submitted to PRD)



PRC 113, 040501 (2026)

Summary

- Fission has been measured at GeV scale energies, both by photofission (JLab) and in UPCs (CERN NA50)
- The EIC presents another possibility to measure fission on these scales in two modes:
 - Collider mode, initiated by electrons/photons
 - Fixed-target mode, initiated in UPCs
 - RHIC already ran U+U collisions so the capability to study U fission in this regime is there