



The 3rd Edition of the Spicy Gluons (胶麻) Workshop for Young Scientists on the Quark-Gluon Matter in Extreme Conditions



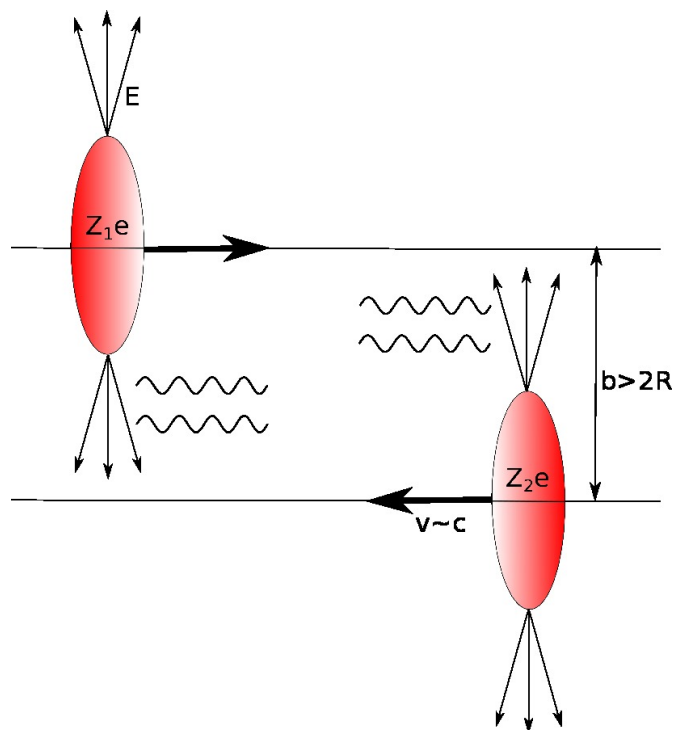
Predictions for Neutron-tagged Coulomb Dissociation in Ultra-peripheral Ru+Ru and Zr+Zr Collisions

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University of Science and Technology of China

Based on the manuscript : <http://arxiv.org/abs/2610.12951>

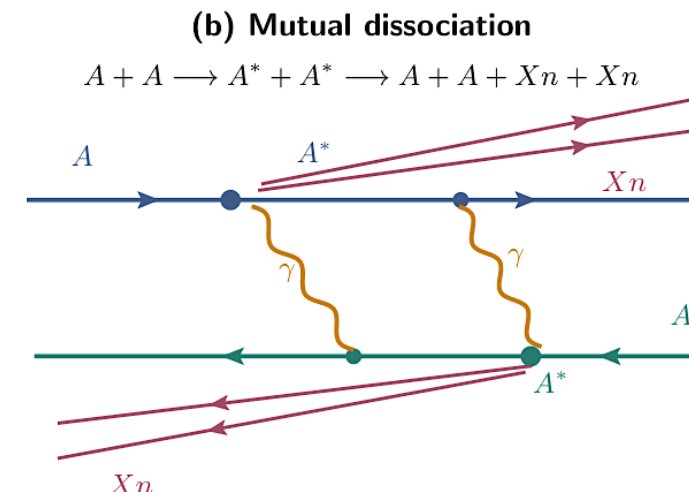
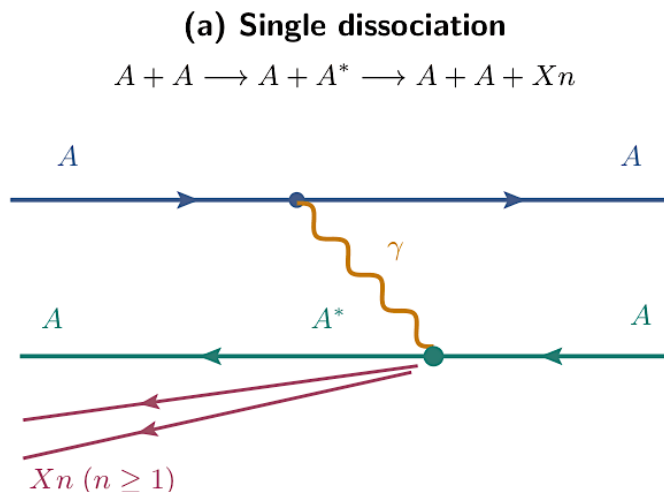
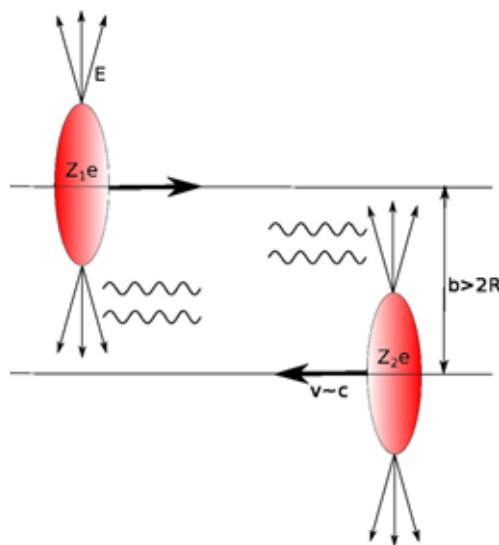
- Physics Motivation
- Mathematical Formulation
- Photonuclear Inputs
- Result & Discussions
- Conclusions



- Quasi-real photons excite a passing nucleus
- Excitation can decay by emitting forward neutrons
- Zero-degree calorimeters provide neutron tags

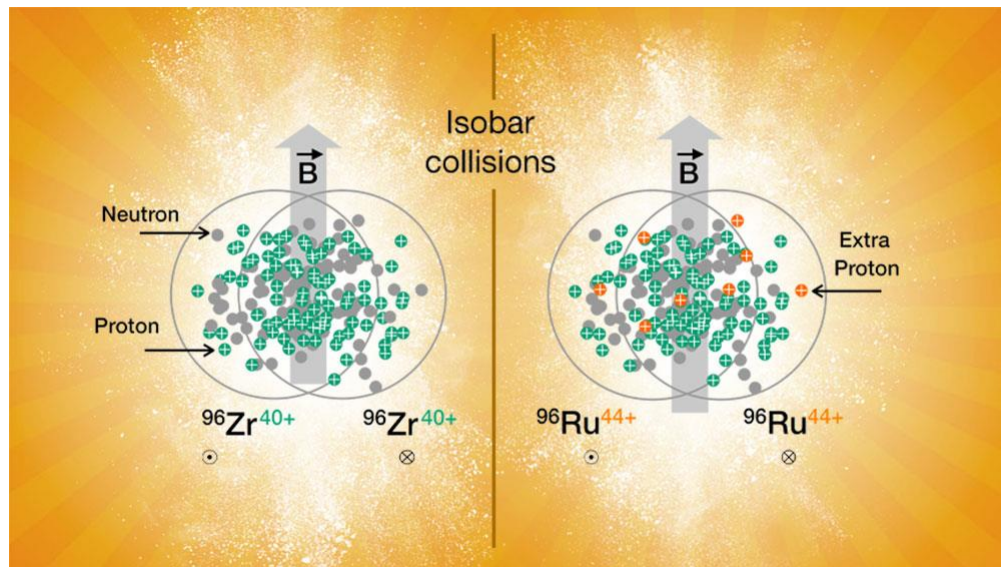
UPC geometry: $b \gtrsim R_1 + R_2$

Coulomb dissociation followed by neutron emission



- Photon excited leads nuclear breakup followed by neutron emission, known as **Coulomb dissociations**
- We investigate two types :
 - a). **Single-Coulomb dissociation (SCD)** : only one specify side neutron-tagged (1n, Xn)
 - b). **Mutual-Coulomb dissociation (MCD)** : both sides neutron-tagged (1n1n, 1nXn, and XnXn)
- The Xn means at least one neutron emission ($Xn \geq 1n$)

The typical **isobar** collisions



<https://www.bnl.gov/newsroom/news.php?a=119062>

Same mass number $A = 96$

Ru : $Z = 44, N = 52$

Zr : $Z = 40, N = 56$

Flux-references for **SCD** & **MCD** :

○ $(44/40)^2 = 1.21$

○ $(44/40)^4 = 1.46$

- **Neutron-tagged Coulomb dissociation probes how nuclear excitation and decay respond to a 10% difference in proton number**
- STAR collected Ru+Ru and Zr+Zr data at $\sqrt{s_{NN}} = 200$ GeV in 2018
- This model provides physics constraint for STAR Isobar neutron-tagged dissociations

- The integral cross-section for Coulomb dissociation is

$$\sigma_{\text{CD}} = \frac{2\alpha Z^2}{\pi\gamma^2} \int_{\omega_{\text{th}}}^{\infty} d\omega \, \omega \sigma_{\gamma A}(\omega) \int_{b_0}^{\infty} db \, b K_1^2\left(\frac{b\omega}{\gamma\hbar c}\right),$$

which formed by $n(\omega, b)$ times $\sigma_{\gamma A}(\omega)$ as photonuclear input

- We utilize **TALYS** [1] (photonuclear model) and **E**valuated **N**uclear **D**ata **F**ile (**ENDF**) which open accessed trough: <https://nds.iaea.org/exfor/endl.htm>

- In real case, when any photon absorbed by target nucleus, the mean number could be described

$$\mu_{Nn}(b) = \int d\omega \, n(\omega, b) \sigma_{\gamma A \rightarrow A^*N}; \quad N = 1, 2, 3, \dots$$

Which μ_{Nn} enable to form the neutron-tagged probability for CD implications

[1] <https://doi.org/10.1140/epja/s10050-023-01034-3>

- The probability of neutron-tagged at any b ranges follows Poisson distribution

$$P_0(b) = e^{-\mu_{xn}(b)},$$

while the total i -neutrons tagged is written as

$$P_{in}(b) = \sum_{k=1}^{\infty} P_i^{(k)}(b).$$

- We apply *hadronic veto* with the survival factor

$$S(b) = e^{(-\sigma_{NN} T_{AA}(b))},$$

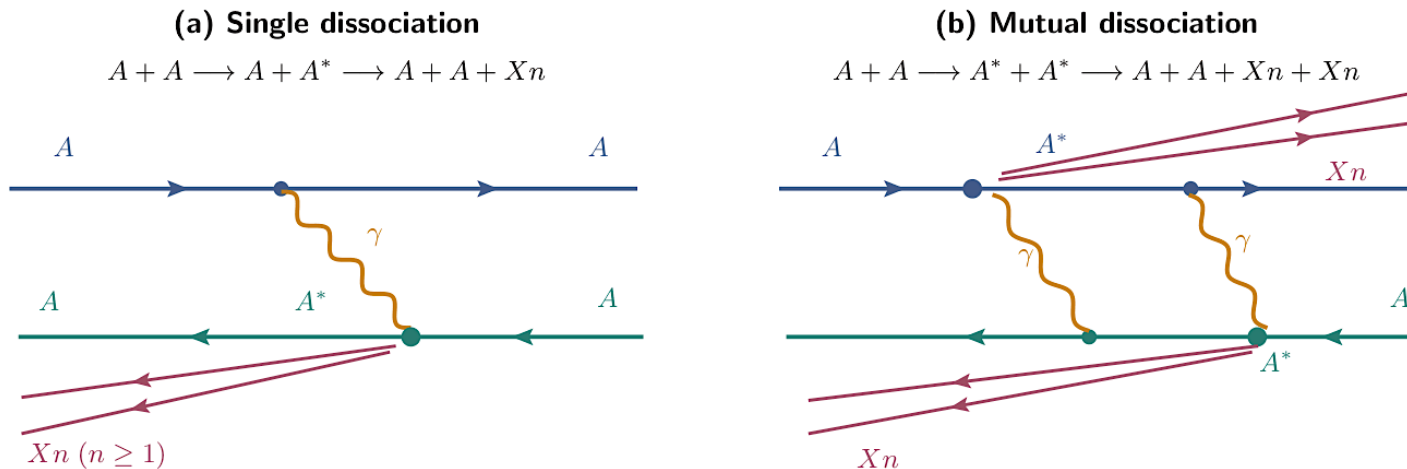
where σ_{NN} is an inelastic cross-section correspond to the collisions system we observed.

The nuclear overlap factor represent as

$$T_{AA}(b) = \int d^2 s T_A(s) T_B(|\vec{b} - \vec{s}|)$$

which T_A and T_B are the nuclear thickness function from Woods-Saxon densities

The final forms of CD cross-sections



- Finally, the integral CD formula can be written

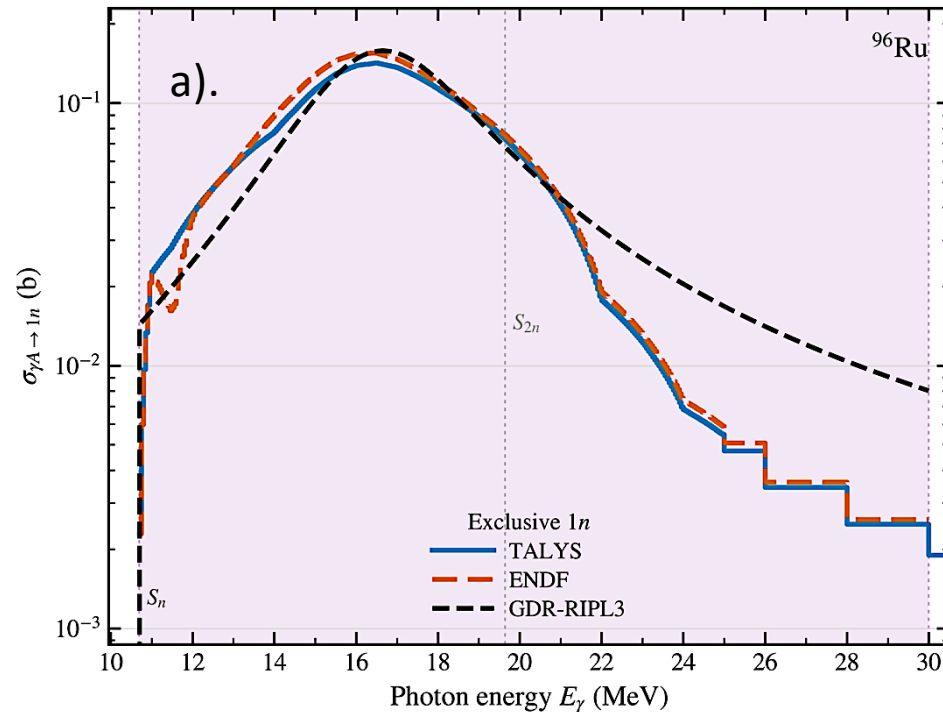
$$\sigma_i = \int_{b_{min}(>2R)}^{b_{max}} 2 \pi b db S(b) P_i(b),$$

for **S**ingle **C**oulomb **d**issociation (**SCD**) such as : σ_{1n} , σ_{Xn}

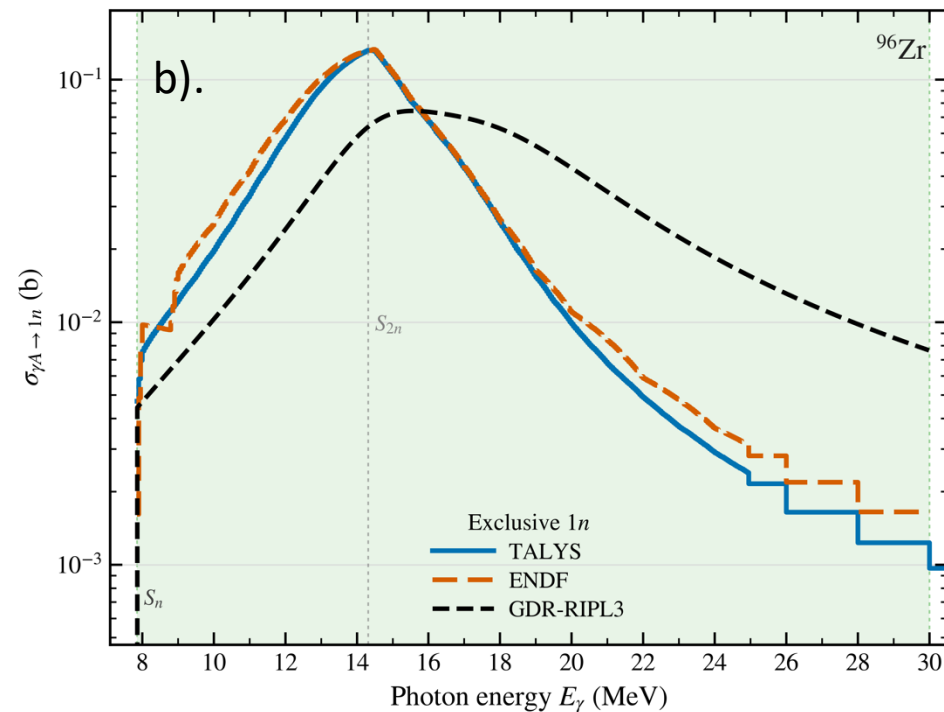
- Then, for **M**utual **C**oulomb **d**issociation (**MCD**) we have

$$\sigma_{ij} = \int_{b_{min}(>2R)}^{b_{max}} 2 \pi b db S(b) P_i(b) P_j(b),$$

index i and j associated with the neutron-tagged channels : σ_{1n1n} , σ_{1nXn} , σ_{XnXn}

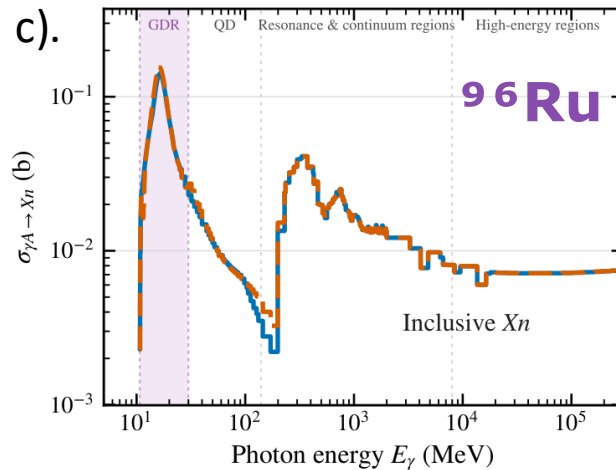


Ru: the GDR peak lies between S_{1n} and S_{2n}



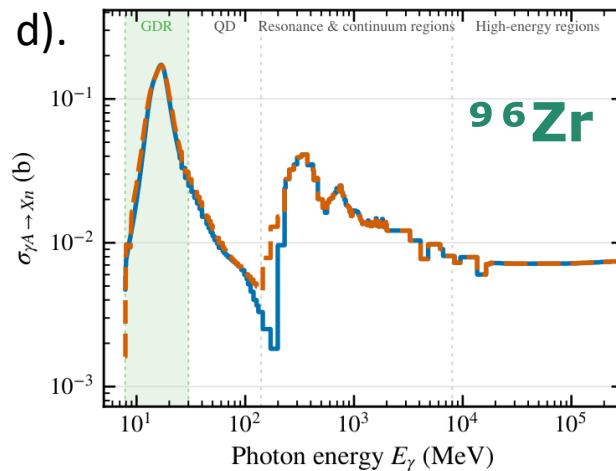
Zr: the GDR peak lies near to the S_{2n}

- We introduce Talys and ENDF as photonuclear inputs for CD neutron-tagged
- The exclusive-1n shows different behavior at GDR regions for both Isobars
- The dashed-line GDR fit parametrization for model comparisons



Inclusive for the higher photonuclear regions

- TALYS provided up to 200 MeV
- ENDF less datasets available
- The higher regions scale to nuclear size-A which follow RELDIS model [2]

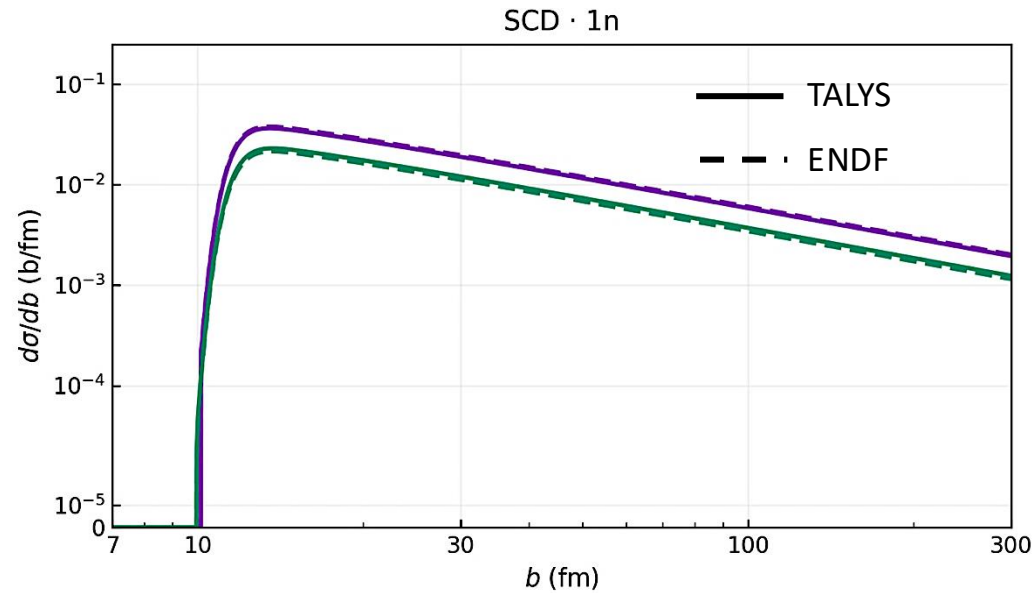


What kind of physics messages can be obtained ?

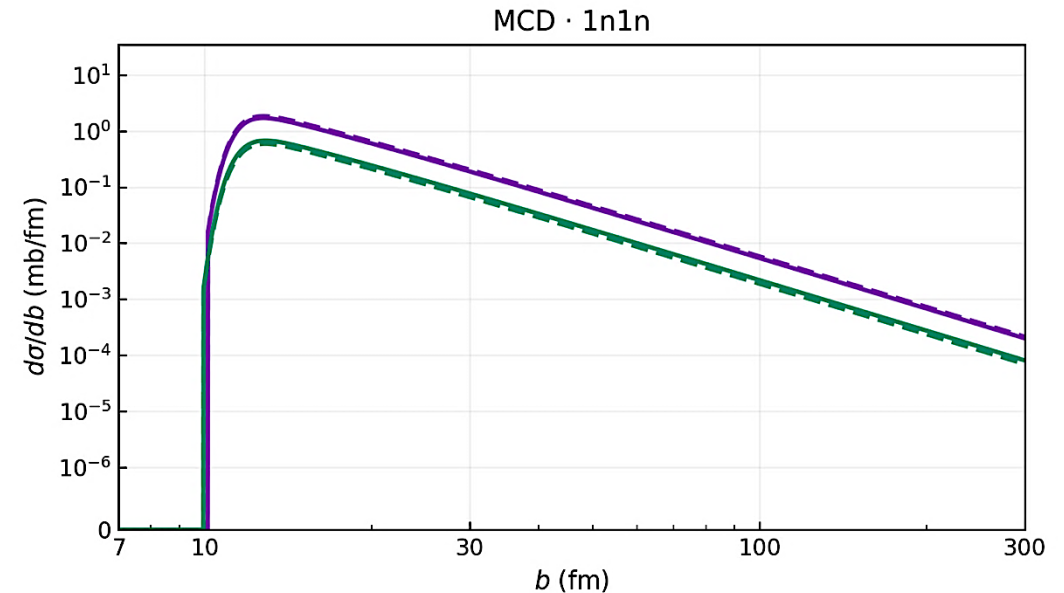
- The 1n emphasizes the GDR region in HEP
- Xn includes higher-energy neutron-channels
- Input spread observed same A sensitivity to observe neutron-tagged behavior

[2] 10.1103/PhysRevC.64.024903

Result : $\frac{d\sigma_{Nn}}{db}$ vs b & σ_{Nn} for exclusive-1n channels



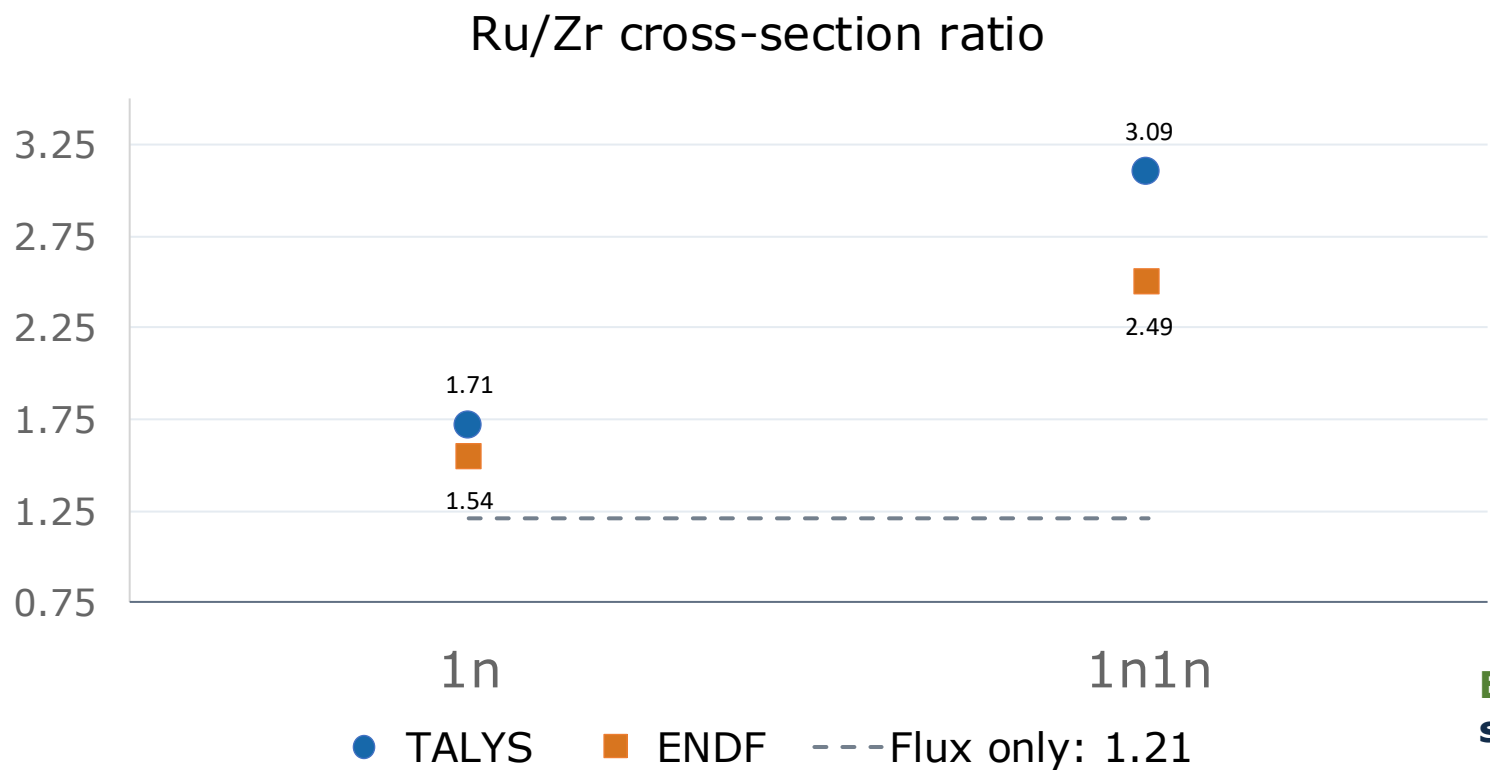
σ (b)	1n
Ru-Ru / ENDF	5.58
Ru-Ru / TALYS	5.73
Zr-Zr / ENDF	3.62
Zr-Zr / TALYS	3.36



σ (mb)	1n1n
Ru-Ru / ENDF	16.62
Ru-Ru / TALYS	17.90
Zr-Zr / ENDF	6.66
Zr-Zr / TALYS	5.79

- The differential cross-sections shows stronger $^{96}_{44}\text{Ru}$ manifestations on exclusive-1n than $^{96}_{40}\text{Zr}$
- The GDR peak in photonuclear input imprint on neutron single- and both- sides tagged
- TALYS and ENDF provided internal evaluation which shows in Isobar CD cross-sections

Exclusive-1n and -1n1n breaks the flux-scale references



1.54–1.71

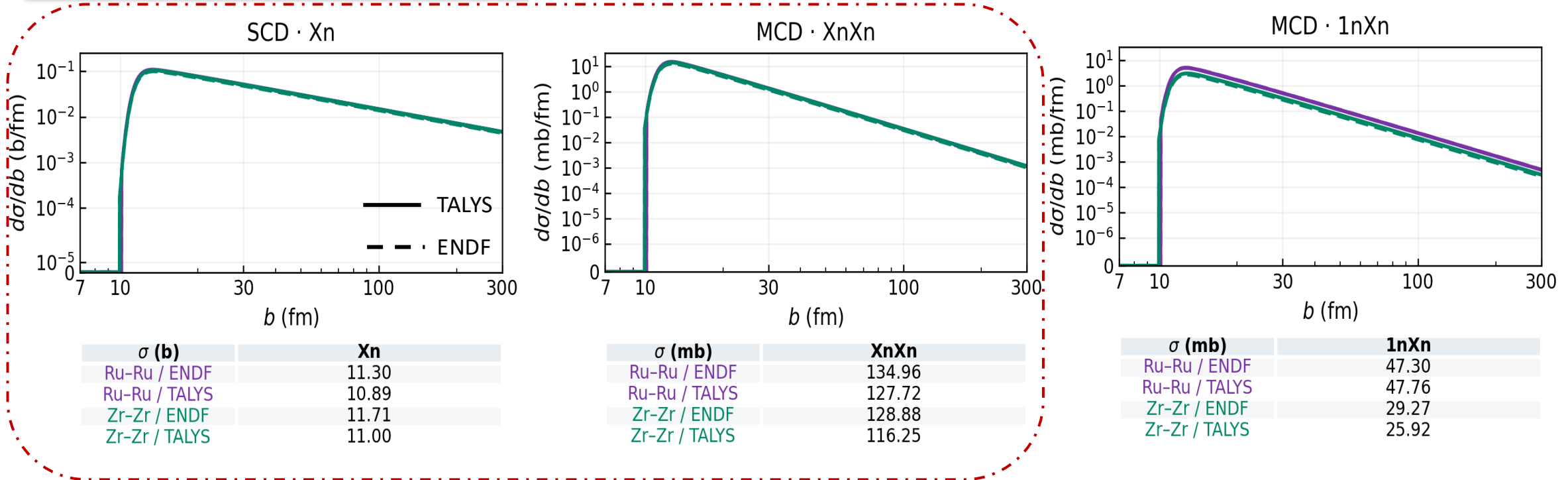
Exclusive-1n ratio reveals sensitivity beyond $Z^2 \approx 1.21$ scaling

2.49–3.09

Exclusive-1n1n ratio amplifies the sensitivity beyond $Z^4 \approx 1.46$ scaling

- Stronger Ru 1n response reinforces its larger photon flux
- The mutual 1n1n channels amplify to the ratio channels

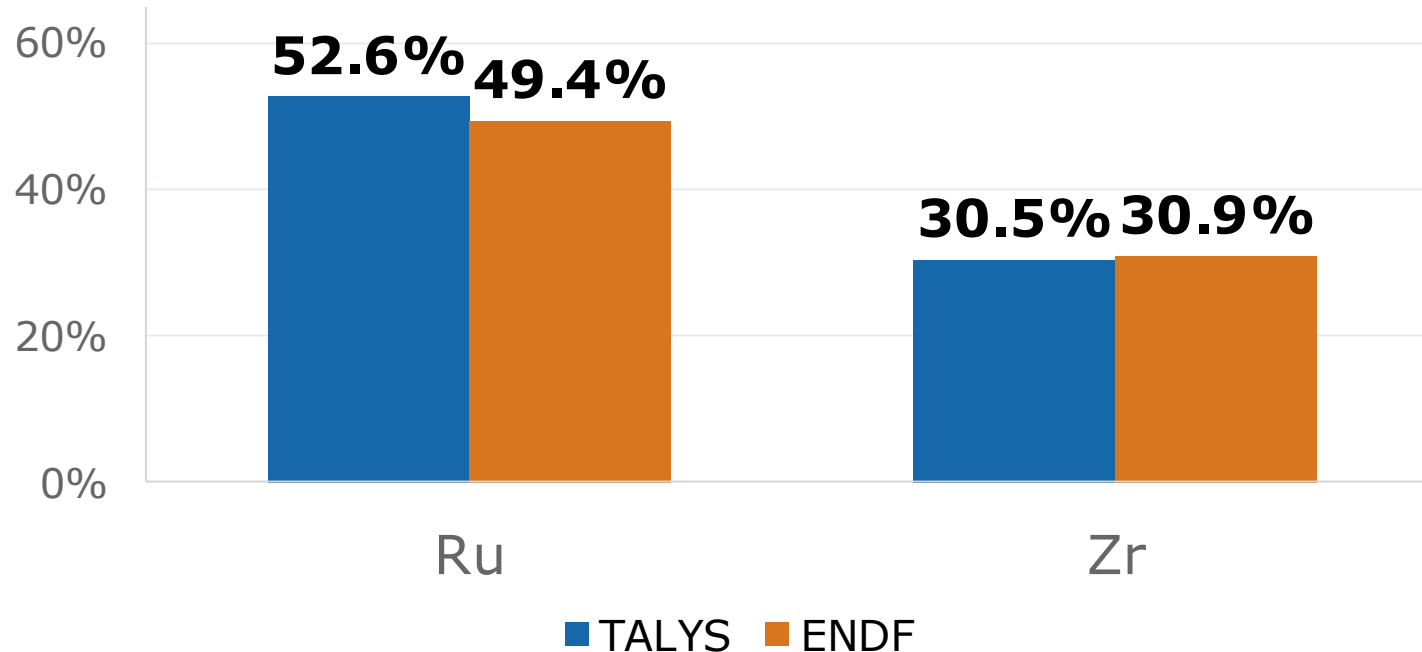
Result : $\frac{d\sigma_{Nn}}{db}$ vs b & σ_{Nn} for inclusive-Xn channels



- The inclusive-Xn channels shows similar trend for both isobar differential cross-sections vs b plot
- The higher Xn photonuclear inputs enter through neutron-tagged channels
- The asymmetric 1nXn tagged channels shows moderates since one side restricted to exclusive-1n

The hidden 1n message on Xn neutron-tagged

Exclusive-1n fraction: $\sigma(1n) / \sigma(Xn)$



Ru: 49–53%

Zr: $\approx 31\%$

Similar Xn yields,
different neutron
composition

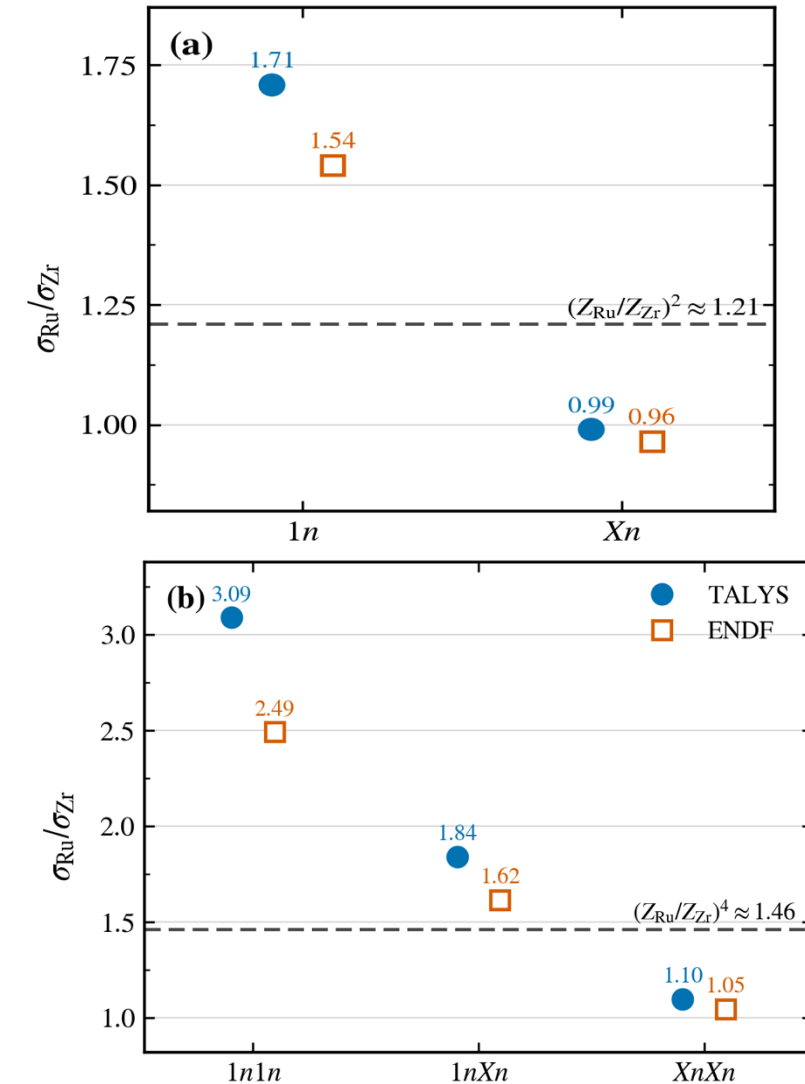
- Integrated UPC yield fractions reflect photonuclear response behavior into neutron-tagged
- The GDR reactions which 1n-tagged more strongly manifest on inclusive Xn neutron-tagged

Conclusion

- We calculated neutron-tagged Coulomb dissociation in Isobar UPCs
- The $1n$ & $1n1n$ channel ratio is significantly higher than Z^2 and Z^4 scaling for SCD and MCD ratio, respectively
- The inclusive Xn & $XnXn$ ratio shows more related nuclear size behavior
- The exclusive- $1n$ indicates GDR reaction still dominant on high energy photoabsorptions
- This provides excellent constraints for experimental neutron-tagged Coulomb dissociations

Outlook:

- Compare to STAR experimental data
- Study the photonuclear response in nuclear structure model



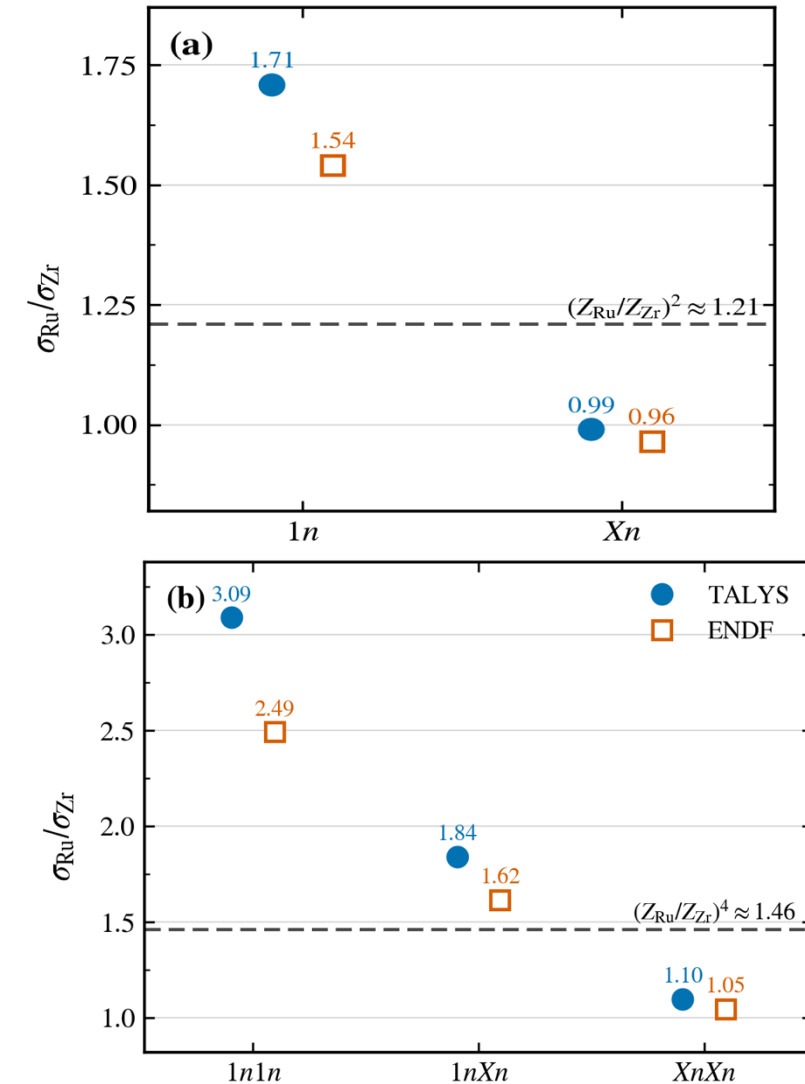
Conclusion

- We calculated neutron-tagged Coulomb dissociation in Isobar UPCs
- The $1n$ & $1n1n$ channel ratio is significantly higher than Z^2 and Z^4 scaling for SCD and MCD ratio, respectively
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- The exclusive- $1n$ indicates GDR reaction still dominant on high energy photoabsorptions
- This provides excellent constraints for experimental neutron-tagged Coulomb dissociations

Thank You !

Outlook:

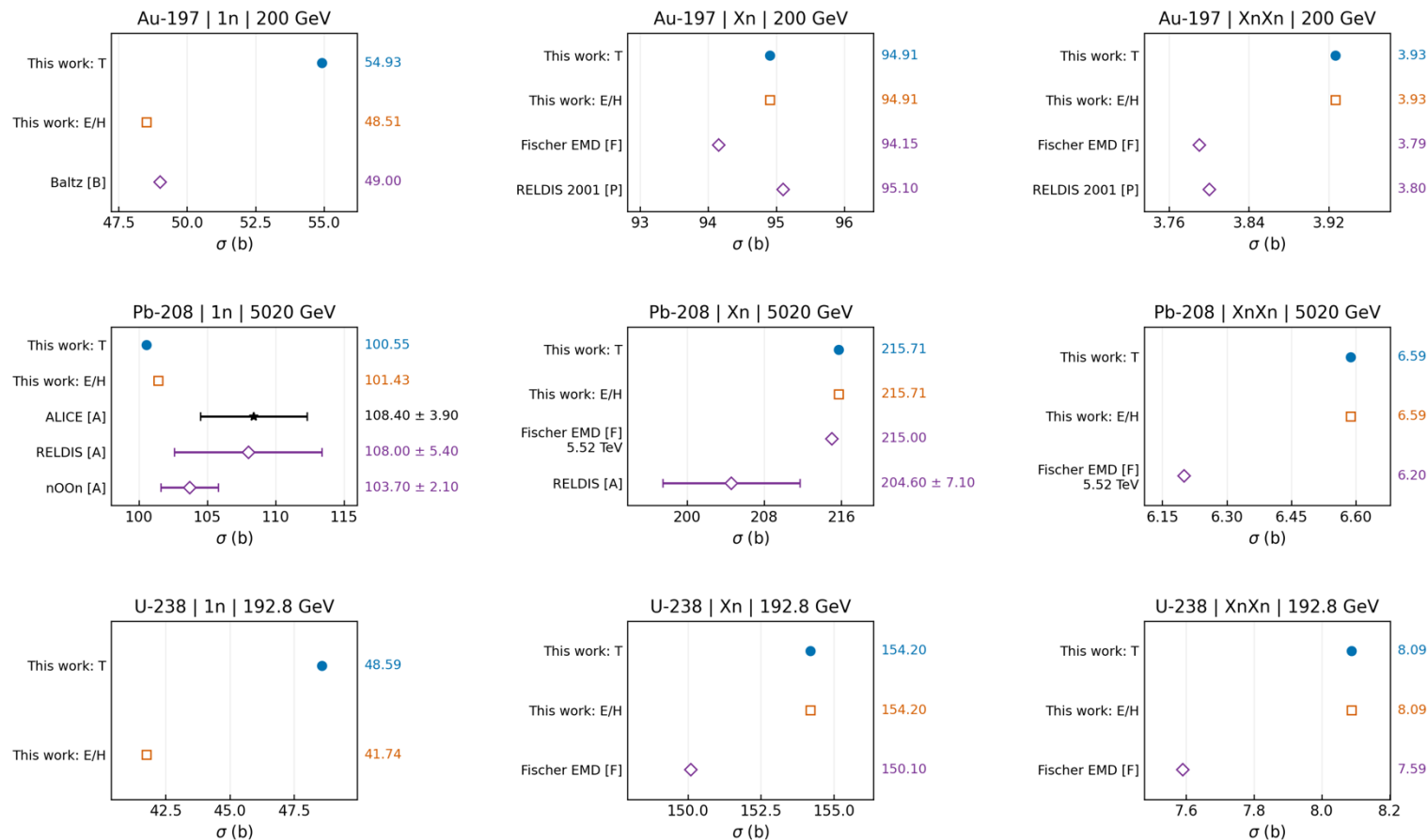
- Compare to STAR experimental data
- Study the photonuclear response in nuclear structure model



Backup

Au, Pb and U: detailed comparison with published references

Blue / orange: current inputs Black star: experiment Purple diamonds: published models



T = TALYS-based; E/H = ENDF / hybrid. Errors are published reference errors; ALICE statistical and systematic errors are combined.

Total EMD [F, P] and neutron-tagged EMD have different scope. Pb [F] uses 5.52 TeV; current Pb uses 5.02 TeV. U 1n has no external reference here.

[A] ALICE, PRC 107 (2023) 064902 [B] Baltz et al., NIM A 417 (1998) 1 [P] Pshenichnov et al., PRC 64 (2001) 024903 [F] Fischer et al., PRC 89 (2014) 014906

Table for other ion systems and any comparisons

All-ion benchmark table | Cross sections in barns

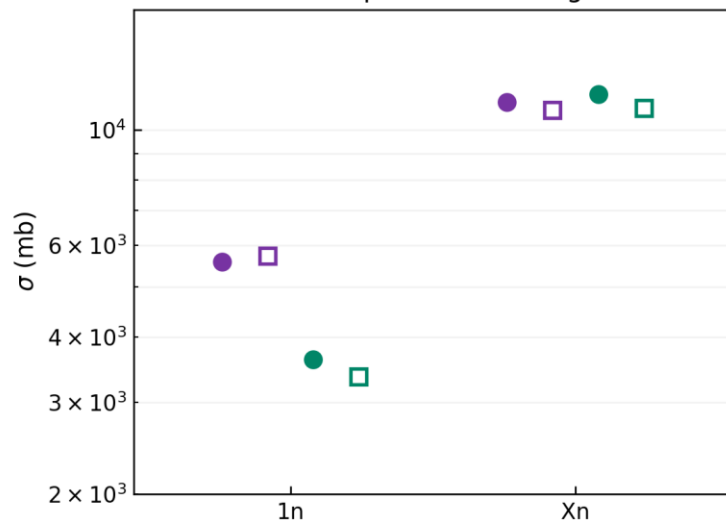
Current production outputs; two photonuclear input choices shown separately

System	$\sqrt{s_{NN}}$ (GeV)	Channel	This work TALYS-based	This work ENDF / hybrid	Published reference (b)
O-16 + O-16	200	1n	0.0104	0.006471	Baltz scaling: 0.05 [B]
		Xn	0.03684	0.03817	Baltz scaling: 0.1 [B]
		XnXn	5.93e-06	6.22e-06	Baltz scaling: 4e-06 [B]
Ru-96 + Ru-96	200	1n	5.73	5.58	No external benchmark in selected sources
		Xn	10.89	11.30	No external benchmark in selected sources
		XnXn	0.1277	0.135	No external benchmark in selected sources
Zr-96 + Zr-96	200	1n	3.36	3.62	No external benchmark in selected sources
		Xn	11.00	11.71	No external benchmark in selected sources
		XnXn	0.1162	0.1289	No external benchmark in selected sources
Au-197 + Au-197	200	1n	54.93	48.51	Baltz: 49.00 [B]
		Xn	94.91	94.91	Fischer EMD: 94.15 [F] RELDIS 2001: 95.10 [P]
		XnXn	3.93	3.93	Fischer EMD: 3.79 [F] RELDIS 2001: 3.80 [P]
Pb-208 + Pb-208	5020	1n	100.55	101.43	ALICE: 108.40 ± 3.90 [A] RELDIS: 108.00 ± 5.40 [A] nOOn: 103.70 ± 2.10 [A]
		Xn	215.71	215.71	Fischer EMD: 215.00 [F] (5.52 TeV) RELDIS: 204.60 ± 7.10 [A]
		XnXn	6.59	6.59	Fischer EMD: 6.20 [F] (5.52 TeV)
U-238 + U-238	192.8	1n	48.59	41.74	No external benchmark in selected sources
		Xn	154.20	154.20	Fischer EMD: 150.10 [F]
		XnXn	8.09	8.09	Fischer EMD: 7.59 [F]

$^{96}\text{Ru} + ^{96}\text{Ru}$ and $^{96}\text{Zr} + ^{96}\text{Zr} \mid \sqrt{s_{NN}} = 200 \text{ GeV}$

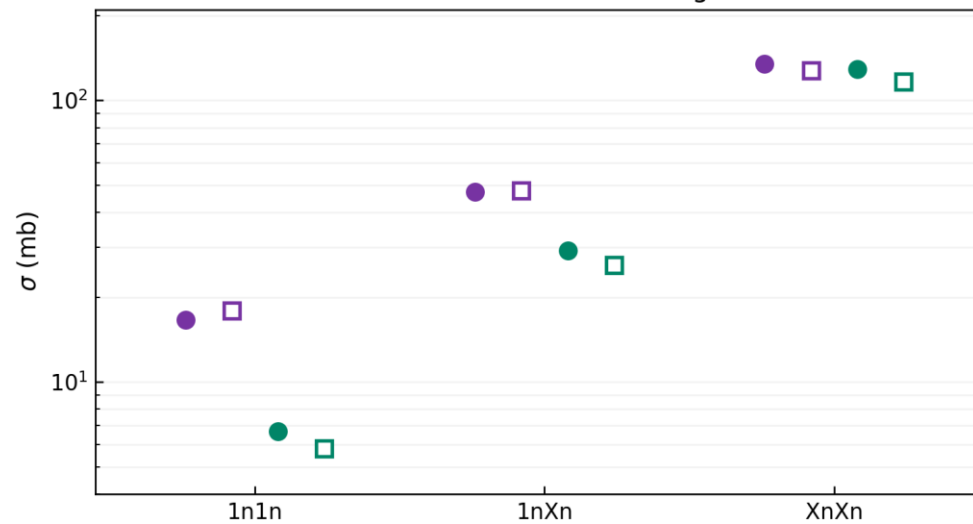
● Ru-Ru / ENDF □ Ru-Ru / TALYS ● Zr-Zr / ENDF □ Zr-Zr / TALYS

SCD · specified-side tags

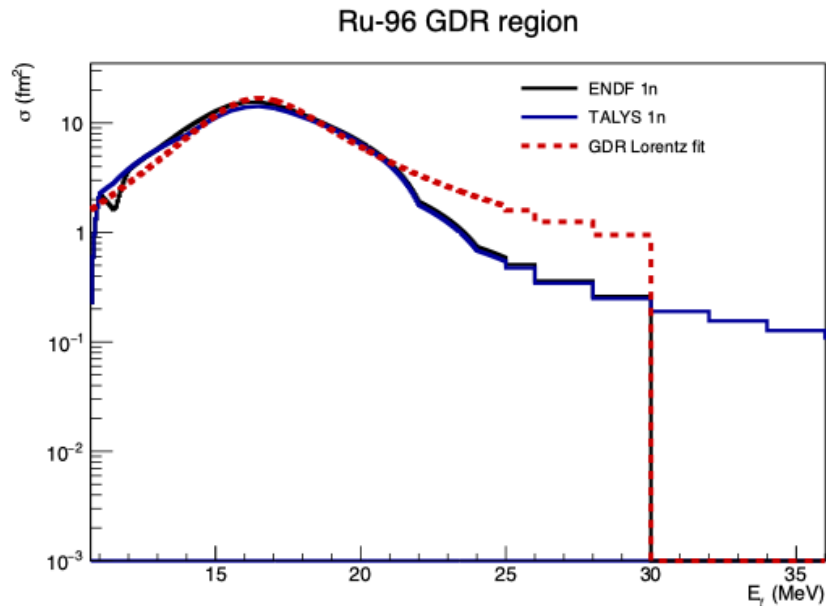


$\sigma \text{ (mb)}$	1n	Xn
Ru-Ru / ENDF	5,581.66	11,302.13
Ru-Ru / TALYS	5,734.02	10,894.75
Zr-Zr / ENDF	3,621.72	11,713.16
Zr-Zr / TALYS	3,355.50	10,999.31

MCD · ordered mutual tags



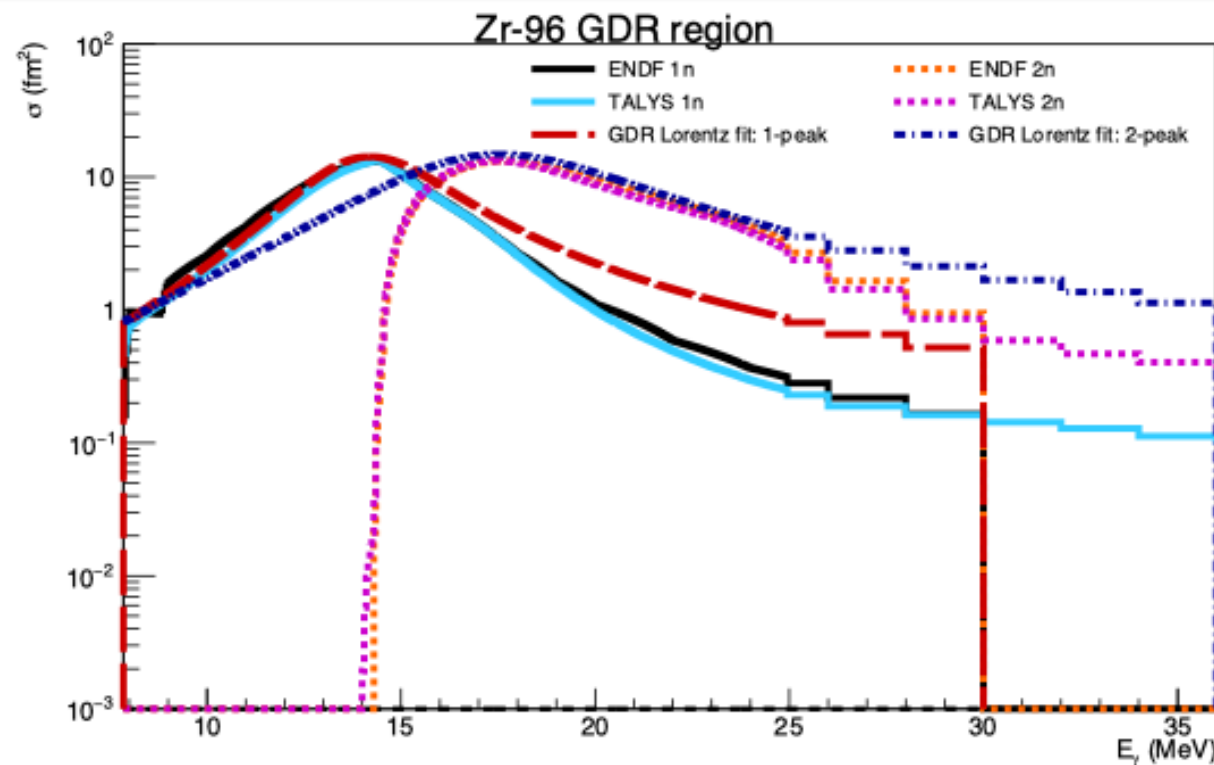
$\sigma \text{ (mb)}$	1n1n	1nXn	XnXn
Ru-Ru / ENDF	16.62	47.30	134.96
Ru-Ru / TALYS	17.90	47.76	127.72
Zr-Zr / ENDF	6.66	29.27	128.88
Zr-Zr / TALYS	5.79	25.92	116.25



Theoretical Predictions of GDR Parameters

Z	A	El	Eta	E1 [MeV]	G1 [MeV]	E2 [MeV]	G2 [MeV]
44	96	Ru	1.108	16.65	4.80	16.65	4.80

- The exclusive 1n photonuclear inputs of Ru96 from: Talys & ENDF, we evaluated with GDR Lorentz fit parameterization
- The theoretical RIPL-3 parameters and σ_{peak} from fitting, we show in the dashed plot as comparison
- The 1n peak from low region of Talys & ENDF are suitable each other as compare to the GDR fit
- The different distributions only appears after $E_\gamma > 21$ since may the GDR fit set the interpolation only until 30 MeV



Theoretical Predictions of GDR Parameters

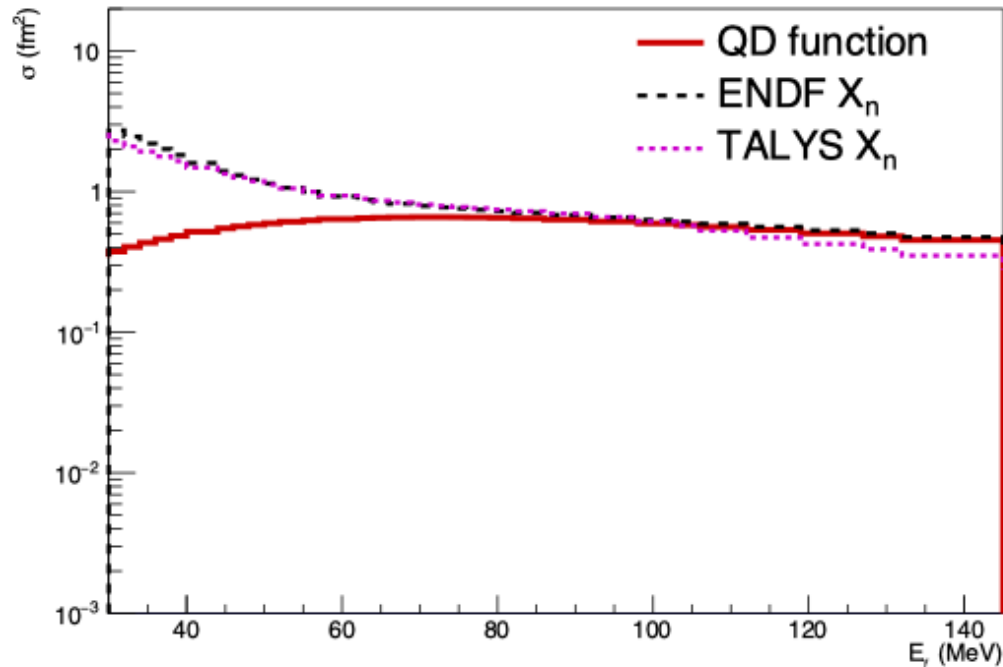
Z	A	El	Eta	E1 [MeV]	G1 [MeV]	E2 [MeV]	G2 [MeV]
40	96	Zr	1.198	14.86	4.30	17.54	7.54

Descriptions

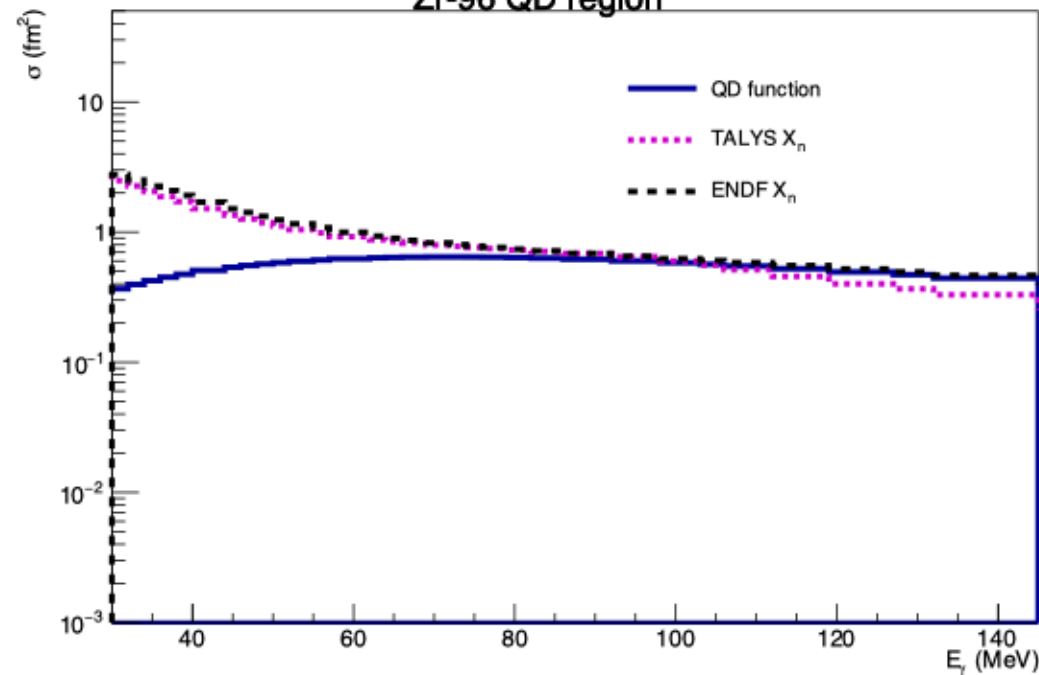
- For Zr96, since we found any two electric dipoles in the RIPL-3 parameter, we used all the parameters for GDR Lorentz plot
- We compare with 1n & 2n of Talys and ENDF input to evaluate with two GDR Lorentz fits
- GDR Lorentz can shape the 1n and 2n peak from both Talys and ENDF

Photonuclear in QD-Region

Ru-96 QD region

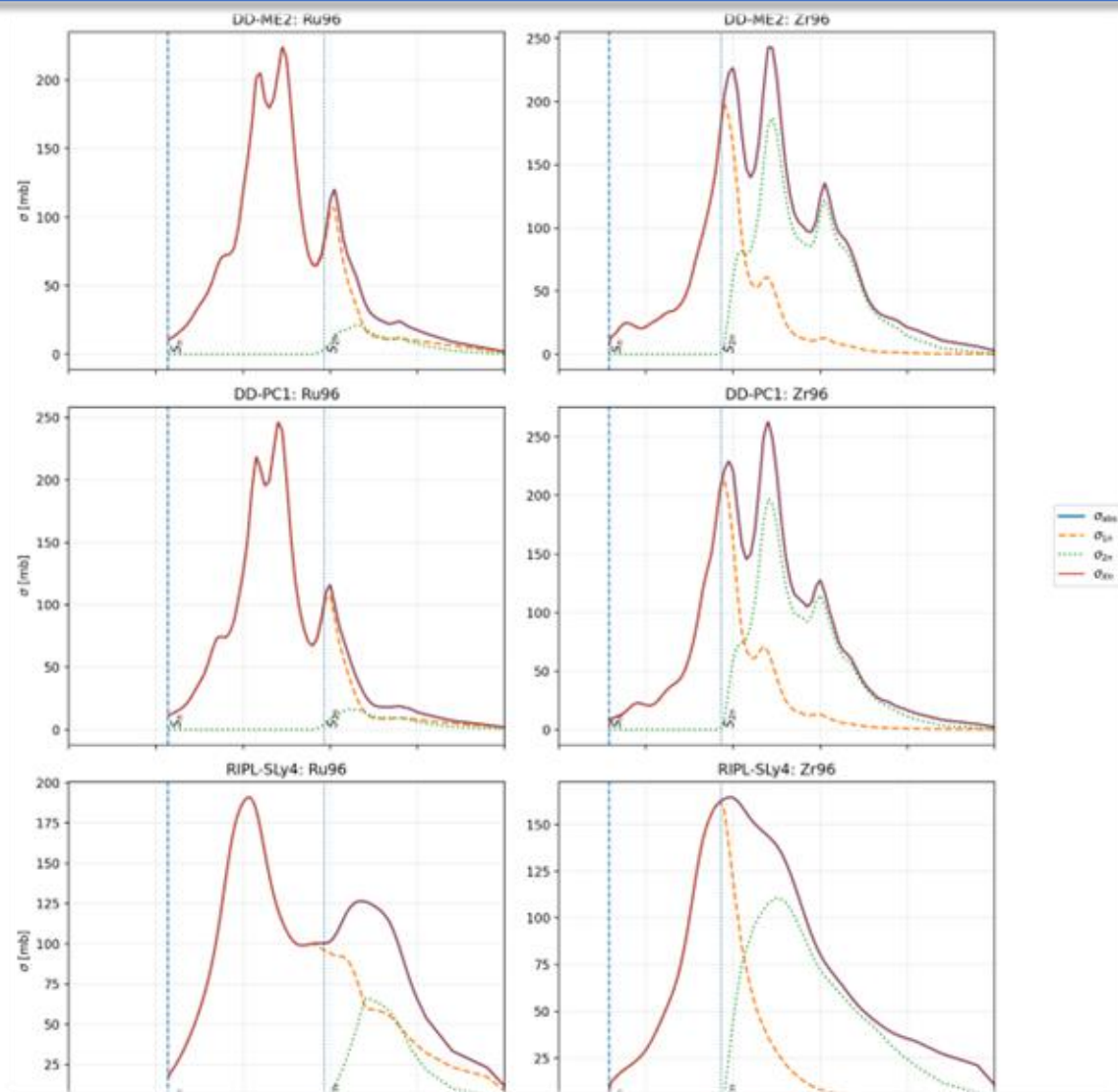


Zr-96 QD region



- Beyond GDR region, which are $40 < E_\gamma < 140$, the Quasi-deuteron regions is dominant.
- We evaluate both TALYS and ENDF photonuclear input with QD plot as show in figures.
- The similar trend as happened with those two inputs at QD regions which means the higher region also promising to be used
- Since the limited data for high energy photonuclear inputs, we scaled the photonuclear regions higher than QD or around 200 MeV as follow with existing models

Photonuclear input with EDF model dependence



- We show some EDF model for observing photonuclear input at GDR regions
- The Photon Strength Function distributions explicitly show different distribution
- Ru has more 1n-region for PSF peak, meanwhile PSF for Zr has balance peak for 1n- and 2n-regions
- This may reflect to behaviour 1n and 2n emission on both Isobars even though in high energy Coulomb dissociations



TALYS: modeling of nuclear reactions

This is now the basic reference
for TALYS

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Received: 16 February 2023 / Accepted: 6 May 2023

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Communicated by Nicolas Alamanos

Abstract TALYS is a software package for the simulation of nuclear reactions below 200 MeV. It is used worldwide for the analysis and prediction of nuclear reactions and is based on state-of-art nuclear structure and nuclear reaction models. A general overview of the implemented physics and capabilities of TALYS is given. The general nuclear reaction mechanisms described are the optical model, direct reactions, compound nucleus model, pre-equilibrium reactions and fission. The most important nuclear structure models are those for masses, discrete levels, level densities, photon strength functions and fission barriers. A wide variety of nuclear reactions simulated with TALYS will be demonstrated, ranging from low-energy neutron cross sections, astrophysics, high-energy charged particle reactions and other reactions. TALYS is a nuclear reaction software which aims to give a complete description of nuclear reaction observables, and to be an important link between fundamental nuclear physics and applications.

2.3.4	Residual production cross sections
2.3.5	Gamma-ray production cross sections
2.3.6	Fission cross sections
2.4	Spectra and angular distributions
2.4.1	Discrete angular distributions
2.4.2	Exclusive spectra
2.4.3	Binary spectra
2.4.4	Total particle production spectra
2.4.5	Double-differential cross sections
2.4.6	Recoils
3	Optical model
3.1	Spherical OMP: neutrons and protons
3.1.1	Dispersive OMP: neutrons
3.1.2	Semi-microscopic JLMb OMP
3.1.3	Extension to 1 GeV
3.2	Deformed OMP: neutrons
3.3	Spherical OMP: complex particles
3.3.1	Deuterons
3.3.2	Tritons

- TALYS is a software package for simulating nuclear reactions.
- It is effectively used for energy < 200 MeV
- We will utilize the TALYS tools for the GDR neutron emission reactions.

- Create input files for Ru^{96} and Zr^{96}
- Set the energy range for the typical reactions of interest
- Obtain output reactions corresponding to the defined energy range
- We also extend to 200 MeV in order to have more neutron data

• Ru^{96}

```
Users > hudaphysics > workphys > apk > taly
1  projectile g
2  element Ru
3  mass 96
4  energy energies_5_200.dat
5
```

• Zr^{96}

```
Users > hudaphysics > workphys > apk > taly
1  projectile g
2  element Zr
3  mass 96
4  energy energies_5_200.dat
5
```

```
Users > hudaphysics > workphys > apk > taly
1  5.0
2  6.0
3  7.0
4  8.0
5  9.0
6  10.0
7  10.5
8  11.0
9  11.2
10 11.4
11 11.6
12 11.8
13 12.0
14 12.2
15 12.4
16 12.6
17 12.8
18 13.0
19 13.2
20 13.4
21 13.6
22 13.8
23 14.0
24 14.2
25 14.4
26 14.6
27 14.8
28 15.0
29 15.2
30 15.4
31 15.6
32 15.8
33 16.0
34 16.2
35 16.4
36 16.6
37 16.8
38 17.0
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