The $(p, 3p)$ reaction mechanism in neutron-rich medium-mass nuclei

SFB 2021 Workshop - Project A08

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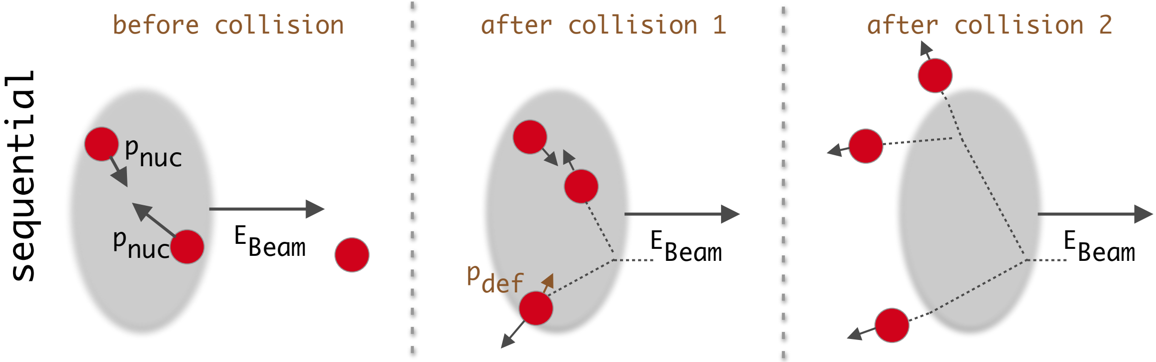
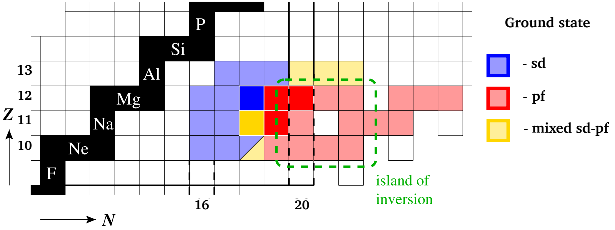
SEASTAR14,15 Collaboration

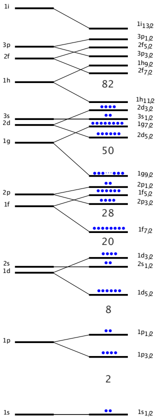


Shell evolution

- Shell model used to describe nuclear structure
- Shell evolution driven by single-particle energies and correlations
- SP states vs. correlations $\rightsquigarrow$ intruder states, islands of inversion
- Example: ^{32}Mg (0^+_2 0p-0h vs. 0^+_1 2p-2h state)



$N = 20$ Island of inversion. Adapted from Butler *et al.* J. Phys. G **44.4** 2017



From PhD-Thesis N. Paul (2019)

$(p,3p)$ selectivity

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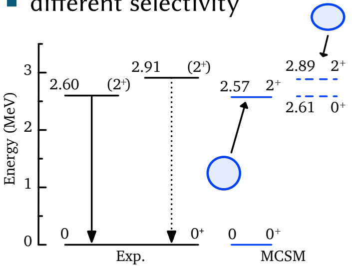
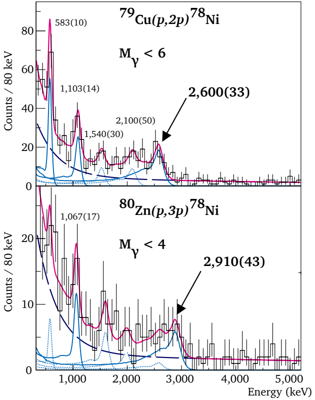
- Example for 2p-2h State: ^{78}Ni
- excited 2_1^+ $(p,2p)$, 2_2^+ $(p,3p)$
- different selectivity



Simplified Level Scheme ^{78}Ni



Taniuchi *et al.* Nature **569** 7754 (2019)

- Wimmer *et al.* PRL **109**, 202505 (2012)
- 140 MeV/u ^{40}Ar on ^{9}Be @ NSCL
- $\rightsquigarrow$ 56(12) % pair knockout
- access to momentum distribution of p-p pairs?
- reaction mechanism needs clarification

SEASTAR - Campaigns

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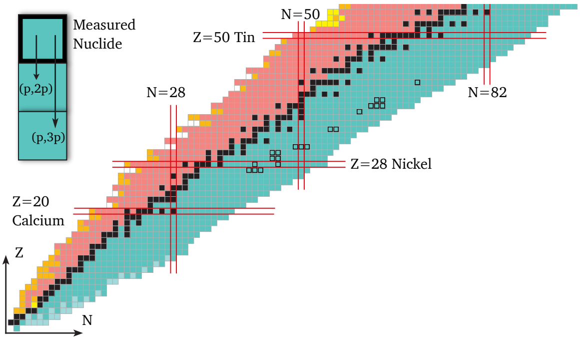
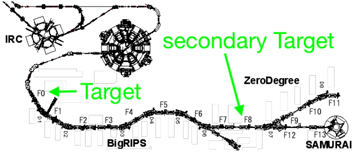
- SEASTAR = **S**hell **e**volution **a**nd **s**earch for **t**wo-plus energies **a**t the **R**IBF
- measurement campaign at RIBF in RIKEN, Japan
- **Goals of this work**:
  - $(p, 2p)$ & $(p, 3p)$ reaction cross sections
  - understanding $(p, 3p)$ reaction mechanism (single vs multistep process)
- two campaigns: 2014, 2015
- Mass range 65-114, chosen for spectroscopy, tuned to (p,2p)



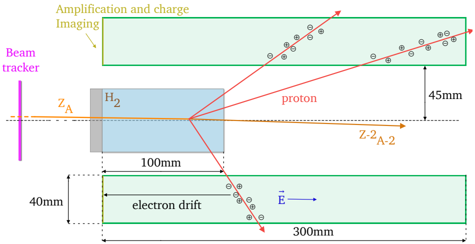
Adapted from Sóti *et al.* EPJ **5** (2019) p.6

Setup

- ^{238}U @ $12_{(S1)}$ - $35_{(S2)}$ pnA @ 345 MeV/u
- BigRIPS + ZeroDegree spectrometers
- Settings:
  - (^{66}Cr, ^{70}Fe, ^{78}Ni)$_1$
  - (^{110}Nb, ^{88}Ge, ^{94}Se, ^{100}Kr)$_2$
- LH$_2$-target with surrounding TPC (MINOS) and γ-Arrays
- large coverage for three protons (TPC)

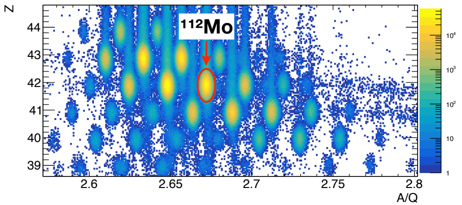


Overview of RIBF, N. Fukuda (2013) NIM **317**, 323-332

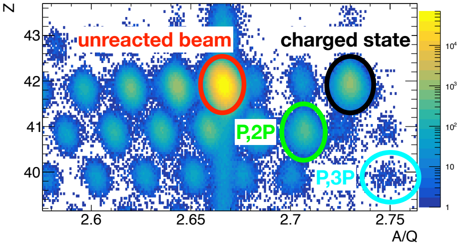


PID generation & reaction determination

- for $(p,2p)$ and $(p,3p)$ reactions PID is needed in front (F3-F7) and after (F8-F11) the LH_2-Target
- select reaction by cutting out particle blob



- mainly unreacted beam
- $(p,2p)$ and $(p,3p)$ well separated
- charge state problematic (subtracted)



cross sections and cross section ratios

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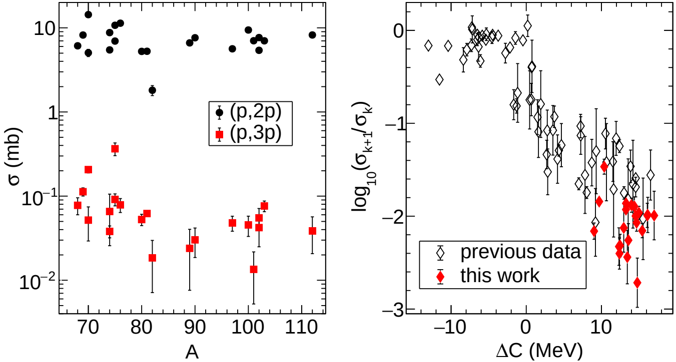
- $(p, 2p)$ cross sections flat, agree with N. Paul *et al.* PRL **122**, 162503
- $(p, 3p)$ cross sections in expected region ($\approx 0.1\ mb$)
- ΔC = evaporation cost asymmetry $\Delta C = S_p + V_C - S_n$
- $\sigma_{(p,3p)}/\sigma_{(p,2p)}$, $(k = 1)$ is reproduced well in cascade process



Previous data: L. Audirac *et al.* PRC **88**, 041602(R) (2013) and references therein.

$(p,3p)$ exclusive measurement

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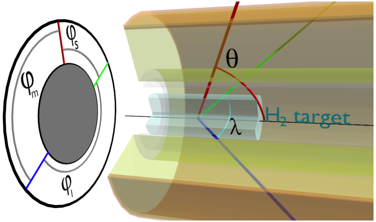
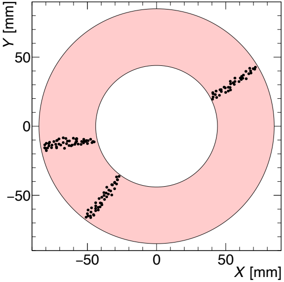
- exclusive 3D measurements with MINOS
- reaction identification with ZDS
- 51% 2 track efficiency for $(p,2p)$
- 21% 3 track efficiency for $(p,3p)$
- event defined by: θ, λ, φ





$(p,3p)$ event observed in ^{90}Se.

- $(p,3p)$ events identified via BigRIPS/ZeroDegree
- two consecutive $(p,2p)$ events $\rightsquigarrow$ same signature
- Solution: Vertex Proximity Cut (10 mm)

$(p,3p)$ reaction mechanism models

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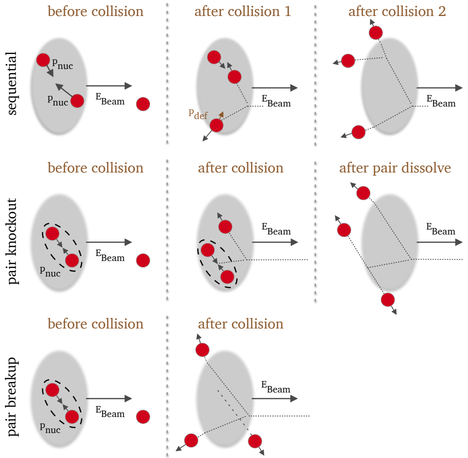
- three kinematical models developed by M. Gómez (AvH fellow 2019-2021)
- classical, relativistic
- isotropic collisions in CoM
- parameters fit to corresponding $(p,2p)$ channel
  - intrinsic momentum of participating protons
  - cutoff energy (exiting the nucleus)
  - deflection (on potential well of nucleus)



$(p, 3p)$ proton-distribution

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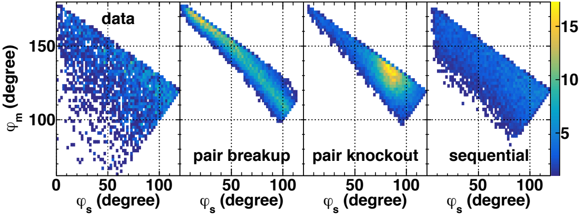
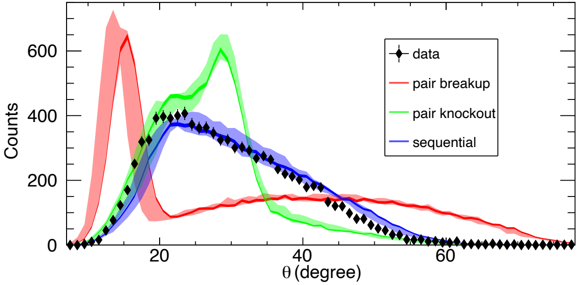
- ^{81}Ga$(p, 3p)$ is mainly sequential
- pair breakup and - knockout model fail miserably
- distributions normalised to data
- error envelopes from different parameter sets



^{81}Ga$(p, 3p)$. φ-distribution and fitted parameters.



^{81}Ga$(p, 3p)$. θ-distribution and different models.

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Conclusions and perspective

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- twenty-one cross section ratios $\rightsquigarrow$ cascade process (sequential)
- Exclusive angular distribution measurements for ^{81}Ga(p, 3p), ^{69}Co(p, 3p) and ^{70}Ni(p, 3p)
  - only possible using MINOS
- three classical, relativistic, parameter-free models developed by M. Gómez
  - quantification through χ^2-minimisation
  - sequential part $\geq$ 80 %
- cross section and nature of (p, 3p) reactions published: A.F. *et al.* PRL**125**, 012501 (2020)
- (p, 3p) mechanism for medium-mass neutron-rich isotopes at high energies is **sequential**

- Exclusive cross section data from SEASTAR3 (T. Pohl [A03] *et al.*)
- Microscopic description of (p,3p) (M. Gómez, in preparation)
- foundation for physics program of A08

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thank you!

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reaction model parameters

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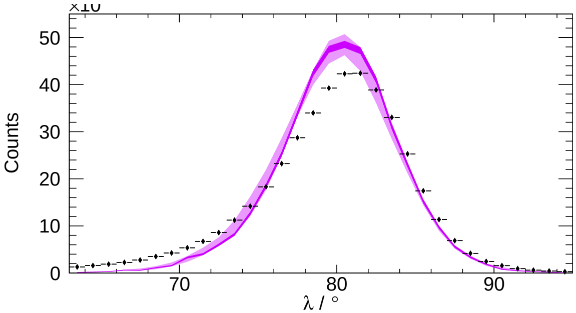
- the intrinsic momentum $p_{\mathrm{nuc}} = 200\ \mathrm{MeV/c}$
- cutoff energy $E_{\mathrm{thresh}} = 30\ \mathrm{MeV}$
- deflection $p_{\mathrm{def}} = 18\ \mathrm{MeV/c}$
- parameters fixed on corresponding $(p, 2p)$ channel
- **not** linearly independent
- χ^2 minimisation on 3D parameter space



$^{81}\mathrm{Ga}(p, 2p)$. λ-distribution and fitted parameters.

1D φ, θ, λ distributions

- ^{81}Ga$(p, 3p)$ is mainly sequential
- pair breakup and - knockout model fail miserably
- distributions normalised to data
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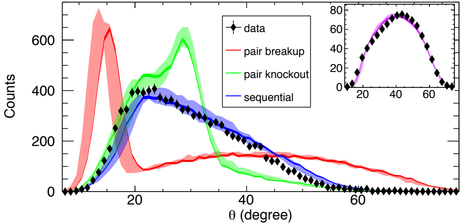

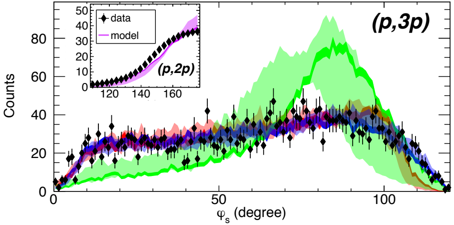

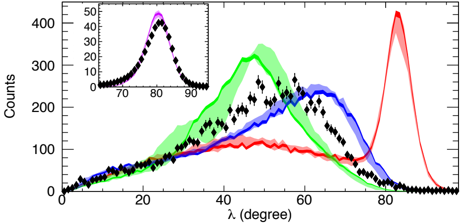

Results

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Reaction	Model	$p[\%]$	$p_-[\%]$	$p_+[\%]$
^{69}Co	sequential	100	76	100
	pair knockout	0	0	24
	pair breakup	0	0	6
^{70}Ni	sequential	82	66	100
	pair knockout	17	0	31
	pair breakup	1	0	7
^{81}Ga	sequential	86	80	96
	pair knockout	14	4	21
	pair breakup	0	0	2