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EXPERIMENT AND OPTICAL POTENTIALS: A USER’S POINT OF VIEW

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DFG Deutsche Forschungsgemeinschaft German Research Foundation

SFB 1245

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OUTLINE

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- **Direct reactions: needs and reality**
  Aumann et al., PPNP (2021); Aumann et al., PRL (2017); Ponnath et al., PLB (2024)

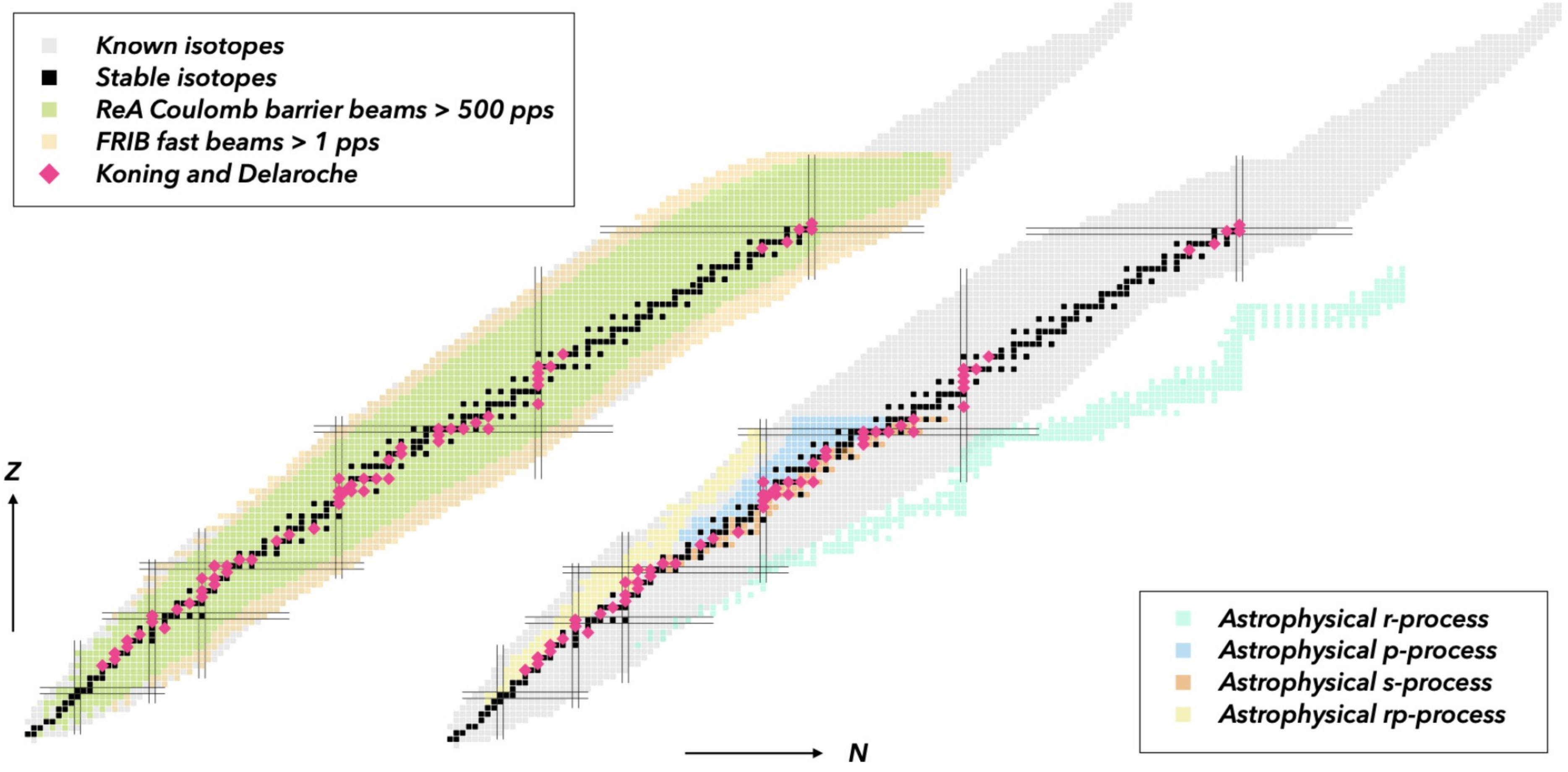
- **One nucleon transfer from ^{14}O: a sensitivity study**
  Flavigny et al., PRL (2013); Flavigny et al., PRC (2018)

- **Quasifree scattering**
  Enciu et al., PRL (2022)

- **Uncertainties and energy dependence**
  Pohl et al., PRL (2023); Bertulani, PLB (2023); Gomez-Ramos et al., PLB (2023)

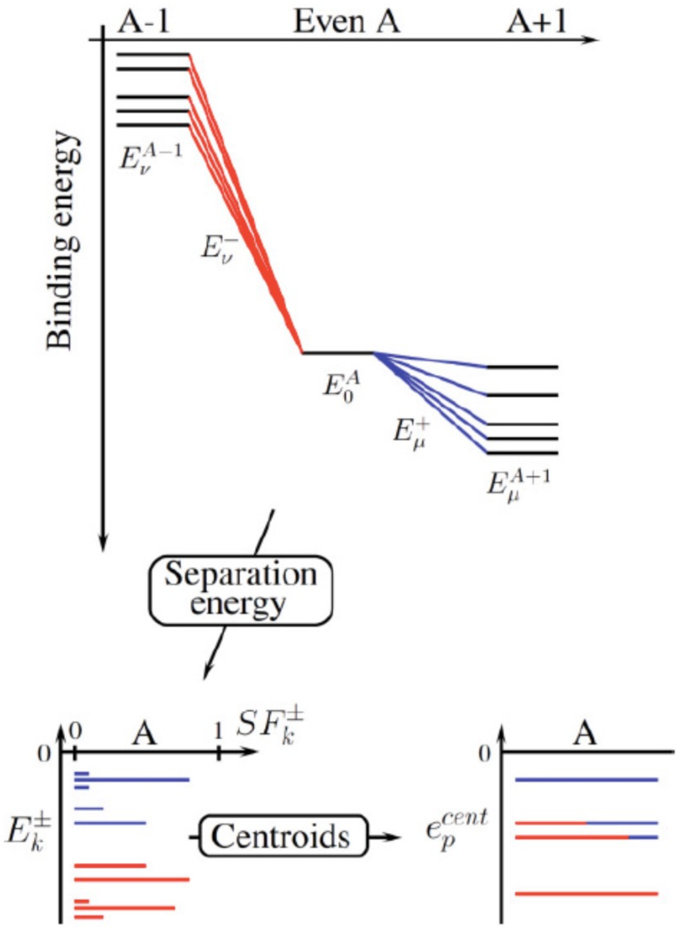
- **Stripping from low-energy antiprotons**
  Aumann et al. (PUMA collaboration), EPJA (2022)

THE AIM OF DIRECT REACTIONS



Hebborn et al., JPG (2023), shown at Haloweek 2024

THE AIM OF DIRECT REACTIONS



Hagen, Duguet, PRC (2012)

- One nucleon pickup or stripping used to probe the structure of nuclear states through spectroscopic strength

$$S_k^{n\ell j,+} = |\langle \Psi_k^{A+1} | a_{n\ell j}^\dagger | \Psi_0^A \rangle|^2 \qquad S_k^{n\ell j,-} = |\langle \Psi_k^{A-1} | a_{n\ell j} | \Psi_0^A \rangle|^2$$

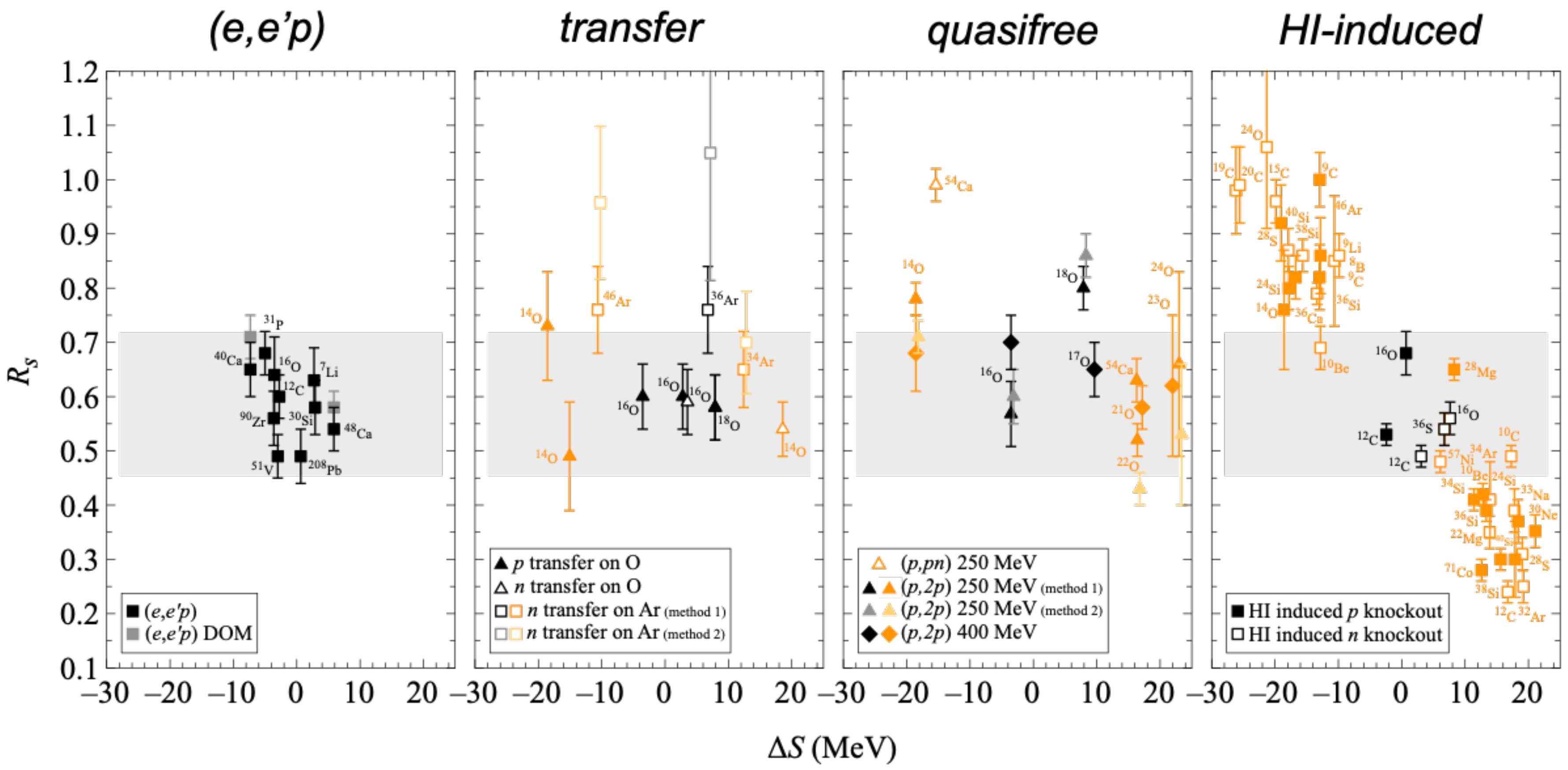
- Single-particle energies relate to physical state energies via the Baranger relation

$$e_{n\ell j} = \frac{\sum_k S_k^{n\ell j,+}(E_k - E_0) + S_k^{n\ell j,-}(E_0 - E_k)}{\sum_k S_k^{n\ell j} + S_k^{n\ell j}}$$

- Limitations:
  - Non observability of single particles and spectroscopic factors
  - Surface or asymptotic sensitivity of direct reactions
  - **Reaction model approximations and undefined uncertainties**
  - Experimental uncertainties and incomplete data sets

TODAY'S REALITY

Reaching accuracy and precision of 10% would be a game changer



Aumann et al., Prog. Part. Nucl. Phys. (2021)

SKINS FROM NEUTRON REMOVAL

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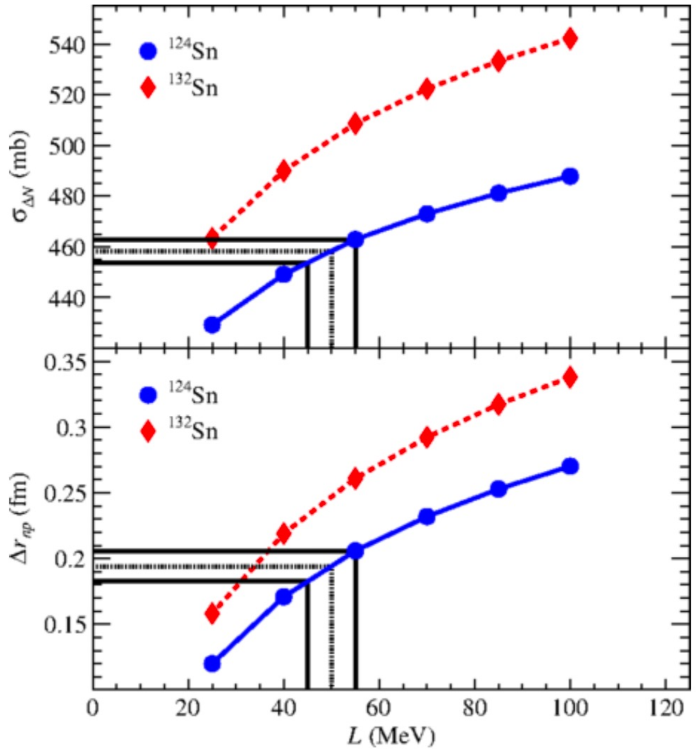
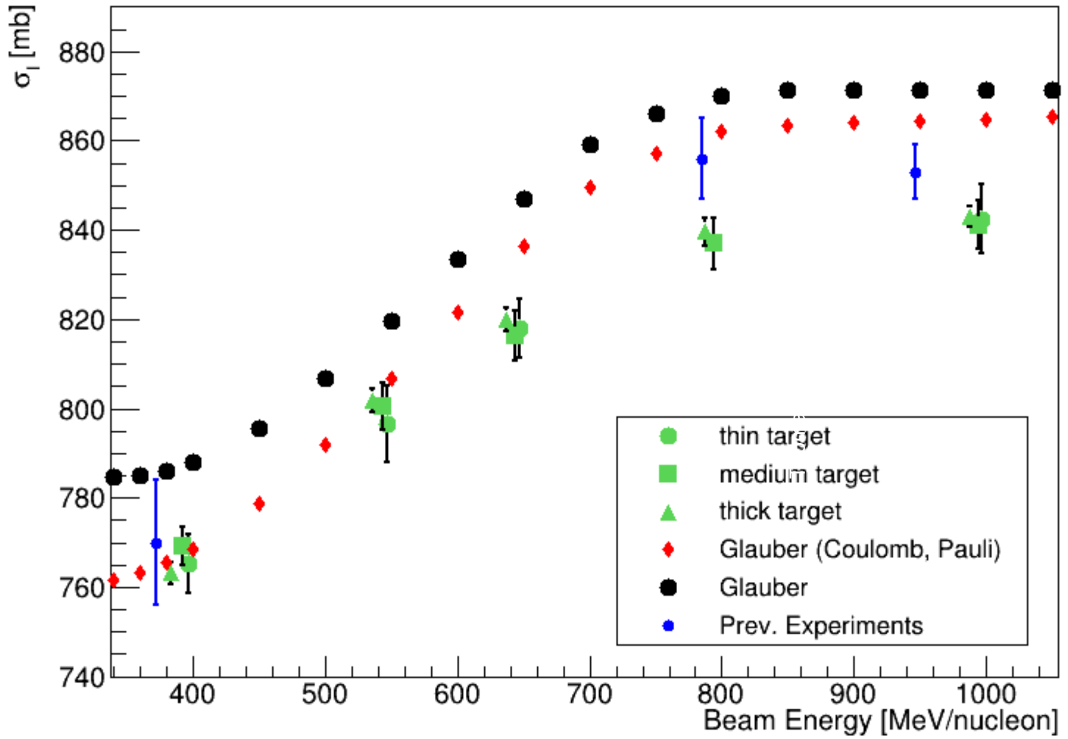
- Sensitivity to symmetry term of EOS from neutron removal cross sections would require a 1% accuracy
- ^{12}C-^{12}C interaction cross section reproduced at 3% by Glauber



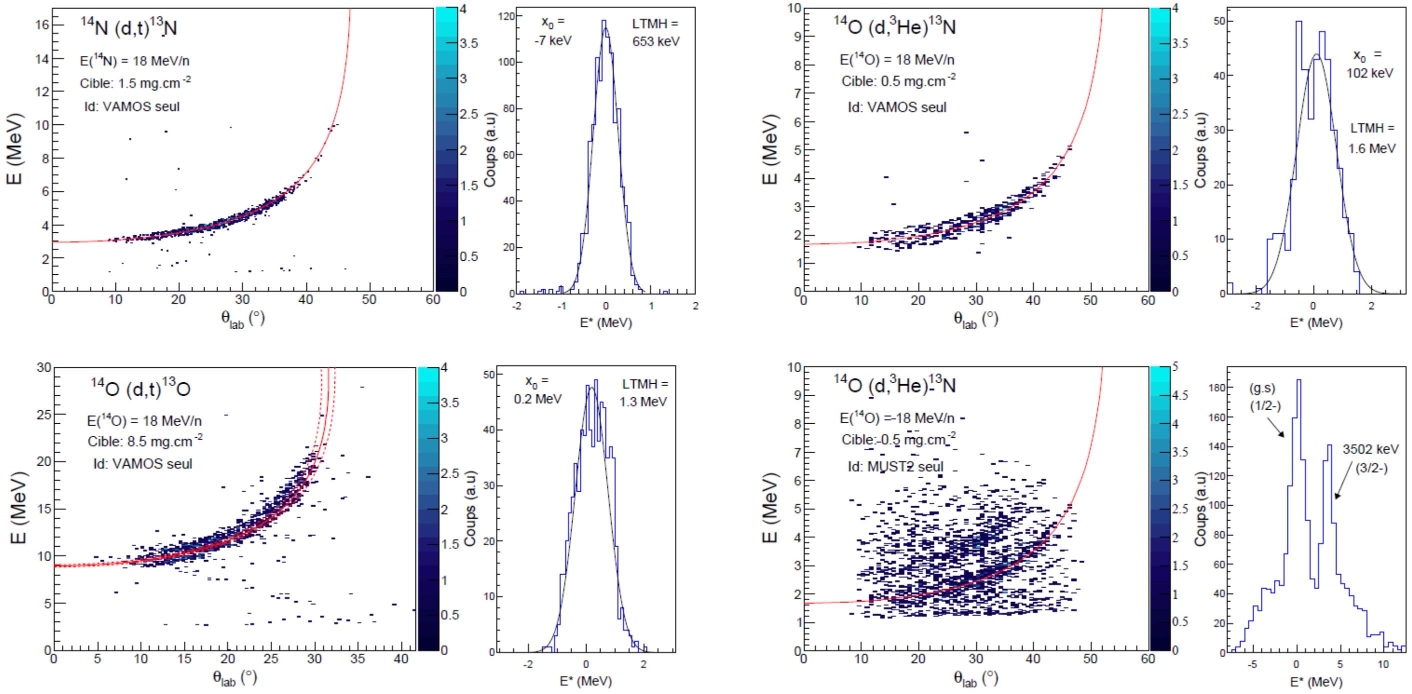
Aumann et al., PRL (2017)

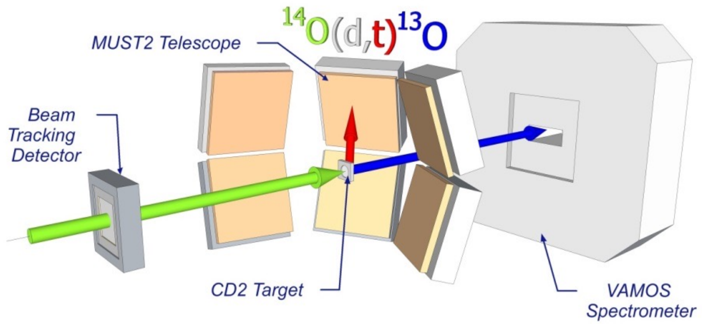


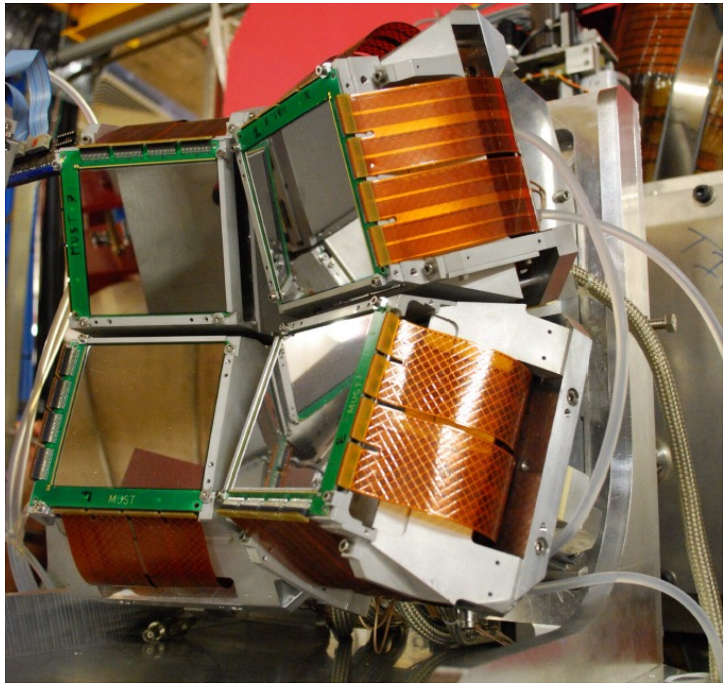
Ponnath et al., PLB (2024)

TRANSFER: AN EXAMPLE

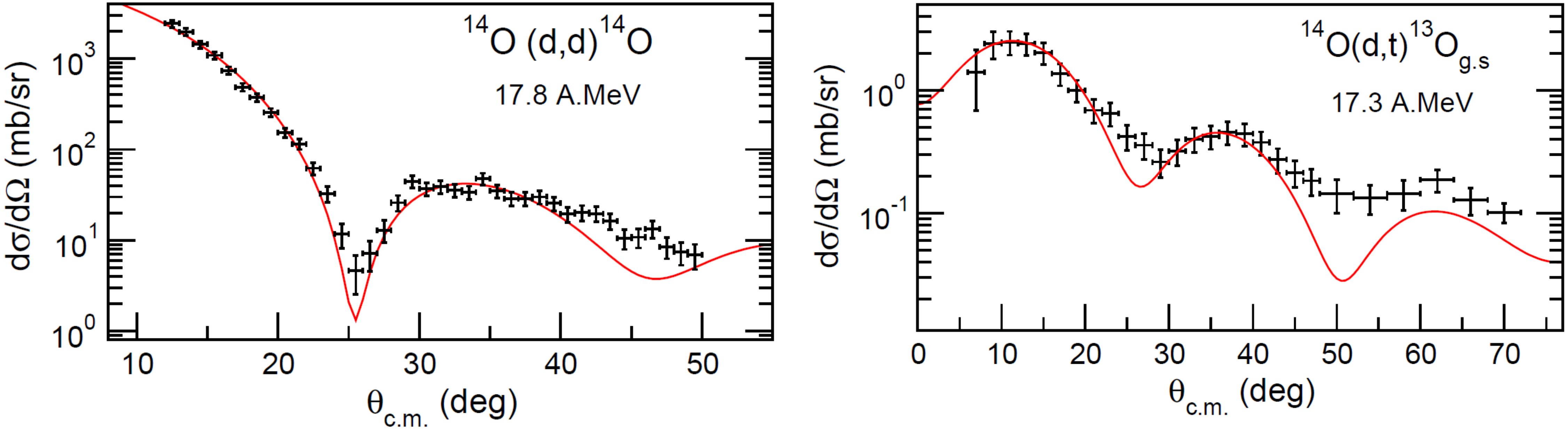
SPIRAL beam: ^{14}O at 18 MeV/nucleon
Intensity: 5. 10^4 pps
Targets: CD_2
Reactions: (d,d), (d,t) and (d,^{3}He), *fully exclusive measurements*







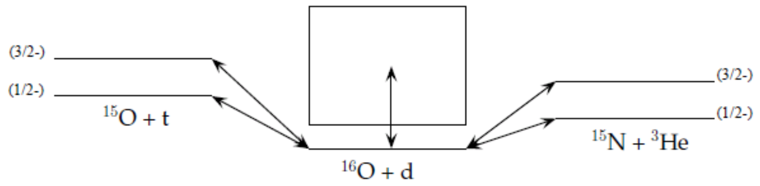
TRANSFER AND ELASTIC SCATTERING DIFFERENTIAL CROSS SECTIONS



Flavigny et al., PRL (2013)

ANALYSIS

- Coupled Reaction Channels (CRC) analysis (FRESCO code)

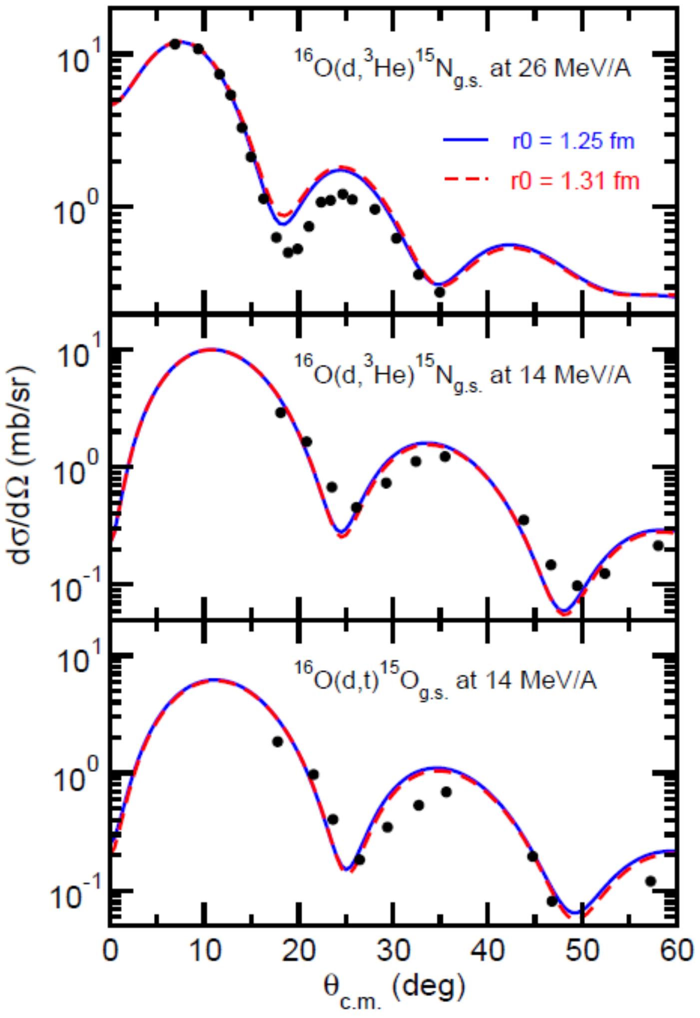


- Potentials
  - Entrance: Global N-nucleus + folding *ex.* Konig and Delaroche, NPA (2003)
  - Renormalised entrance potential on elastic scattering (V:1.1, W:0.8)
  - Exit: Global t/3He – nucleus *ex.* Perey and Perey, ADNDT (1976)

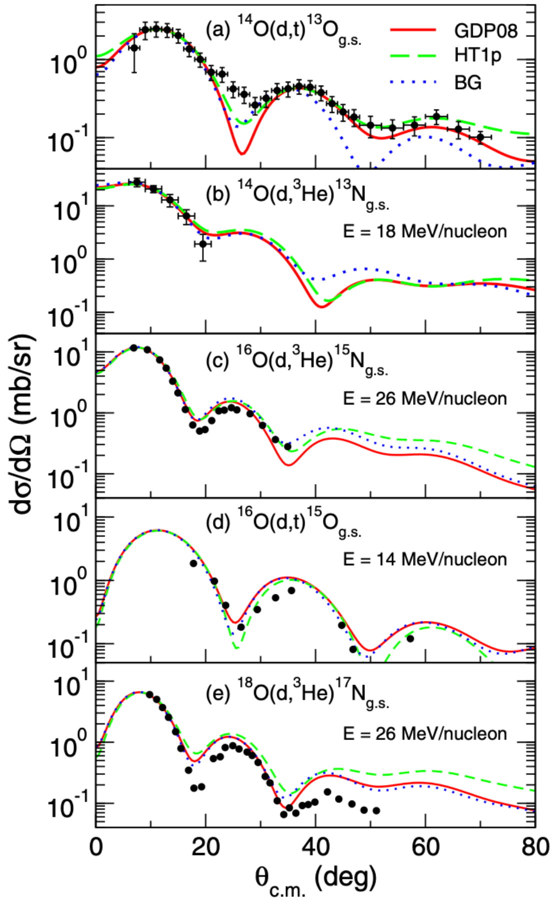
- Form factors
  - WS, r_0=1.31 fm from (e,e'p) or r_0=1.25 fm and a_0=0.65 fm

	Notre analyse		(e,e'p)[3]
	$r_0 = 1.25$ fm	$r_0 = 1.31$ fm	$r_0 = 1.31$ fm
C^2S_{exp}	1.5(3)	0.94(30)	1.17(7)
C^2S_{th}	1.51	1.51	1.51
R_s	1.0(2)	0.62(20)	0.77(5)

  - Microscopic from SCGF theory



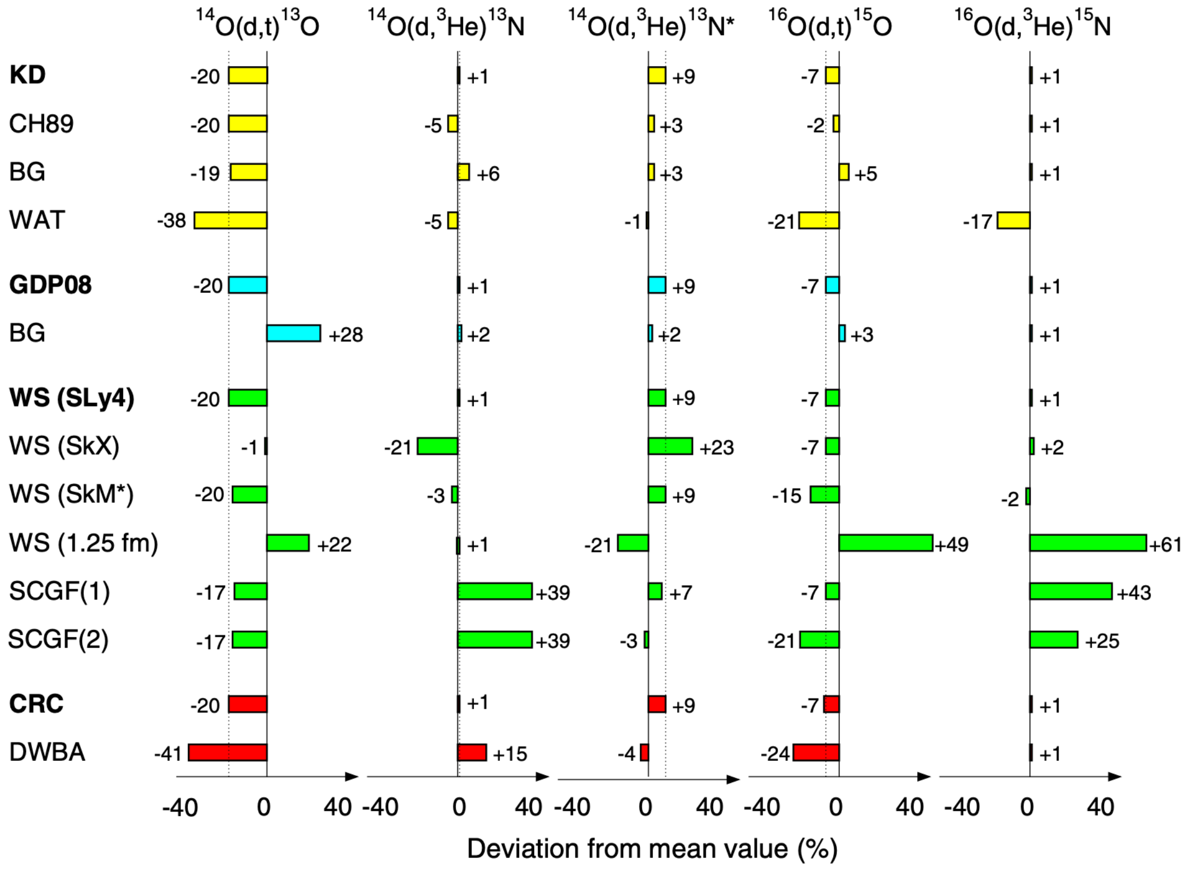
SENSITIVITY STUDY



Flavigny et al., PRC (2018)

Konig & D., NPA (2003)
Varner et al., PR (1991)
Becchetti & G., PR (1969)
Watson et al., PR (1969)

Pang et al., PRC (2009)



Global potentials fitted on data from stable nuclei, leading to non-estimated systematic errors from to isospin / binding energy dependence

THE EXAMPLE OF ^{52}CA(P,PN)^{51}CA

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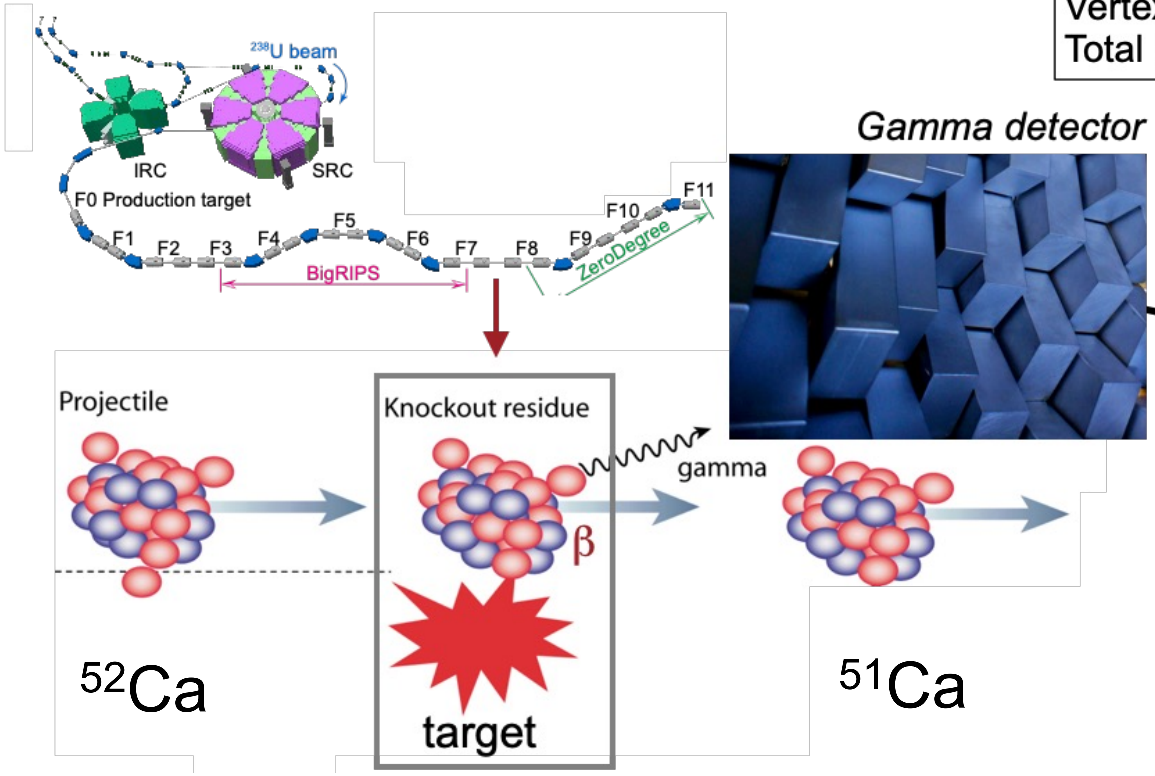
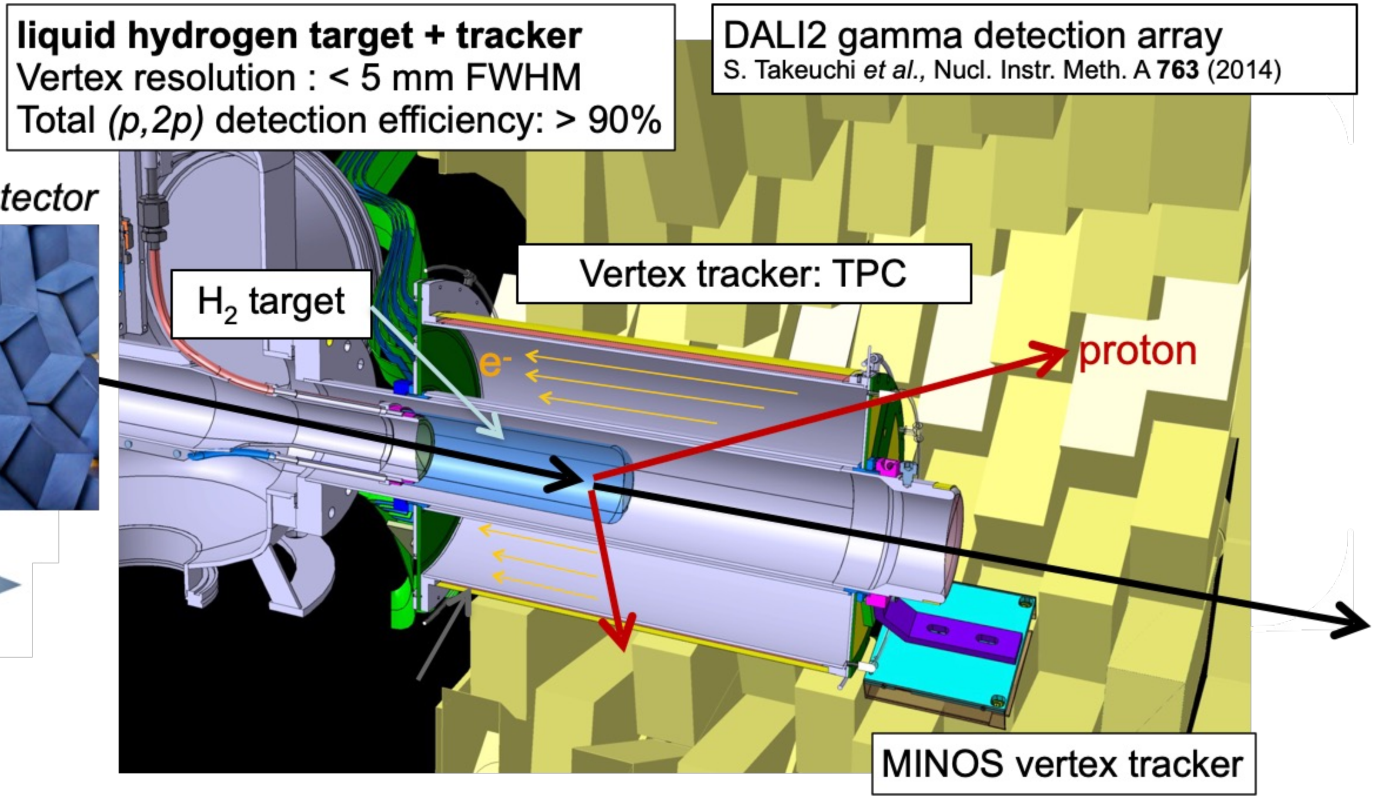
- RIBF, RIKEN
- ^{70}Zn primary beam at 345 MeV/nucleon, 200 pnA
- ^{52}Ca(p,pn)^{51}Ca at 230 MeV / nucleon





AO et al., EPJA (2014)

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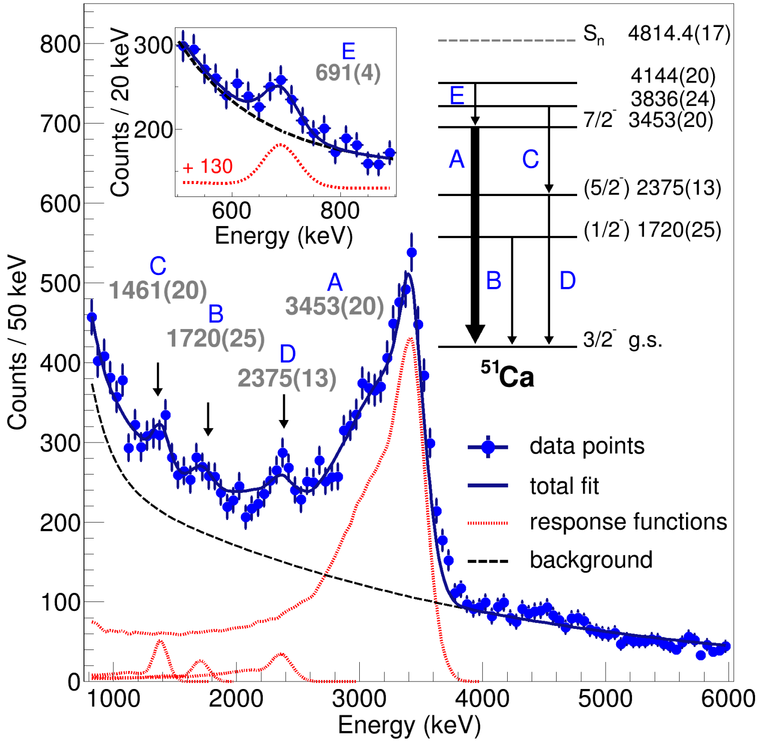
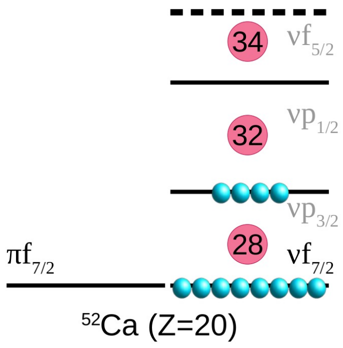
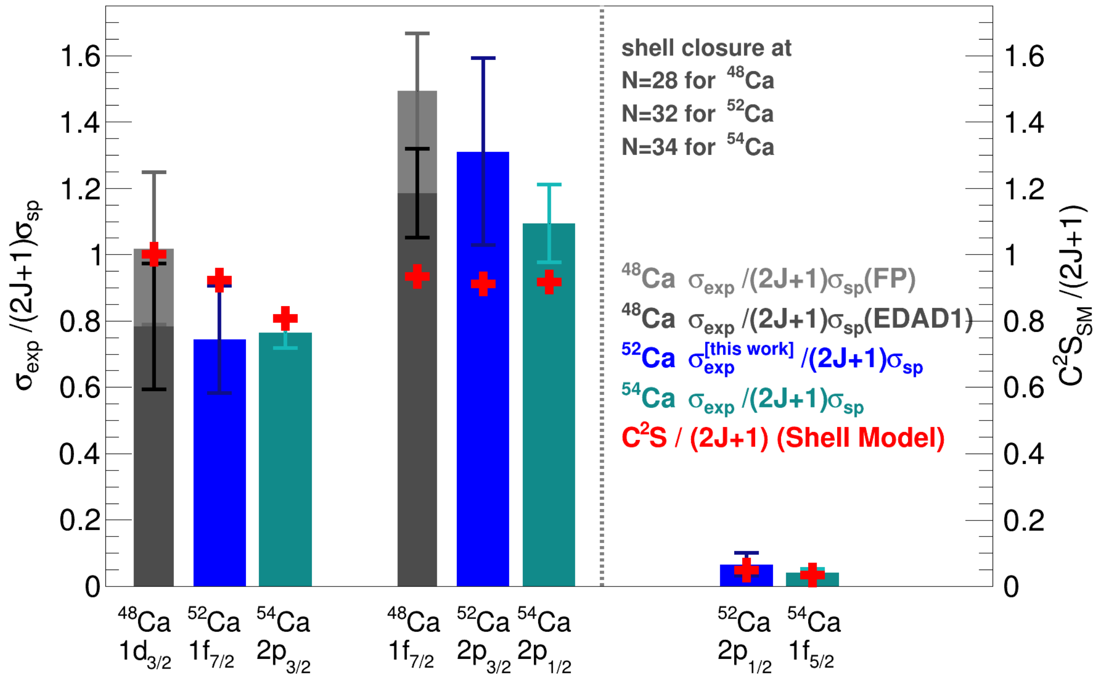
THE EXAMPLE OF ^{52}CA(P,PN)^{51}CA

- DWIA single-particle cross sections: K. Ogata, K. Yoshida (**see talk by K. Yoshida**)
- Effect of OP for p-nucleus interaction estimated to 15% at 150 MeV/n (^{48}Ca), less than 5% above 200 MeV/n
- Folding potential with Melbourne G matrix: Amos et al., ANP (2000), DIRAC potential: Cooper et al., PRC (1993)







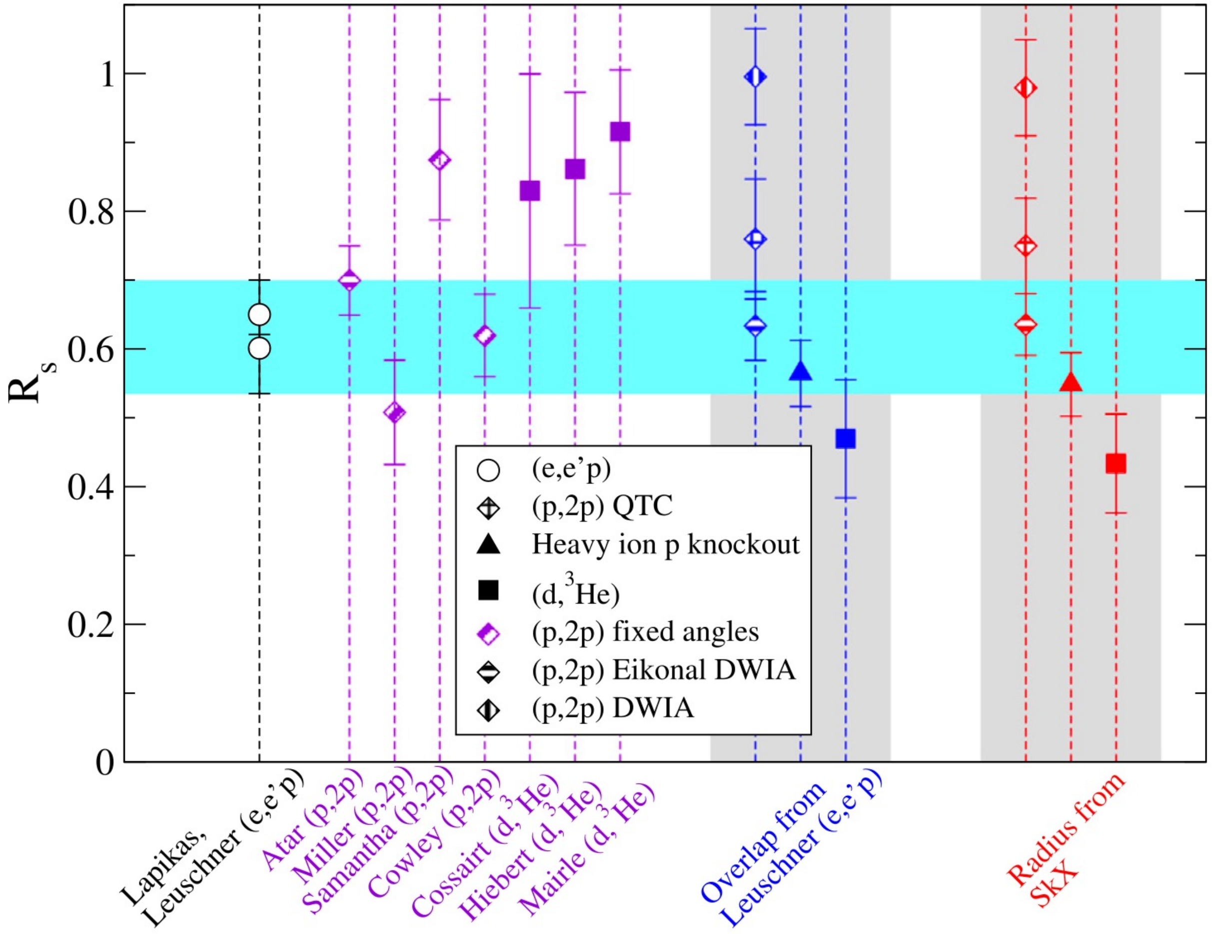
Enciu et al., PRL (2022)

SENSITIVITY STUDY

- One proton removal from ^{16}O (inclusive to 1/2- ground state and 3/2- state in ^{15}N)
- Comparison of analysis from (e,e'p), transfer, quasifree scattering and light-ion induced knockout
- DWIA, eikonal DWIA and QTC (Quantum Transfer to the Continuum) compared: variations of Rs from 0.6 to 1, i.e. ~40%
- Effect of pA optical potential (QTC) : ~10%

DWIA $T_{p,pN} = \sqrt{S(lj)} \left\langle \chi^{(-)}_{\mathbf{k}'_p} \chi^{(-)}_{\mathbf{k}_N} \left| \tau_{pN} \right| \chi^{(+)}_{\mathbf{k}_p} \psi_{jlm} \right\rangle$

QTC $\mathcal{T}^{3b}_{if} = \langle \Psi^{3b(-)}_f | V_{pN} + U_{pC} - U_{pA} | \phi_{CA} \chi^{(+)}_{pA} \rangle$



Aumann et al., Prog. Part. Nucl. Phys. (2021)

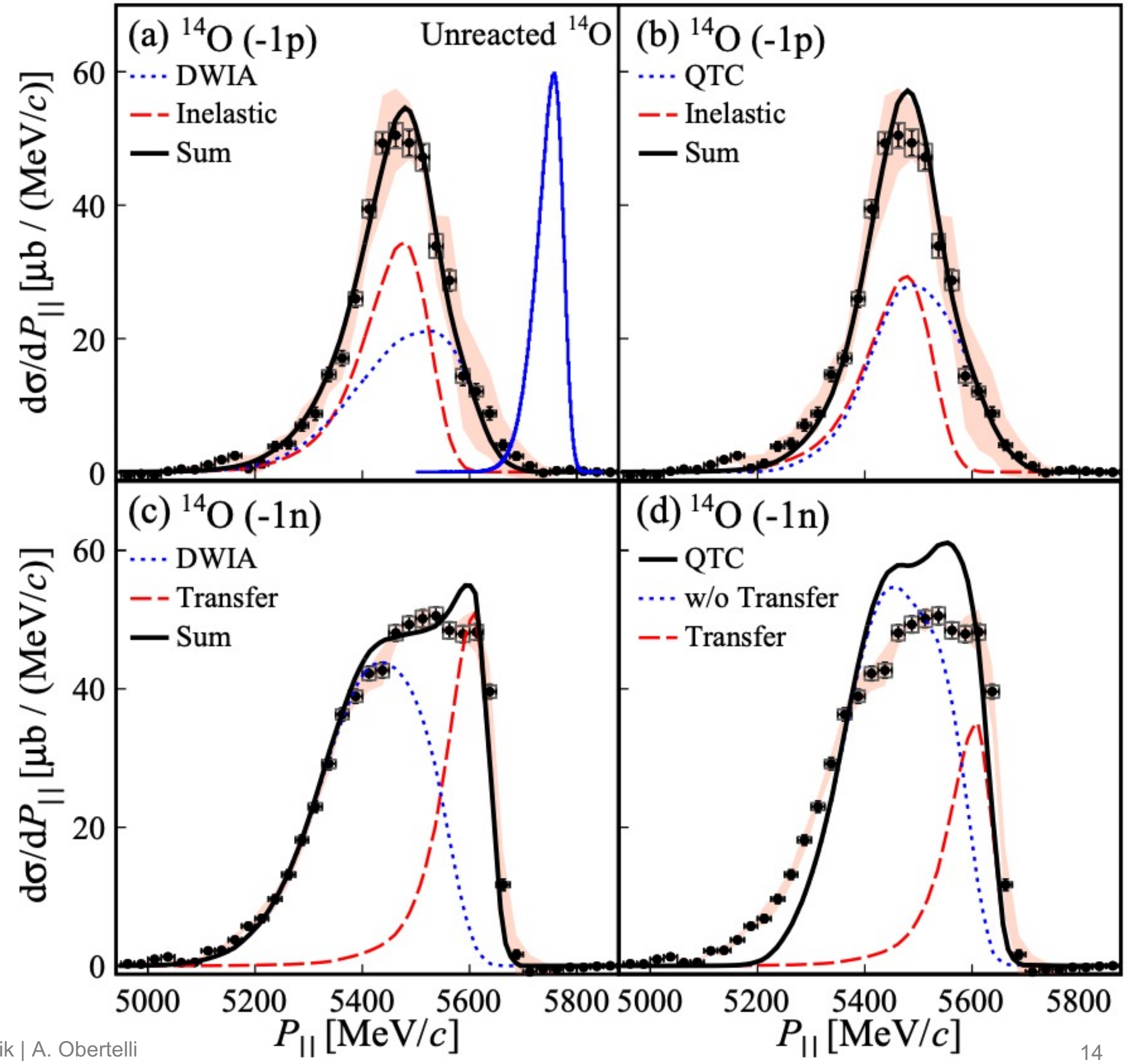
PROTON-INDUCED REMOVAL AT 94 MEV/U

- Nucleon removal from ^{14}O on hydrogen, 94 MeV/nucleon. ^{14}O: S_n= 23 MeV, S_p= 4.6 MeV.
- Interpreted with Quantum Transfer to the Continuum (QTC) and eikonal DWIA.

Residue	J^π	σ_{exp} [mb]	SF	Theory	σ_{sp} [mb]	σ_{th} [mb]	R_s
$^{13}N_{g.s.}$	$1/2^-$	10.7(16)	1.58	DWIA	5.2	8.8	1.22(18)
				Inelastic	-	9	
				Sum		17.8	0.60(9)
				QTC	7.0	11.9	0.90(13)
				Inelastic	-	9	
				Sum		20.9	0.51(8)
$^{13}O_{g.s.}$	$3/2^-$	16.7(24)	3.42	DWIA	6.3	23.2	0.72(10)
				Transfer	3	11	
				Sum		34.2	0.49(7)
				QTC w/o transfer	10.2	37.6	0.44(6)
				QTC	13.5	49.7	0.34(5)

- See also: Bonnaccorso, Brink, PRC (1991), Flavigny et al., PRL (2013)

Pohl et al., PRL (2023)



CORE DESTRUCTION IN KNOCKOUT

Letter

Isospin dependence in single-nucleon removal cross sections explained through valence-core destruction effects

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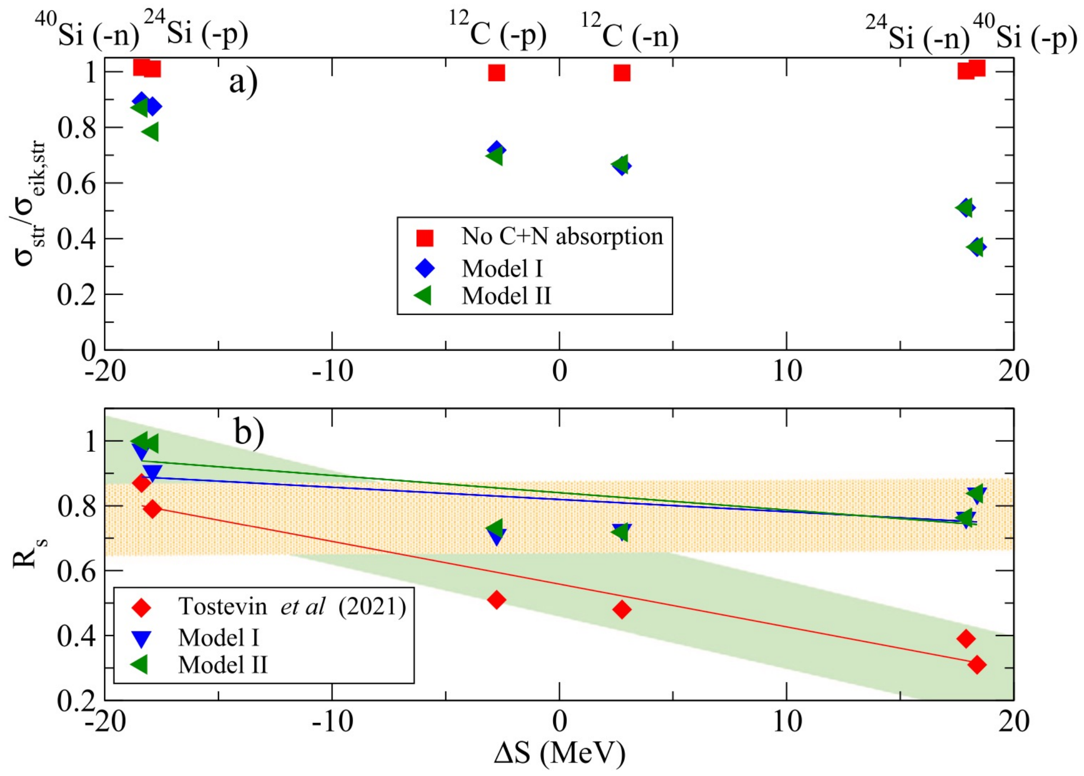
[b] *Centro Nacional de Aceleradores (U. Sevilla, J. Andalucía, CSIC), Tomás Alva Edison, 7, 41092 Sevilla, Spain*
[c] *Instituto Interuniversitario Carlos I de Física Teórica y Computacional (iC1), Apdo. 1065, E-41080 Sevilla, Spain*

$$P_{\mathrm{str}}(\vec{b}) \simeq \int dx\,dy\, \rho^{(2)\mathrm{eff}}(x,y) \times |S^0_{CT}(b_{CT})|^2 \left(1 - |S^0_{VT}(b_{VT})|^2\right)$$

$$\rho^{(2)\mathrm{eff}}(x,y) = \int d^3\vec{r}_1 \int d^3\vec{r}_2\, \langle \vec{r}_2|\rho_f|\vec{r}_1\rangle \phi^*_g(\vec{r}_2)\phi_g(\vec{r}_1) \times \delta\left(x - \frac{x_1+x_2}{2}\right)\delta\left(y - \sqrt{\frac{y_1^2+y_2^2}{2}}\right),$$

- Stripping from light ion target (^{9}Be, ^{12}C)
- Nucleon – core interaction from rescaled global energy-dependent dispersive potential Morillon et al., PRC (2007)
- **large impact on cross section** and **isospin dependence**

- Conclusions at variance with Bertulani, PLB (2023)
- See also: Louchart et al., PRC (2011), Hebborn et al., PRC (2023)



Gomez-Ramos et al., PLB (2023)

CORE DESTRUCTION IN KNOCKOUT

(SLIDE ADDED AFTER TALK)

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- Eikonal formalism
- **Reduction as much as 9.5 % found**
- **No nucleon-binding-energy dependence found**

$$(1-|S_n|^2)|S_c|^2 \to (1-|S_n|^2)\,|S_c|^2\left(1-\left\langle|S_{nc}|^2\right\rangle\right),$$

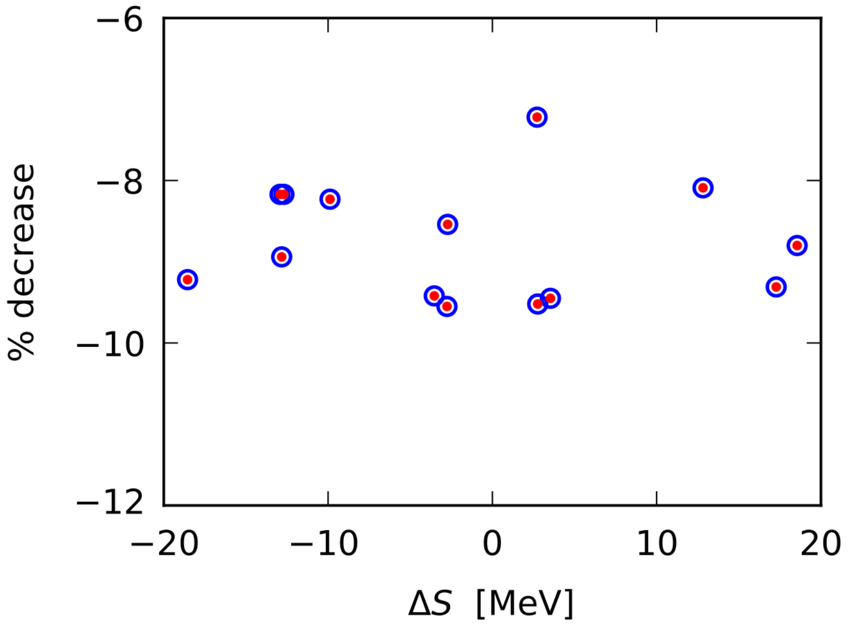
with

$$\left\langle|S_{nc}|^2\right\rangle = \frac{1}{\sigma_{NN}^{el}}\int d\Omega \frac{d\sigma_{NN}^{el}(\theta)}{d\Omega}|S_{nc}(b_{nc}(\theta,\phi))|^2,$$

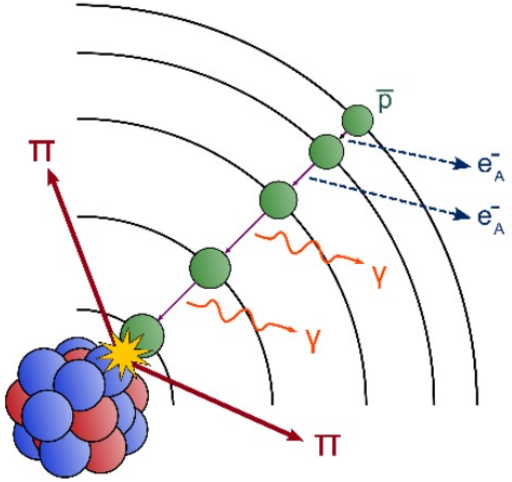
Bertulani, PLB (2023)

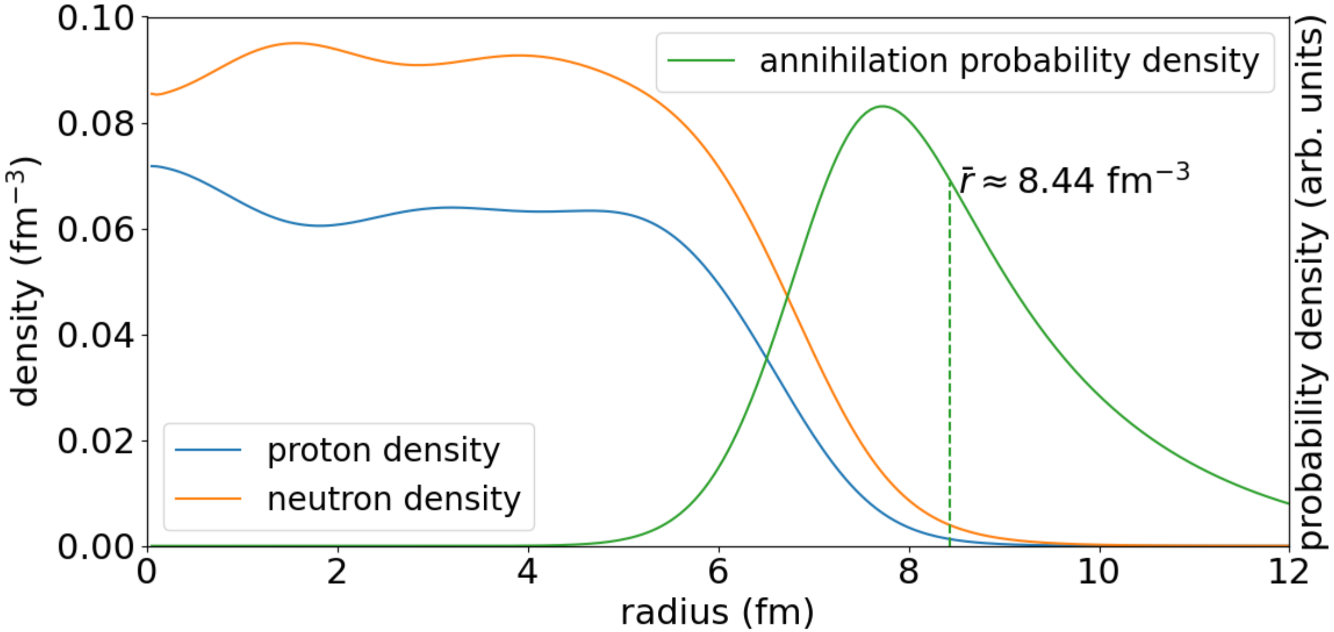
Table 1
Theoretical values for one-nucleon-removal stripping cross sections for selected single-particle states. $\Delta S = S_n - S_p$ for neutron removal or $\Delta S = S_p - S_n$ for proton removal.

Reaction	E_{beam} MeV/nucleon	$S_p[S_n]$ MeV	ΔS MeV	$J^\pi(j)$ mb	σ_{str} mb	$\sigma_{str}^{rescatt}$	% change
$^9B(^7Li,^6He)$	80	9.98	2.723	$0^+(3/2)$	20.49	19.01	−7.22
$^9B(^7Li,^6Li)$	120	7.25	−2.723	$1^+(3/2)$	24.23	22.16	−8.54
$^{12}C(^8B,^7Be)$	285	0.137	−12.690	$3/2^-(3/2)$	42.49	39.02	−8.17
$^{12}C(^9C,^8B)$	78	1.3	−12.925	$2^+(3/2)$	40.14	36.86	−8.17
$^{12}C(^9Li,^8Li)$	100	4.06	−9.882	$2^+(3/2)$	40.32	37.00	−8.23
$^9Be(^{10}Be,^9Li)$	80	19.64	12.824	$3/2^-(3/2)$	35.33	32.47	−8.09
$^9Be(^{10}Be,^9Be)$	120	6.812	−12.824	$3/2^-(3/2)$	77.62	70.68	−8.94
$^9Be(^{10}C,^9C)$	120	21.28	17.277	$3/2^-(3/2)$	44.57	40.50	−9.31
$^{12}C(^{12}C,^{11}B)$	250	15.95	−2.764	$3/2^-(3/2)$	64.68	58.70	−9.55
$^{12}C(^{12}C,^{11}C)$	250	18.72	2.764	$3/2^-(3/2)$	74.16	67.10	−9.52
$^{12}C(^{14}O,^{13}N)$	305	1.531	−18.552	$1/2^-(1/2)$	37.45	33.99	−9.22
$^9Be(^{14}O,^{13}O)$	53	3.234	18.552	$3/2^-(3/2)$	25.57	23.32	−8.80
$^{12}C(^{16}O,^{15}N)$	2100	22.04	−3.537	$3/2^-(3/2)$	46.90	42.48	−9.42
$^{12}C(^{16}O,^{15}O)$	2100	22.04	3.537	$3/2^-(3/2)$	44.46	40.26	−9.45



STRIPPING FROM ANNIHILATION





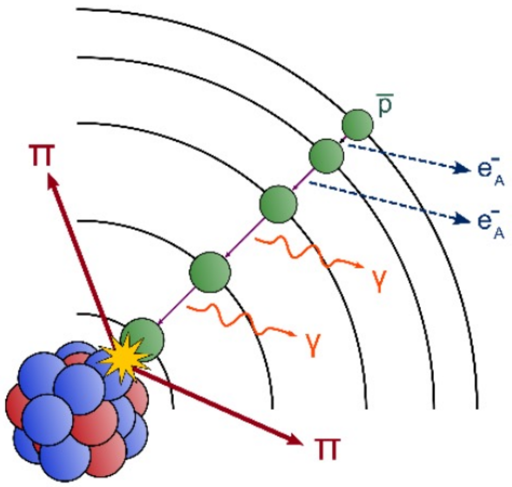
- $\bar{p}$ captured in antiprotonic orbital (~QED)
- then annihilate in tail $\rho_{n/p}(r)$ (QCD)

Two main methods applied in the past (LEAR at CERN) for nuclear structure:

- X rays from lower orbitals
- pions from annihilation

The interpretation of both methods depends on $\bar{p}$ - nucleus optical potenial

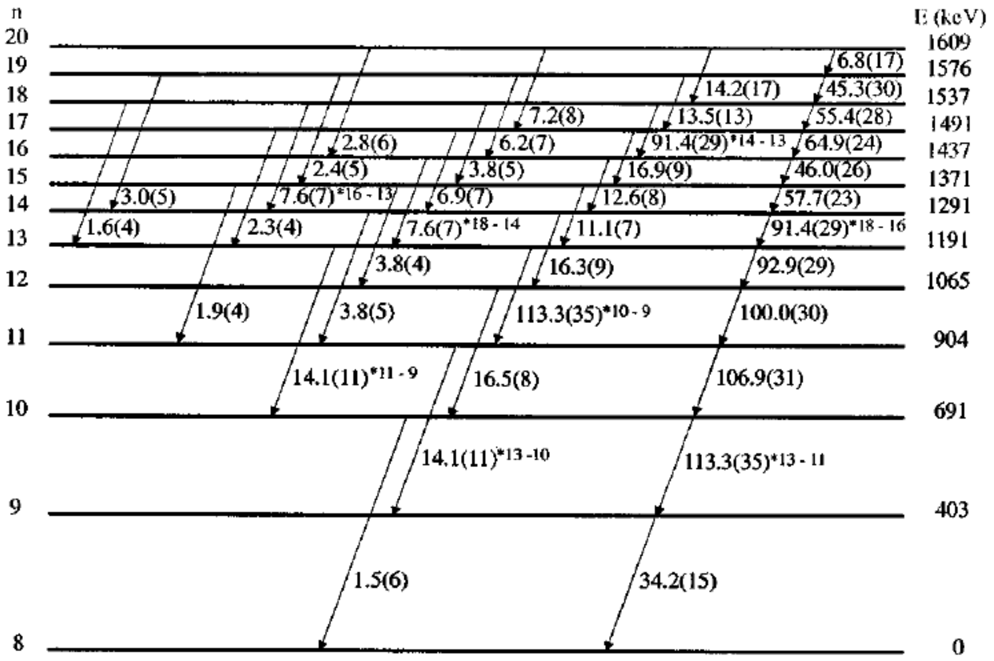
STRIPPING FROM ANNIHILATION



- $\bar{p}$ captured in antiprotonic orbital (~QED)
- Energy shifts and decay widths of inner levels sensitive to the matter distribution

$$\Gamma_{n\ell} = \int \mathrm{Im}\, V(r) \left|\Psi_{n\ell}(r)\right|^2 r^2 dr$$

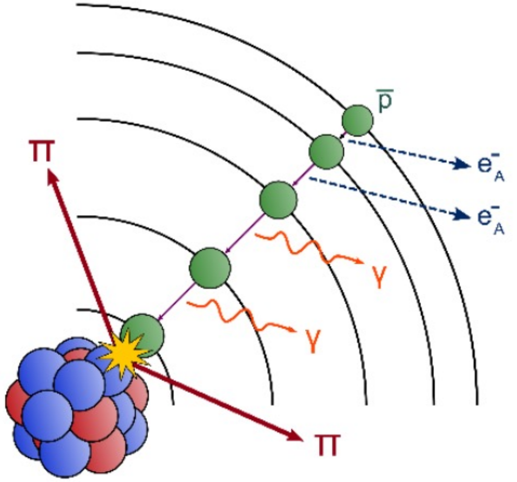
$$with\; V(r) = \frac{2\pi}{\mu} a\rho(r)$$

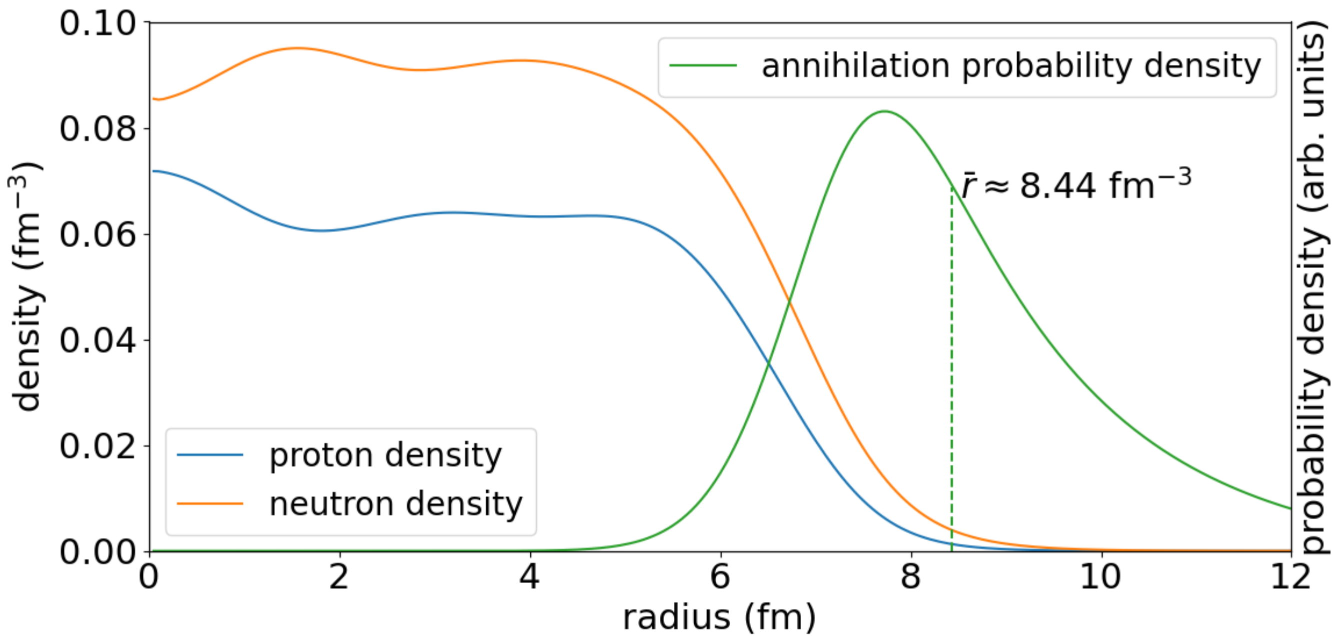


172Y @ CERN, R. Schmidt et al., PRC (1998)

Nuclear potential induces shift of inner level energies of few 100 eV (X ray energies: 100 keV)

STRIPPING FROM ANNIHILATION





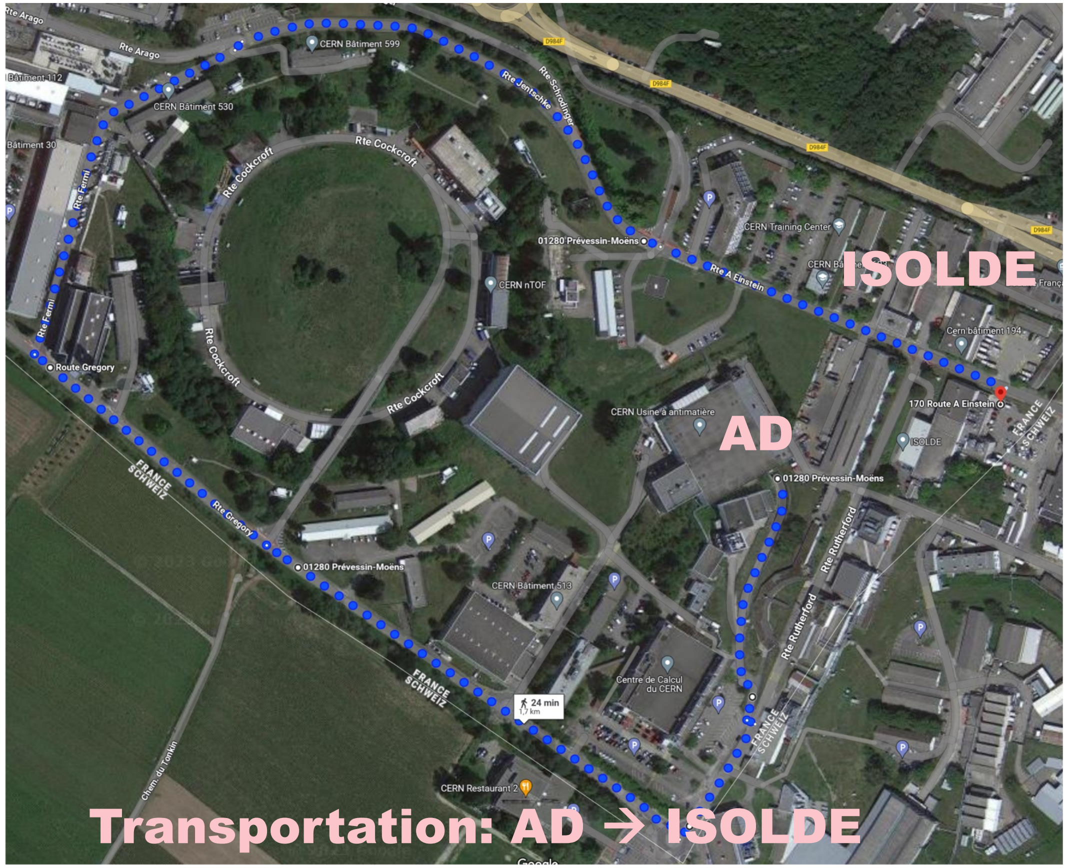
- $\bar{p}$ captured in antiprotonic orbital (~QED)
- then annihilate in tail $\rho_{n/p}(r)$ (QCD)
- Conservation of total charge

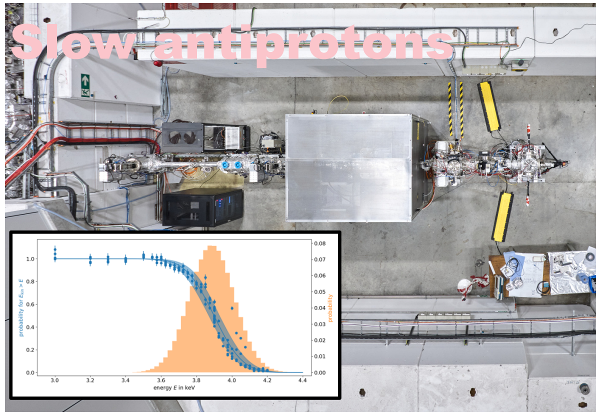
$$\sum_{\pi} q_{\pi} = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$

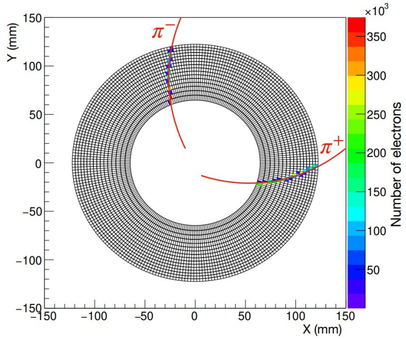
- First application of method: Bugg et al., PRL (1973)
- Application to rare isotopes first proposed by: Wada and Yamazaki, NIM B (2004)
- First experiments at PUMA, CERN, in 2025

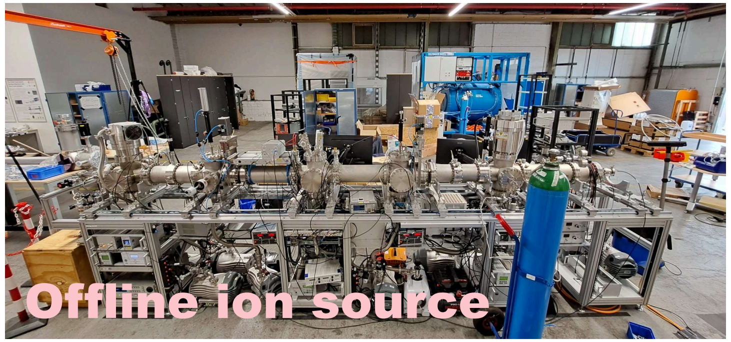
- Collaboration with Lazauskas, Hupin et al. (theory)
- See talks by: **Duerinck and FInelli**

THE PUMA EXPERIMENT









Aumann et al. (PUMA collaboration), EPJA (2022)

Alexander von HUMBOLDT STIFTUNG

SUMMARY

- Direct reactions are unique to probe the wavefunction of nuclear states.

- Optical potentials are major components for the analysis and interpretation of direct reaction cross sections
  Accuracy and precision of 10% or less for cross sections would allow quantitative statements

- In **transfer reactions**, uncertainties from isospin dependence and separation energy are lacking
  Variations of cross sections of ~O(10)-O(100) % due to optical potentials

- **Nucleon quasifree scattering**: optical potentials lead to variations of cross sections of ~O(10)%
  Cluster knockout (deuteron, … not discussed in this talk) is expected to be more dependent on the OP
  Systematic uncertainties from reaction formalism and related approximations are large (> 20%)

- Inclusive stripping reactions at or below ~150 MeV / nucleon may deviate significantly from eikonal and favour larger uncertainties than at higher energies (Pauli blocking, core excitation from FSI, transfer)

- **Low-energy antiprotons** sensitive to nuclear surface; soon applied to RI at CERN

SCOPE AND AIMS

- Optical potentials from ab initio theory, Dispersive optical model (DOM) and other microscopic methods
- Consistency among structure and reaction mechanisms
- Uncertainties
- Implementation of microscopic nucleon-nucleus OP in actual reactions
- Applications
  - structure of nuclei away from stability investigated at facilities at various energy regimes
  - antiproton-nucleus optical potentials
  - deformed nuclei
  - astrophysics