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NUCLEAR REACTIONS

23rd STFC Nuclear Physics Summer School

Kathrin Wimmer
Institute for Nuclear Physics

August 5 – 7, 2026

Who are you?

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- PhD at TU München on two-neutron transfer reactions at ISOLDE/CERN
- Postdoc at NSCL: reaction dynamics in two-proton knockout reactions
- Ass. Prof. at Central Michigan University, worked within GRETA project
- Moved to the University of Tokyo in 2014, lecturer
  In-beam γ-ray spectroscopy with relativistic beams
  Development for transfer reactions with energy degraded beams (TiNA and triton target)
- 2019 Ramon y Cajal fellow at CSIC Madrid
  Spokesperson of HiCARI (high-resolution in-beam γ-ray spectroscopy at RIBF)
- 2021 Researcher at GSI Darmstadt
  Project manager for AGATA at FAIR
  LISA “LIfetime measurements with Solid Active targets”
- 2023 Habilitation University of Heidelberg
- 2025 Full Professor Institute for Nuclear Physics, University of Cologne

My work usually focuses on direct reactions with exotic beams mostly in combination with γ-ray spectroscopy

Transfer reactions

- Introduction and definitions
- Transfer reactions with radioactive beams
- Example: The neutron-rich Ca isotopes
- Extra: Is ^{46}Ar a bubble?
- Summary

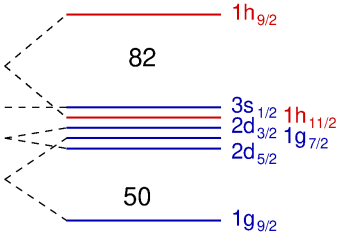
Introduction and definitions

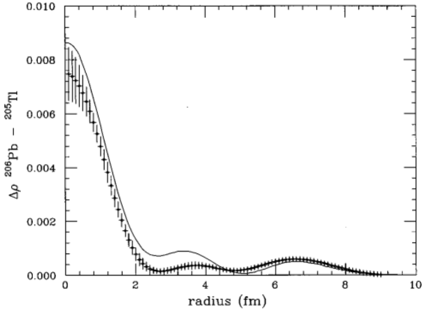
Probing nuclear shell structure

- Single-particle picture is consistent with charge density distributions measured in electron elastic scattering

$$\rho_Z(r) - \rho_{Z-1}(r) = \sum_{i=1}^{Z} |\phi_i(r)|^2 - \sum_{i=1}^{Z-1} |\phi_i(r)|^2 = |\phi_{i=Z}(r)|^2$$

- Charge density difference between ^{206}Pb and ^{205}Tl
- Shell model expectation: last proton in $3s_{1/2}$ orbital





V. Pandharipande et al., Rev. Mod. Phys. **69** (1997) 981.

Nuclear reactions

Direct reactions:

- Projectile and target are within the range of nuclear forces for the very short time allowing for an interaction involving only one or a few nucleons
- One-step transition from the initial state in the entrance to the final state in the exit channel

Compound reactions:

- Longer interaction time, large number of interactions between nucleons
- Depends on interaction time, cf. orbit time 10^{-22} s
- System "forgets" about the formation process, decay is statistical. The relative probability for decay into any specific final partition is independent of the formation energy of the compound system

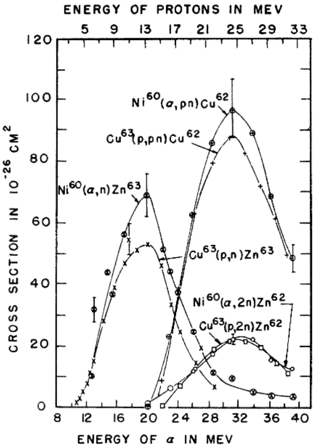
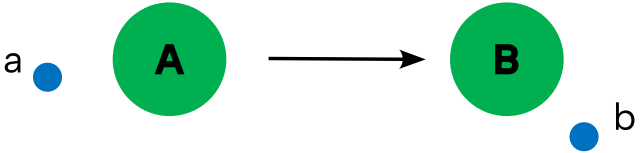


FIG. 1. Experimental cross sections for (p,n), $(p,2n)$, (p,pn) reactions on Cu^{63} and for (α,n), $(\alpha,2n)$, (α,pn) reactions on Ni^{60} plotted against ϵ_p and ϵ_α respectively. The scale of ϵ_p has been shifted by 7 Mev with respect to the scale of ϵ_α.

Transfer reactions

Transfer reactions are direct reactions which link entrance channel $a + A$ and exit channel $b + B$

$$a + A \rightarrow B + b$$



- Direct reactions: short time scale
- Cross section related to transition amplitude / matrix element $\sigma \propto |\langle \mathrm{i}|\hat{O}|\mathrm{f}\rangle|^2$

See Euroschool lecture notes Vol. IV:
"A Pedestrian Approach to the Theory of Transfer Reactions: Application to Weakly-Bound and Unbound Exotic Nuclei" Joaquín Gómez Camacho and Antonio M. Moro

Transfer reactions

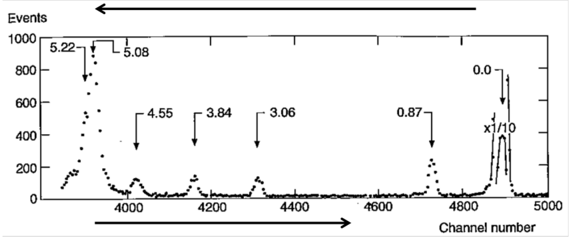
Determine the Q value by measuring the beam energy T_a, the kinetic energy of the light particle T_b, and the scattering angle θ

$$Q = T_b \left(1 + \frac{m_b}{m_B}\right) - T_a \left(1 + \frac{m_a}{m_B}\right) - 2\sqrt{\frac{m_a m_b}{m_B^2} T_a T_b} \cos\theta$$

and from this the excitation energy of the ejectile → missing mass technique

- Traditionally done at beam energies around 10–20 MeV
- Measurement of θ and T_b with magnetic spectrometer
- Example: $^{16}O(d,p)^{17}O$
- Done extensively in the past with light ion beams from tandem accelerators (p, d, ^3H, ^3He, α)

excitation energy of ^{17}O



proton energy

Transfer reactions

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- In 1950, it was realized that the angular distributions of different reaction channels look different
- Semi-classical picture:
  place nucleon in orbit with $L = Rq$
- Momentum transfer $q^2 = p_\mathrm{i}^2 + p_\mathrm{f}^2 - 2p_\mathrm{i}p_\mathrm{f}\cos\theta$
- Higher values of $L \longrightarrow$ Maximum at larger angles

$$L \propto \sin\theta/2$$

- Reality: quantum mechanics and interference

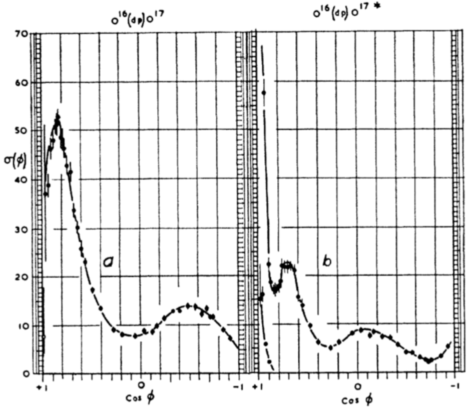

FIG. 1. $O^{16}(d,p)O^{17}$ angular distributions in the center-of-mass (c.m.) system: ϕ = c.m. angle, $\sigma(\phi)$ = c.m. differential cross section in arbitrary units. Curve a is for formation of O^{17} in the ground state, and curve b is for the 0.88-Mev excited state.

Transfer reactions

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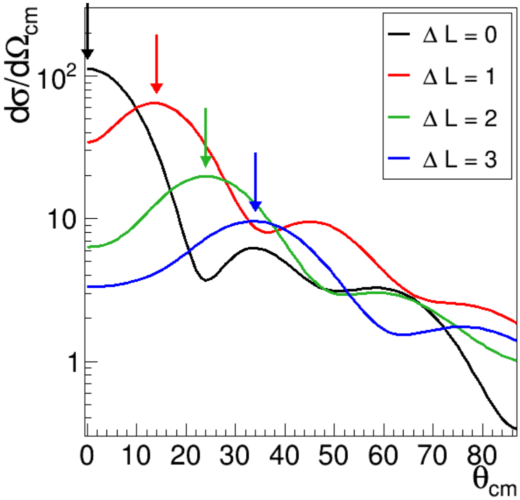
- Higher values of $L \rightarrow$ Maximum at larger angles

$$L \propto \sin\theta/2$$

- Reality: quantum mechanics and interference
- The position of the first maximum is indicative of the transferred angular momentum.
- Note: $j = l + 1/2$ and $j = l - 1/2$ have same angular distribution



Spectroscopic factors

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- The measured cross section is compared with a calculated single-particle cross section, i.e. one nucleon is placed into a certain single-particle orbit

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{exp}} = C^2 S \cdot \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{sp}}$$

- C^2S spectroscopic factor
- Theoretically: norm of the one-body overlap function

$$C^2 S = \int \mathrm{d}^3 r |\psi_{nlj}(r)|^2 \quad \text{with} \quad \psi_{nlj}(r) = \langle \Psi^{\mathrm{A}+1} | a^{\dagger}_{nlj}(r) | \Psi^{\mathrm{A}} \rangle$$

- Creation operator creates a nucleon in the orbital *nlj*
- Can be easily calculated in the shell model

Spectroscopic factors

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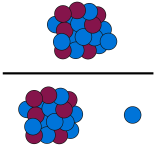
S_{nlj} =



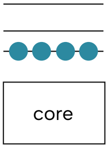
final state

initinal state
+ nucleon

$$C^2S = \int \mathrm{d}^3r |\psi_{nlj}(r)|^2 \quad \text{with} \quad \psi_{nlj}(r) = \langle \Psi^{A+1} | a^\dagger_{nlj}(r) | \Psi^{A} \rangle$$

- Configuration of initial state

initial state =



Spectroscopic factors

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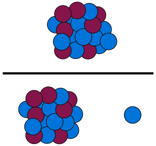
$S_{nlj} =$



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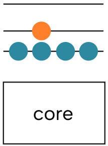
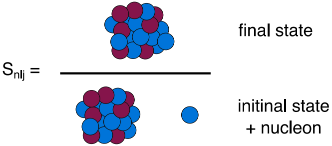
- Configuration of initial state
- Transfer one nucleon into a certain orbital

initial state
+ one nucleon =

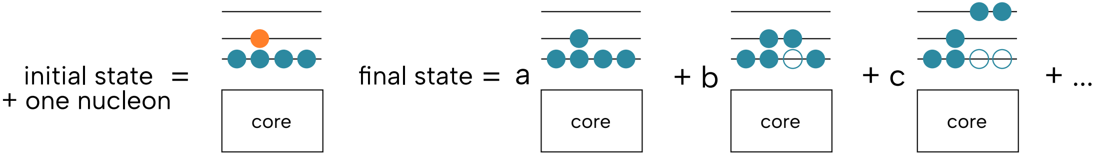


Spectroscopic factors



$$C^2S = \int \mathrm{d}^3r |\psi_{nlj}(r)|^2 \quad \text{with} \quad \psi_{nlj}(r) = \langle \Psi^{A+1} | a^\dagger_{nlj}(r) | \Psi^A \rangle$$

- Configuration of initial state
- Transfer one nucleon into a certain orbital
- Final state can have a very mixed wave function
- Transfer reaction will project out amplitude *a*



Experimental tests of shell structure

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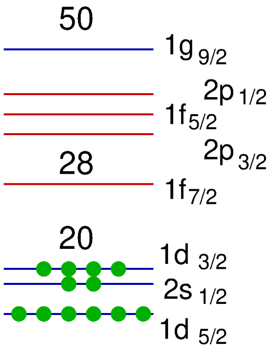
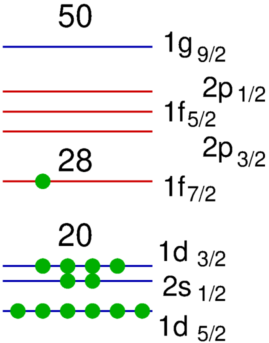
- Measure the energies of levels and determine their occupation

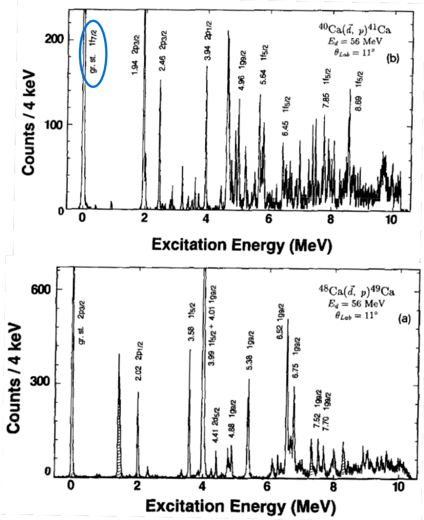


Y. Uozumi et al., Nucl. Phys. A **576** (1994) 123.

Experimental tests of shell structure

- Measure the energies of levels and determine their occupation
- (d, p) transfer reaction to add a neutron





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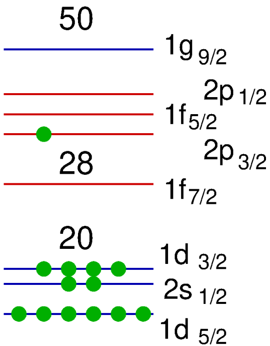

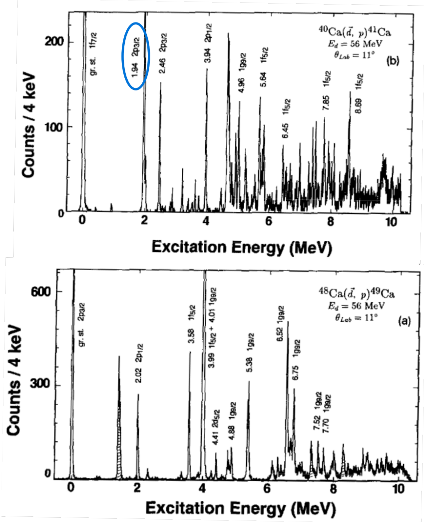

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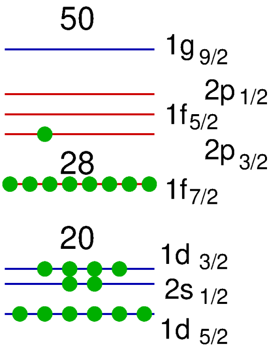

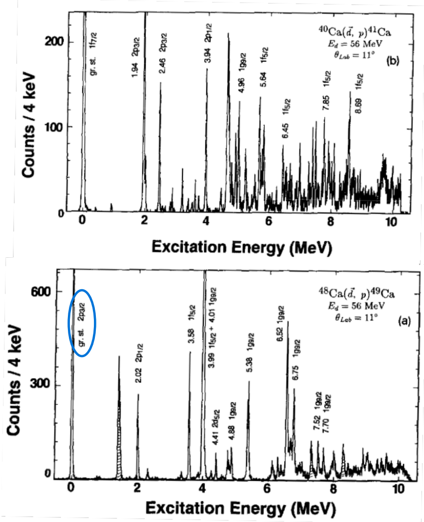

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Experimental tests of shell structure

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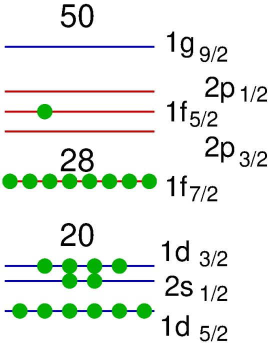
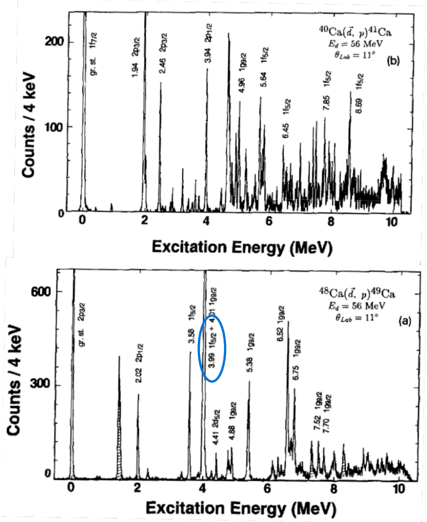
- Measure the energies of levels and determine their occupation
- (d, p) transfer reaction to add a neutron
- Map valence space above a magic number





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Experimental tests of shell structure

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- Transfer reactions provide information on orbital occupancies
- Vacancy of level j is the sum of the spectroscopic factors

$$\text{Vacancy}_j = \sum_j (2j+1) C^2 S_j^+$$

- Spectroscopic factors are obtained from the measured cross section
- One neutron outside a magic nucleus should give $C^2S = 1$ for each single-particle orbital

Experimental tests of shell structure

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- Transfer reactions provide information on orbital occupancies
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- Spectroscopic factors are obtained from the measured cross section
- One neutron outside a magic nucleus should give $C^2S = 1$ for each single-particle orbital
- Observed values $\sim 0.8 - 0.9$
- Not pure configuration
- Residual interaction mixes the pure configurations

Level structure of ^{49}Ca.

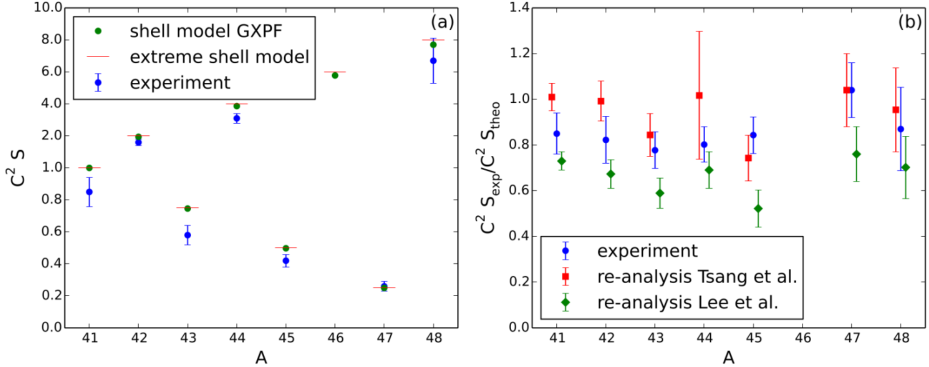
Present work		
E_x (MeV)	j^π	C^2S
Gr. St. [d]	$\frac{3}{2}^-$	0.84
2.021	$\frac{1}{2}^-$	0.91
3.357	$(\frac{9}{2}^+$	0.0037)
3.586	$\frac{5}{2}^-$	0.11
3.888		
3.993	$\frac{5}{2}^-$	0.84
4.018	$\frac{9}{2}^+$	0.14

Y. Uozumi et al., Nucl. Phys. A **576** (1994) 123.

Spectroscopic factors in a single shell

- Successively adding neutrons to the $1f_{7/2}$ orbital
- The calcium isotopes follow the expected single-shell behavior reasonably well
- Spectroscopic factors always only about 70% of IPM

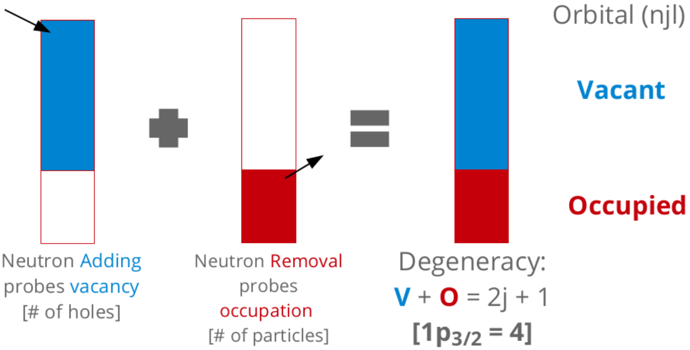
$$C^2S = \begin{cases} 1 - \frac{n}{2j+1}, & \text{if } n \text{ even,} \\ n+1, & \text{if } n \text{ odd.} \end{cases}$$



Occupancies, vacancies and sum rules

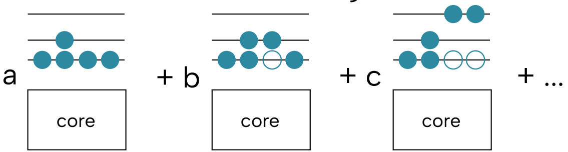
Measurements of particle adding and removing reactions probe the degeneracy of an orbital

$$N = \frac{1}{2j+1}\left(\sum (2j+1)C^2S_{\text{add}} + \sum (2j+1)C^2S_{\text{rem}}\right)$$



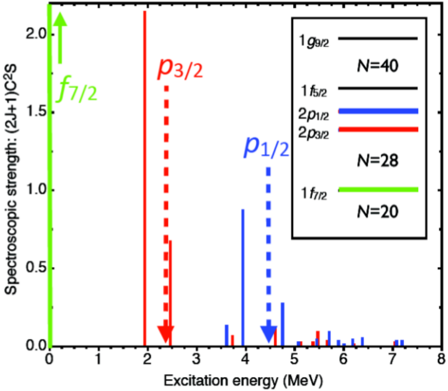
Single-particle energies

- Strength can fragment over several states
- $^{40}Ca(d,p)^{41}Ca$: independent particle model:
  ground state $7/2^-$ with $C^2S = 1$
  excited $3/2^-$ and $1/2^-$ states
- Residual interaction mixes configurations



- Need to sum all fractions of the strength:

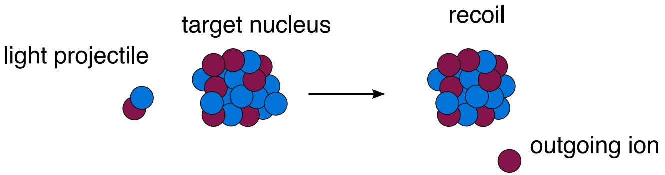
$$\epsilon = \frac{\sum_f (E_0 - E_f^{(-)}) C^2 S_f^{(-)} + \sum_f (E_f^{(+)} - E_0)(2j+1) C^2 S_f^{(+)}}{\sum_f C^2 S_f^{(-)} + \sum_f (2j+1) C^2 S_f^{(+)}}$$



The centroid of the fragmented strength defines the effective single-particle energy

Transfer reactions with radioactive beams

With radioactive beams



- $A(a,b)B$
- Measure ejectile
- Good resolution (10 keV)

- Reactions with exotic nuclei need to be performed in inverse kinematics
- Heavy beam of nucleus of interest impinges on a light target

With radioactive beams

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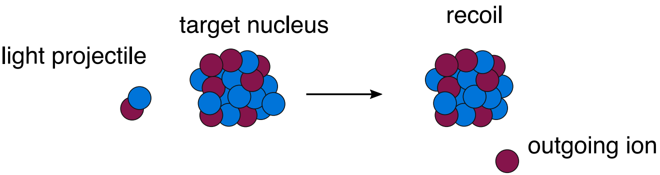

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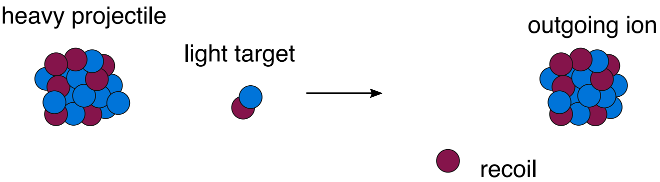
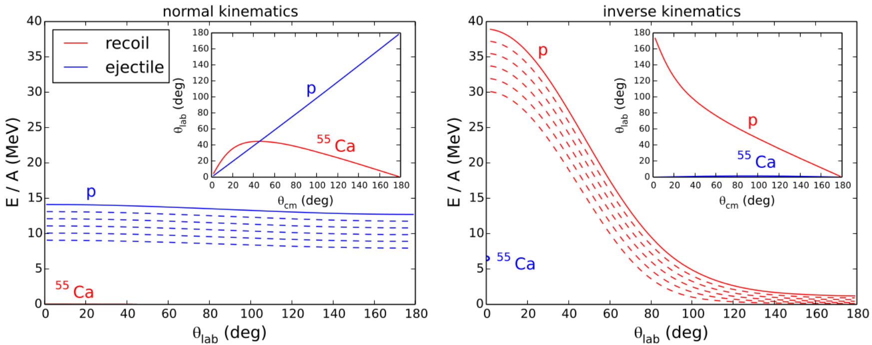


- $a(A,b)B$ at 5–10 AMeV
- HIE-ISOLDE. TRIUMF, GANIL, OEDO
- Measure recoil
- Limited resolution (100 – 500 keV)

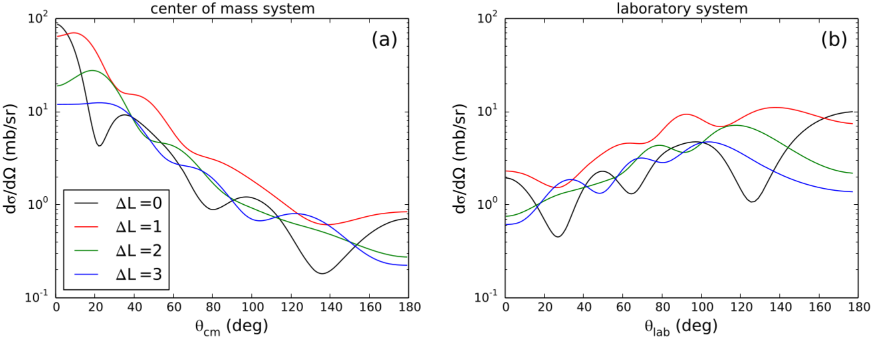
K. Wimmer, Jour. Phys. G **45** (2018) 033002.

Transfer reaction kinematics: $d(^{54}\mathrm{Ca}, p)^{55}\mathrm{Ca}$



- Normal kinematics, almost constant energy of the ejectile
- Inverse kinematics: large variation of the proton energy
- Laboratory system $0^\circ \rightarrow 180^\circ$ center of mass
- Kinematic compression at large lab scattering angles

Transfer reaction kinematics: $d(^{54}\mathrm{Ca}, p)^{55}\mathrm{Ca}$



- Sensitive region at backward angles
- Where the proton energy is very low
  (and the background high, need to tune detection threshold carefully)
- Note: $d\sigma/d\Omega$ is not so useful for experimentalists, $\sin\theta$ factor for yield

Where to put the detector?

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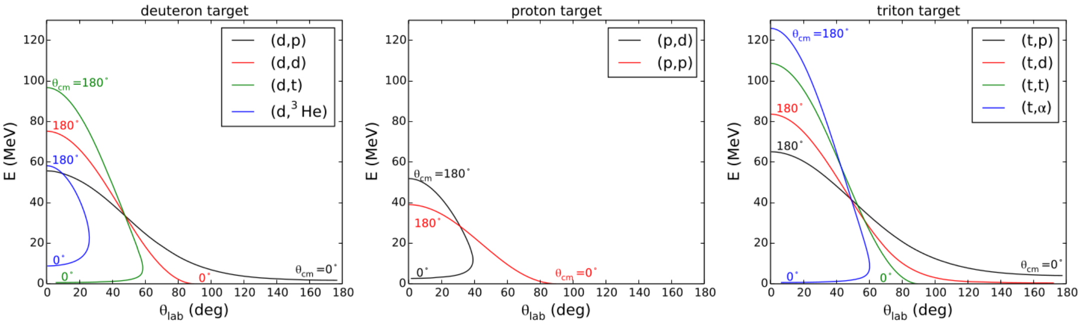
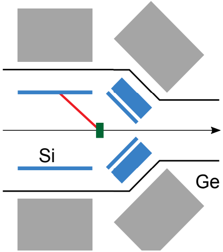


- Elastic scattering: forward of 90°
- Stripping (d, p), (t, p): all ranges of scattering angles
- Pickup reactions (p, d), etc. forward angles (two solutions for kinematics lines)

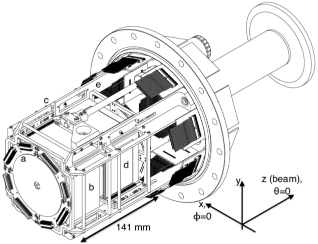
https://github.com/wimmer-k/Reaction

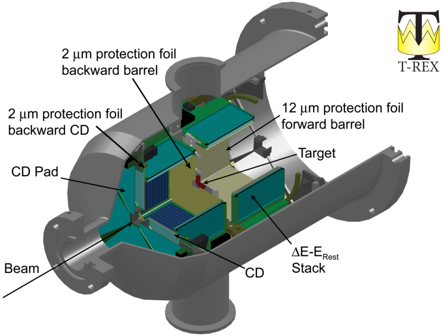
Setups for transfer reactions



- Silicon strip detector box around the target
- Particle identification by energy loss
- Compact and often surrounded by Ge detectors for γ–ray spectroscopy
- Examples: ORRUBA, TIARA, SHARC, T–REX

C. Aa. Diget et al., JINST 6 (2011) P02005, V. Bildstein et al., Eur. Phys. J. A 48 (2012) 85.

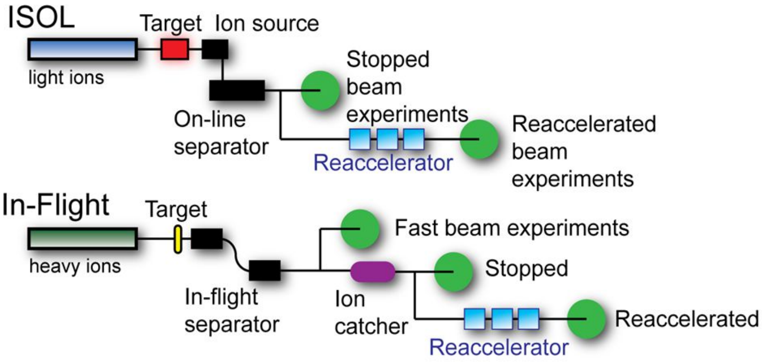




Where to study transfer reactions

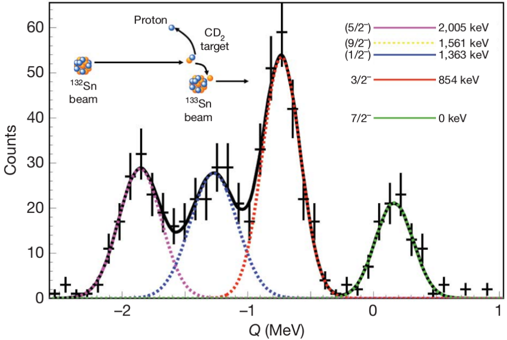
For transfer reactions $\sim 5 - 10$ *A*MeV are needed

- Post-accelerated ISOL beams (ISOLDE, TRIUMF, GANIL)
- Or stopped and re-accelerated in-flight beams (NSCL/FRIB)
- Or decelerated beams (RIBF/OEDO)

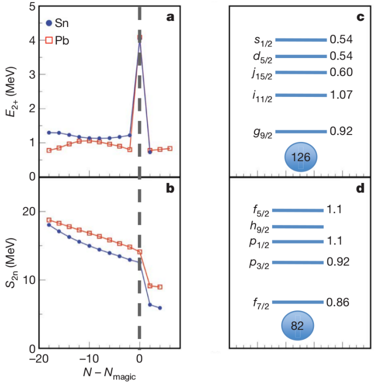


Transfer with radioactive beams

- ^{132}Sn, $Z = 50$, $N = 82$, is a doubly magic nucleus
- Its half-life is only 40 sec
- Experiment has to be performed in inverse kinematics



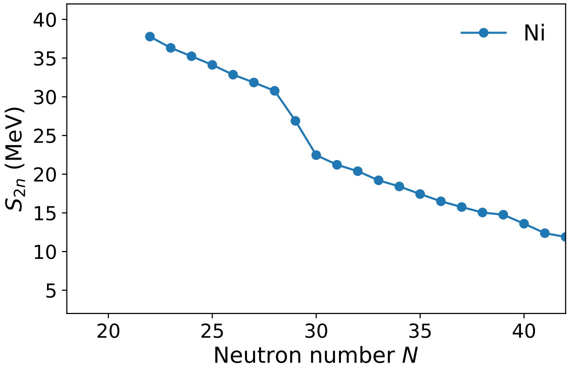
K. L. Jones et al., Nature **465** (2010) 454.

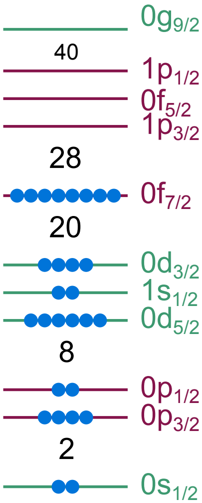


- Similarities between ^{208}Pb and ^{132}Sn
- Spectroscopic factors $C^2S \sim 1$
  $\rightarrow$ good doubly magic nucleus

The neutron-rich Ca isotopes

Shell evolution





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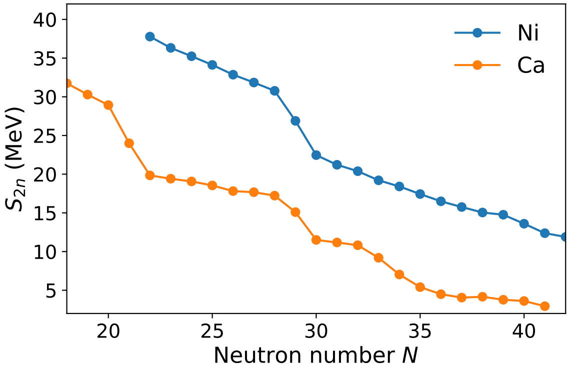

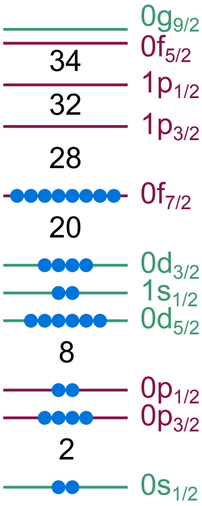

- masses of $^{53-57}$Ca: drops in S_{2n} after shell closure
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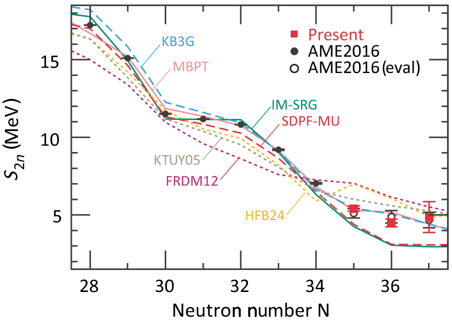
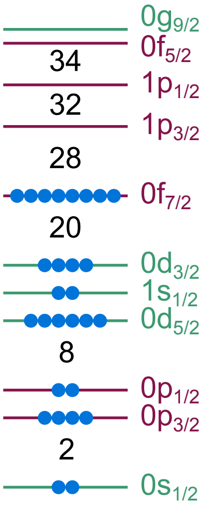
  $\rightarrow$ new magic numbers $N = 32$ and 34

Shell evolution



S. Michimasa et al., Phys. Rev. Lett. **121** (2018) 022506.



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$^{50}Ca(d,p)$

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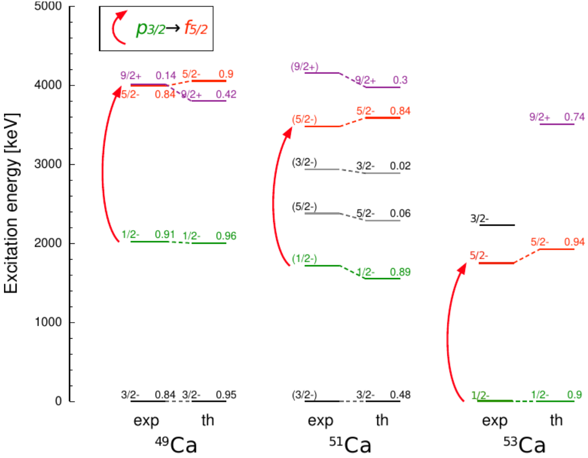
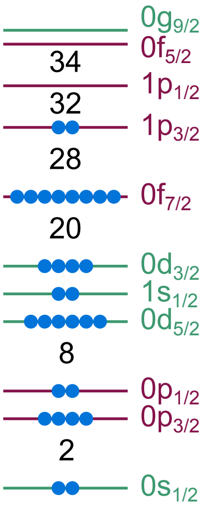
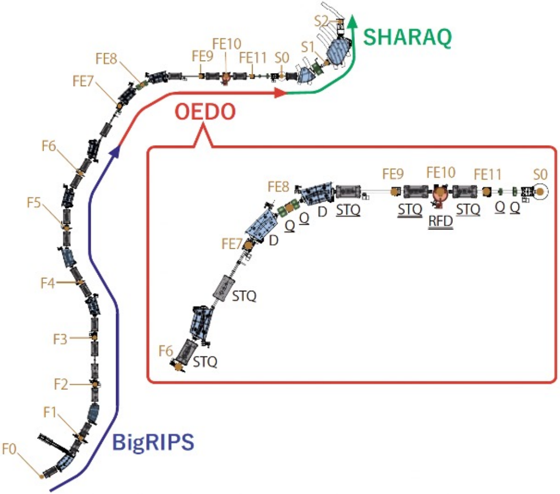
Probe $N = 32, 34$, and 40 shell gaps simultaneously



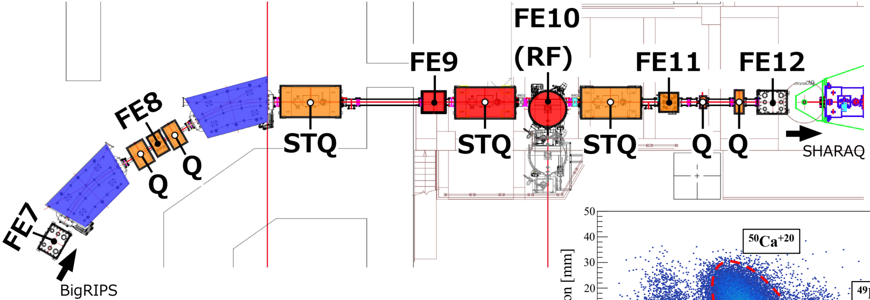


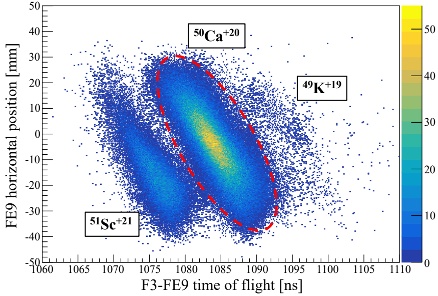
^{50}Ca beam production



- Projectile fragmentation of ^{70}Zn
- Particle identification by time-of-flight and $B\rho$
- Mono-energetic degrader to $\sim$ 15 AMeV

^{50}Ca beam production





- Projectile fragmentation of ^{70}Zn
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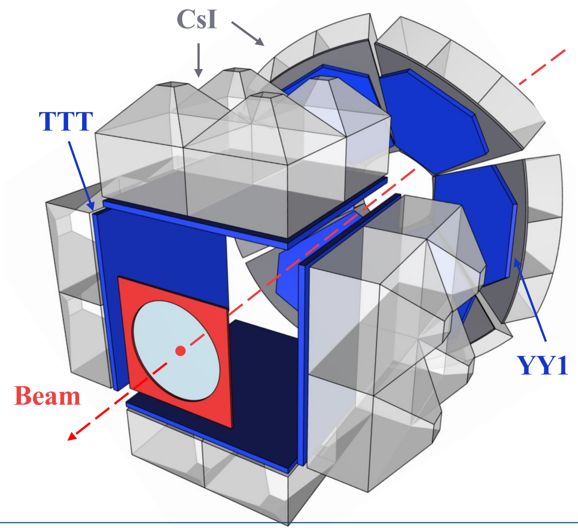
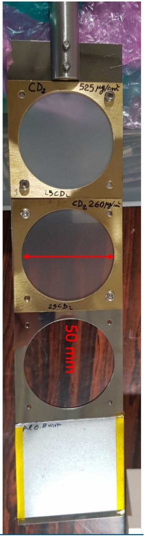
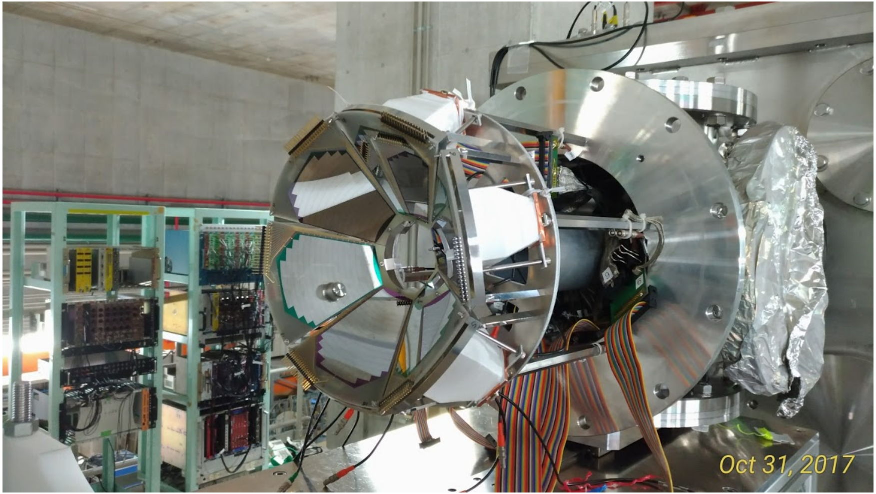
Secondary target and TiNA

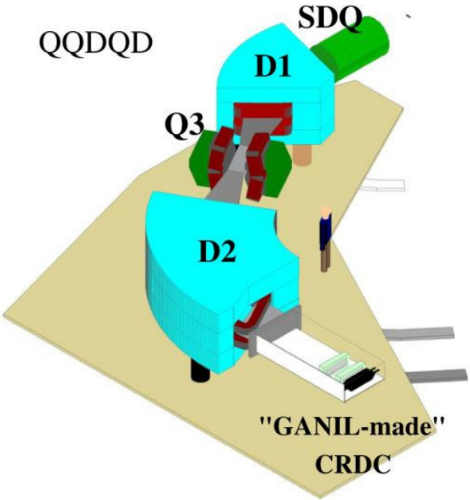


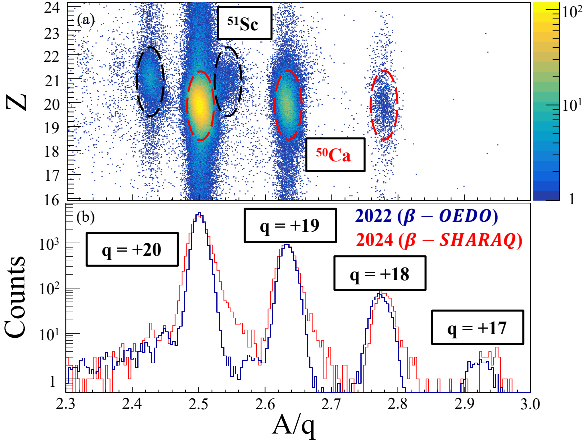


TiNA Si detector



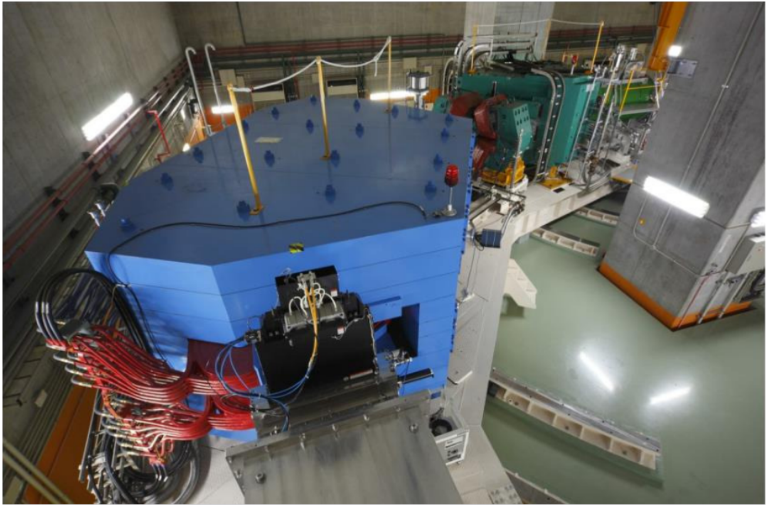
Particle identification after reaction





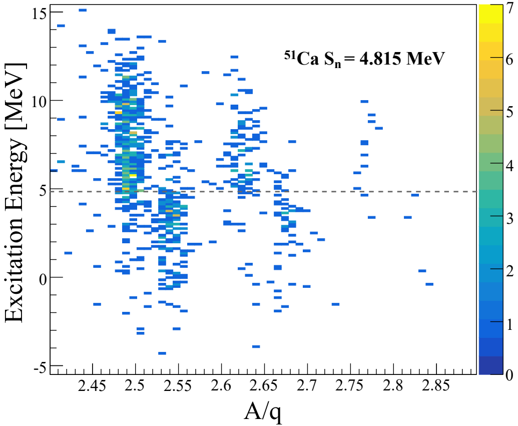
- Different charge states, beam picks up electrons in target

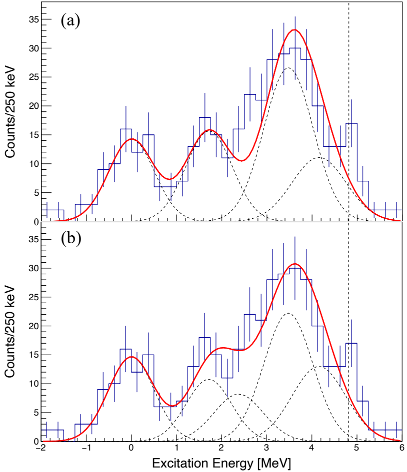
Particle identification after reaction



Results

- Excitation energy reconstruction with limited resolution
- Population of unbound states in ^{51}Ca





Results

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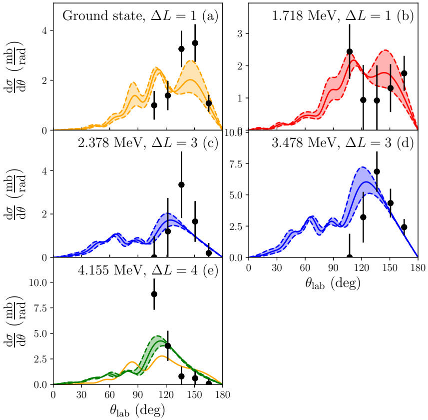
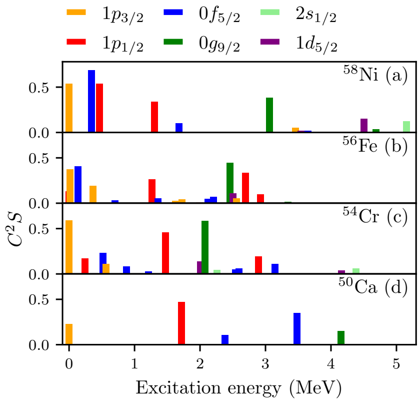
- Angular distributions allow extraction of angular momentum transfer
- Spectroscopic factors are consistent with population of single-particle states





C. Ferrera et al., Phys. Rev. C **113** (2026) 044311.

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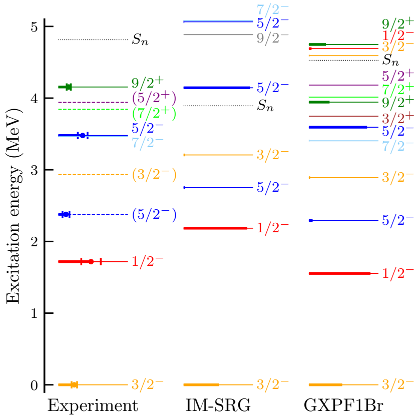
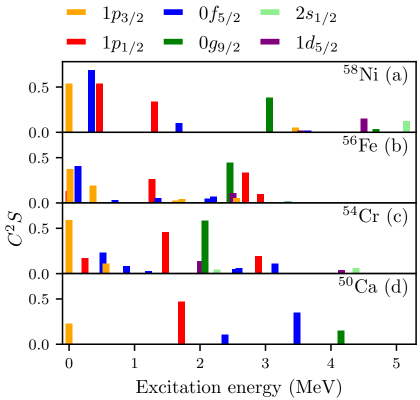


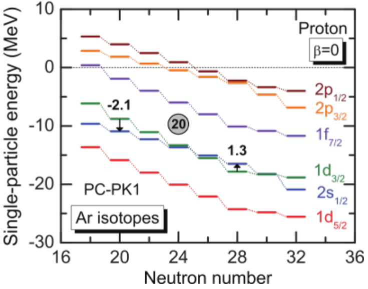


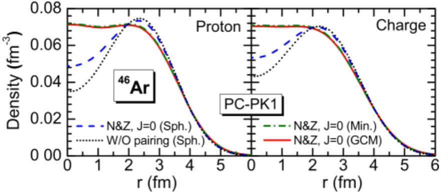
C. Ferrera et al., Phys. Rev. C **113** (2026) 044311.

Is ^{46}Ar a bubble?

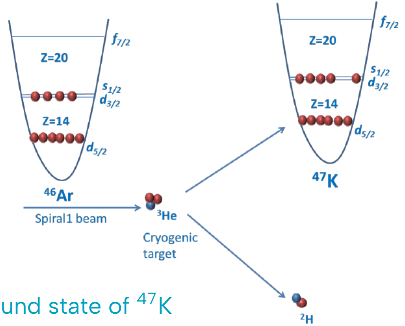
^{46}Ar: a bubble nucleus?

- $Z = 20, N = 28$: the last two protons fill the $2s_{1/2}$ orbital
- Some theoretical calculations of the density distribution predict a proton bubble for ^{46}Ar





- Probe the ^{46}Ar ground state wave function by a direct proton adding reaction

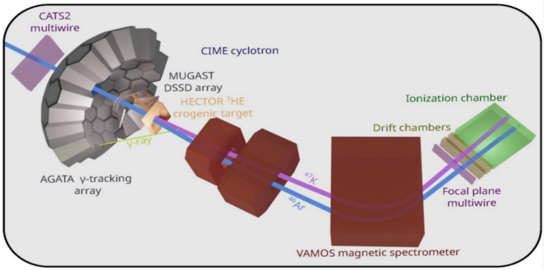


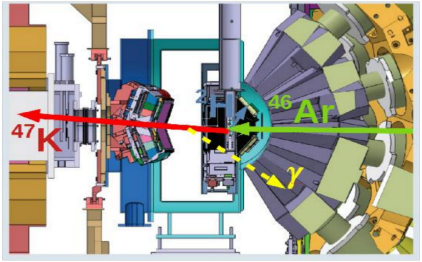
Add proton to $d_{3/2} \rightarrow 3/2^+$ state at 360 keV, $s_{1/2} \rightarrow 1/2^+$ ground state of ^{47}K

^{46}Ar: a bubble nucleus?

Setup for a complete measurement of reaction-related observables

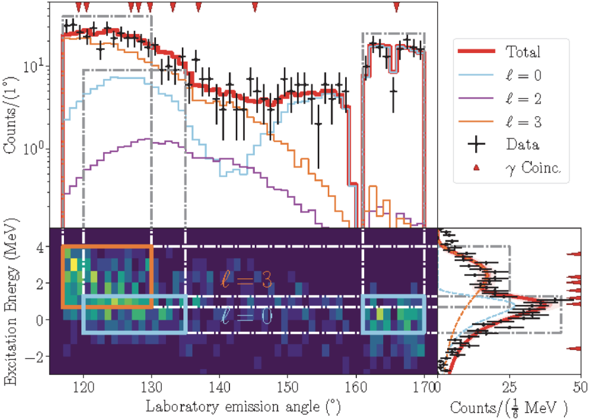
- ^{46}Ar beam produced by projectile fragmentation at GANIL
- Cryogenic (6 K) ^{3}He target
- VAMOS spectrometer for ejectile ^{47}K
- MUGAST to detect deuteron, measure E and θ
- AGATA: γ-ray tracking array, 40 high-purity Ge crystals, 10% efficiency

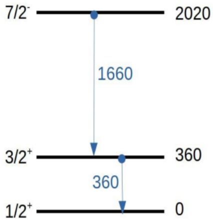


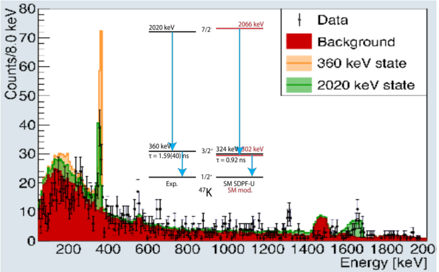


^{46}Ar: a bubble nucleus?

Measure excitation energy and angular distribution of deuterons







D. Brugnara et al.

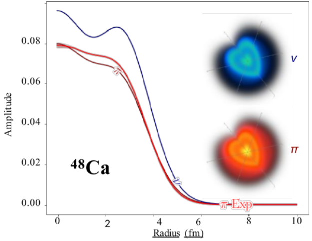
^{46}Ar: a bubble nucleus?

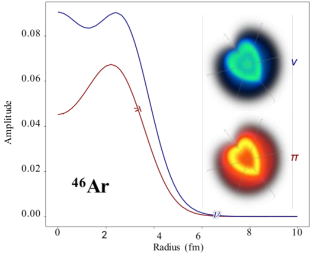
- Cross section to $7/2^-$ state much larger than for $3/2^+$

$C^2S_L/C^2S_{L=0}$	$3/2^+$ state	$7/2^-$ state
Experiment	0.1(1)	1.1(2)
Calculation SDPF-U	0.63	2.6

D. Brugnara et al.

- Small $C^2S \rightarrow 1d_{3/2}$ orbital is full occupied
- $1f_{7/2}$ and $2s_{1/2}$ are both empty, large cross section
- Compared with ab-initio calculations with the NNLO$_{sat}$
- Proton density depletion in the center of ^{46}Ar
- Can we "measure" the density distribution?
  With a setup like SCRIT, highest ^{46}Ar production yield predicted for FRIB (USA), and design value for ERL (energy recovery linear accelerators) like PERLE (France), DICE (Darmstadt), it could be possible to measure (e, e') for ^{46}Ar





Summary: Transfer reactions

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- The single-particle shells are not observables
- Direct nuclear reactions can be used to determine:
  - Energies, spins, and parities of states in the reaction products through missing mass or decay spectroscopy
  - Occupation and vacancy of orbitals
- Single-particle strength in ^{51}Ca probe sub-shell gaps at $N = 32$ and 34
- "Empty" proton *s* orbital in ^{46}Ar makes it a candidate for a bubble nucleus

Discussion

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Let's measure the transfer reaction $^{54}\text{Ca}(d, p)$

- Which orbitals are populated?

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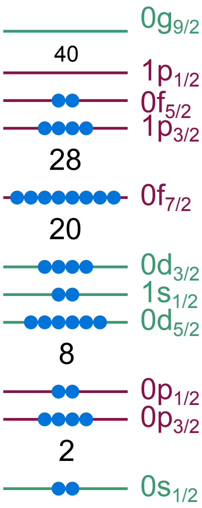
- Estimate the spectroscoppic factors (in the independent particle model) for:
  - Conventional shell ordering



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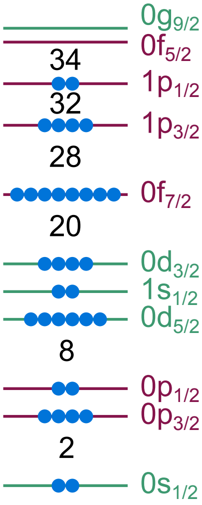
  - Modified ordering with sub-shell gaps at N=32 and 34



Discussion

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- Which orbitals are populated?
- Estimate the spectroscoppic factors (in the independent particle model) for:
  - Conventional shell ordering
  - Modified ordering with sub-shell gaps at N=32 and 34
- Sketch the missing mass spectrum
- Sketch the angular distributions (in the center of mass system)
- How would you do the measurement?