Exotic decay modes of proton drip-line nuclei

Chiara Mazzocchi

Faculty of Physics, University of Warsaw

Nuclear Physics at the Edge of Stability, ECT*

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Zakład Fizyki Jądrowej
Uniwersytet Warszawski

Wydział Fizyki
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Overview

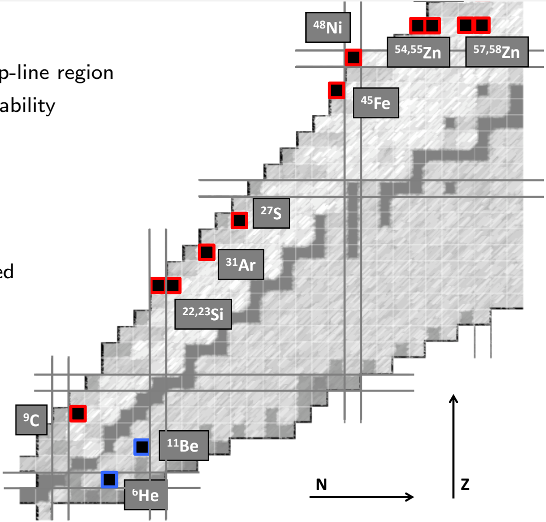
Exotic nuclei

Light and medium mass proton drip-line region

- Nuclear structure far from stability
- New decay modes
- Data for the rp-process

Light n-rich nuclei

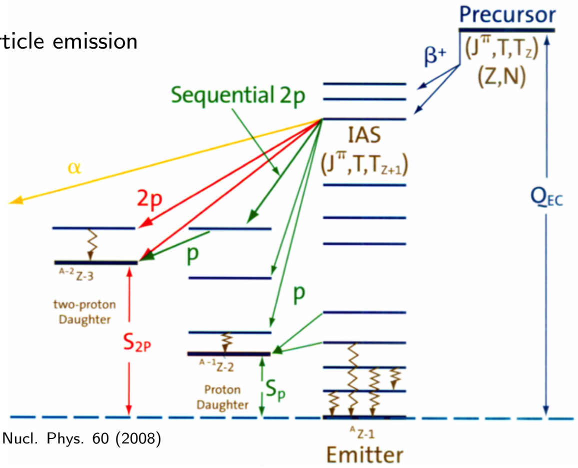
- Emission of β-delayed charged particles (p,d)
- Probing n-halo



Rare decay modes

Proton-rich nuclei

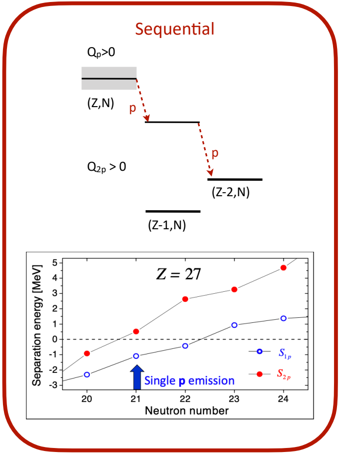
- strong β transitions
- (multi-) charged-particle emission

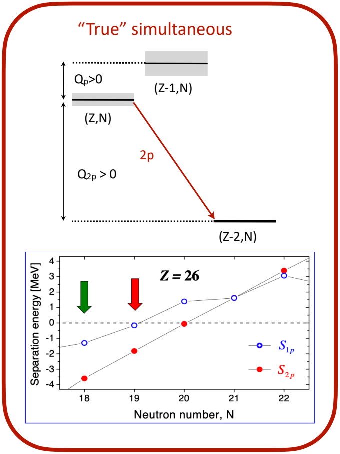


B. Blank, M.J.G. Borge, Prog. Part. Nucl. Phys. 60 (2008)

Two-proton radioactivity

Expected for even-Z nuclei beyond the proton drip-line





Goldanski, Nucl. Phys. 19 (1960) 482

Two-proton emission

Important messenger on

- masses
- nuclear forces
- structure (?)

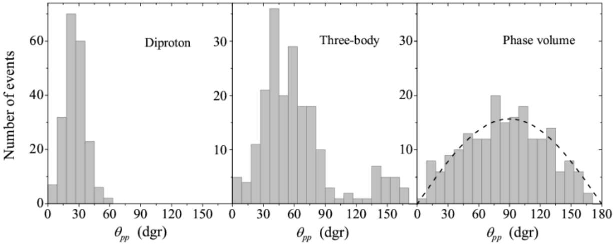
beyond the proton drip-line.

It competes with β^+ decay.

What is the mechanism?

- sequential or simultaneous?
- di-proton, independent, correlated?

$\rightarrow$ measurement of the angular distribution of the two protons

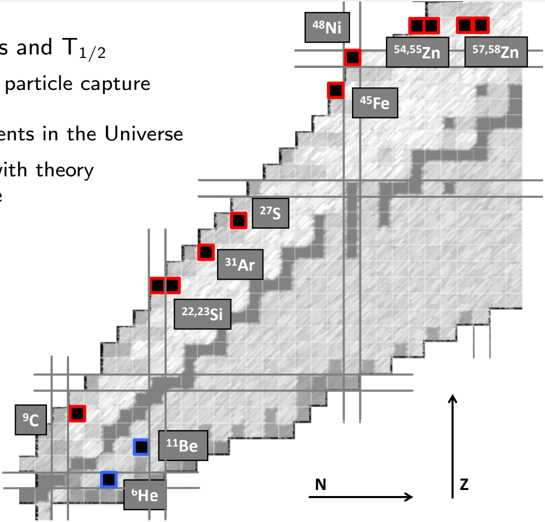


L. Grigorenko, two-proton decay mechanisms of ^{45}Fe

Particle spectroscopy

Measurement of branching ratios and $T_{1/2}$

- competition btw. β decay & particle capture
  $\rightarrow$ shape of rp-process path
  $\Rightarrow$ abundance of heavy elements in the Universe
- comparison of exp. studies with theory
  $\rightarrow$ check of nuclear structure
  and interaction models



Charged particle spectroscopy

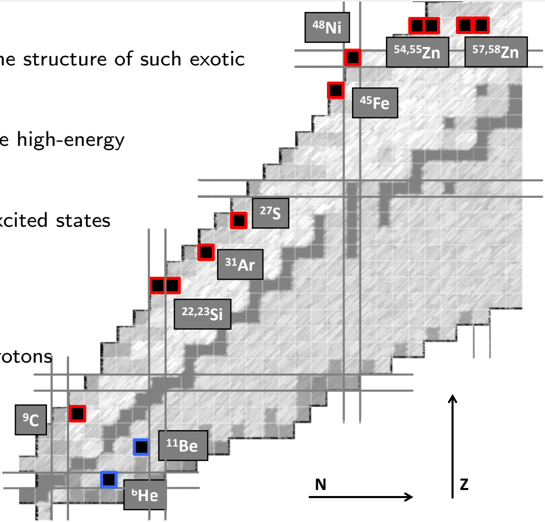
Very powerful tool to investigate the structure of such exotic nuclei

Probing the β-decay strength in the high-energy end of the Q-value window

Determination of Γ_p for selected excited states

β-delayed charged particle decay
$\rightarrow$ competition with $\beta\gamma$ decay

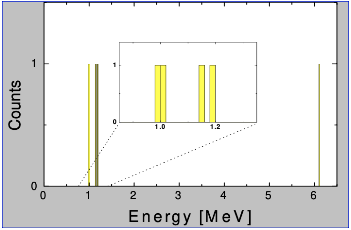
angular correlations between the protons
$\rightarrow$ decay mechanism



The beginning of an adventure: discovery of 2p radioactivity (2002)

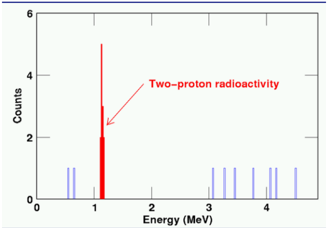
Implantation into Si-det. array
$\rightarrow$ good measurement of total energy but protons not resolved!
$\Rightarrow$ auxiliary detectors needed to prove peak is not βp emission!

GSI: ^{58}Ni *at* 650 @ A·MeV + ^{nat}Be $\rightarrow ^{45}$Fe



M. Pfützner et al., Eur. Phys. J. A14 (2002) 279

GANIL: ^{58}Ni @ 75 A·MeV + ^{nat}Ni $\rightarrow ^{45}$Fe

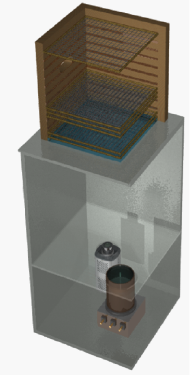


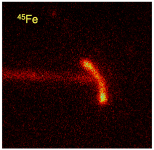
J. Giovinazzo et al., Phys. Rev. Lett. 89 (2002) 102501

The beginning of an adventure: momenta of the 2 protons (2007)

Time-projection chambers developed to measure the momenta of the 2 protons

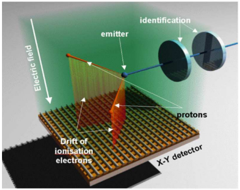
University of Warsaw:: "optical" TPC

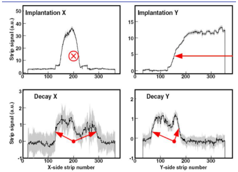




K. Miernik et al., Phys. Rev. Lett. 99 (2007) 192501

CENBG-Bordeaux:: "classical" TPC (electronic readout)





J. Giovinazzo et al., Phys. Rev. Lett. 99 (2007) 102501

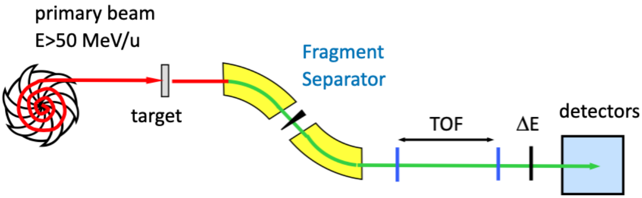
Challenges for experimenters

- exotic nuclei $\rightarrow$ low production rates
- rare decay modes $\rightarrow$ small branching ratios
- high background levels
- physics requirements
  - low-energy particle detection
  - particle correlation measurements

Experimental solution(s)

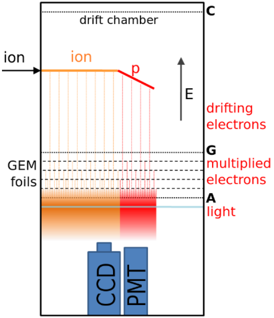
Production of the isotopes of interest

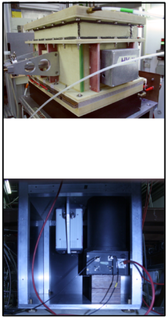
- projectile fragmentation + in-flight separation
  → MARS@TAMU, BIGRIPS@RIKEN, ACCULINNA@DUBNA, FRS@GSI, A1900@NSCL



- ion identification: energy loss (ΔE) vs time-of-flight (ToF) matrices
- implantation of the ions into the Optical Time-Projection Chamber (OTPC)

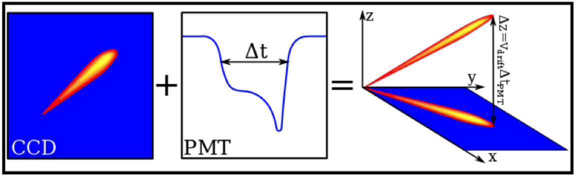
Optical-readout Time-Projection Chamber (OTPC)





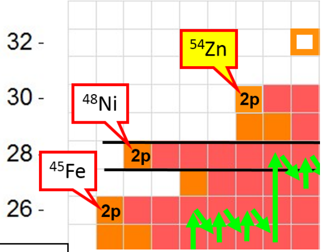
Identified ions implanted in the OTPC

Combination of CCD image and PMT waveform
→ 3D reconstruction of particle tracks

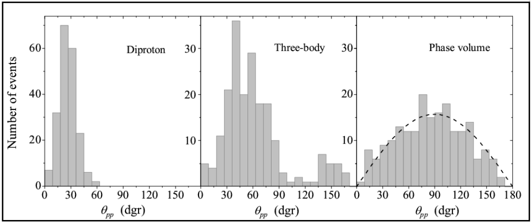


Two-proton decay of ^{54}Zn

Can we see the Z=28 shell closure in the p-p correlations?



^{45}Fe case (Z=28-2)



Two-proton decay of ^{54}Zn

Two-proton radioactivity of ^{54}Zn studied at the BigRIPS spectrometer (RIKEN):

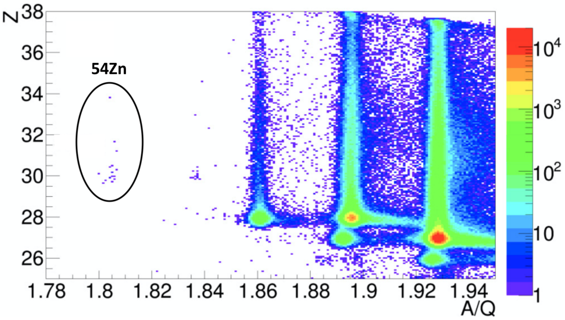
- fragmentation of a ^{78}Kr beam @ 350 MeV/u on Be target
- large beam intensity: 300 pnA
- ion-by-ion identification
- selective triggering
- beam stopped upon good implantation

A. Kubiela et al., Phys. Rev. C 104, 064610 (2021)
A. Kubiela, PhD thesis, University of Warsaw, in preparation

Two-proton decay of ^{54}Zn

Production cross-section of proton-rich Zn isotopes:

- cross section found to be more than 100x smaller than pessimistic predictions
  $\rightarrow$ only a few ^{54}Zn ions observed



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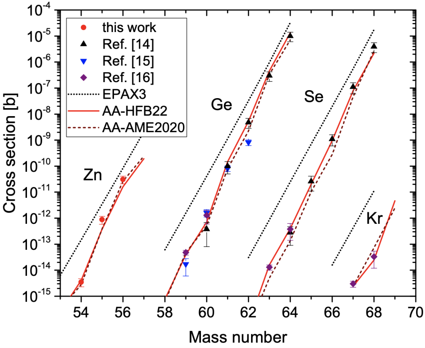
Two-proton decay of ^{54}Zn

Production cross-section of proton-rich Zn isotopes



[14] A. Stolz et al, PLB 627 (2005)
[15] A.A. Ciemny et al, PRC 92 (2015)
[16] B. Blank et al, PRC 93 (2016)

Nucleus	σ_{exp}	σ_{EPAX3}	σ_{AA}	σ_{Ni}
^{56}Zn	$(3.1 \pm 0.1_{(stat)} \pm 1.0_{(syst)}) \times 10^{-11}$	8.45×10^{-11}	1.6×10^{-11}	$5^{+20}_{-2} \times 10^{-10}$
^{55}Zn	$(8.8 \pm 0.3_{(stat)} \pm 3.1_{(syst)}) \times 10^{-13}$	3.47×10^{-12}	3.8×10^{-13}	$2.0^{+0.6}_{-0.5} \times 10^{-11}$
^{54}Zn	$(3.5 \pm 0.7_{(stat)} \pm 1.2_{(syst)}) \times 10^{-15}$	1.47×10^{-13}	4.1×10^{-15}	$\approx 1 \times 10^{-13}$

A. Kubiela et al., Phys. Rev. C 104, 064610 (2021); A. Kubiela, PhD thesis, University of Warsaw, in preparation

Two-proton decay of ^{54}Zn

Production cross-section of proton-rich Zn isotopes

- reaction selection

Lab	Beam	E [MeV/u]	I [pnA]	Target	d [g/cm^2]	σ [fb]	Y [1/day]
GANIL	^{58}Ni^{+26}	75	154	Ni	0.250	100	22
RIKEN	^{78}Kr^{+36}	345	300	Be	1.850	3.5	70

- predictions for productions of new 2-proton emitters

Nucleus	σ [barn]	S_p [MeV]	S_{2p} [MeV]	$T_{1/2}^{2p}$
^{59}Ge	$(4.8 \pm 1) \times 10^{-14}$ [a]	0.349	-0.742	10^{11} s
^{58}Ge	7.6×10^{-16}	0.299	-2.122	0.6 μs
^{63}Se	$(1.3 \pm 0.3) \times 10^{-14}$ [a]	0.589	-1.512	1 s
^{62}Se	8.4×10^{-17}	0.099	-2.612	14 ns

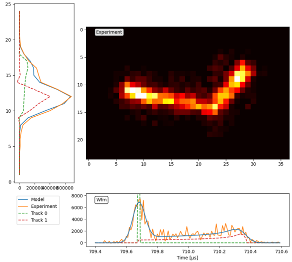
[a]Experimental value from Ref. [16].

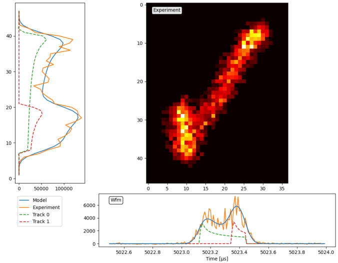
A. Kubiela et al., Phys. Rev. C 104, 064610 (2021); A. Kubiela, PhD thesis, University of Warsaw, in preparation

Two-proton decay of ^{54}Zn

Two-proton radioactivity of ^{54}Zn studied at the BigRIPS spectrometer (RIKEN):

- 5 events observed (4 reconstructed)



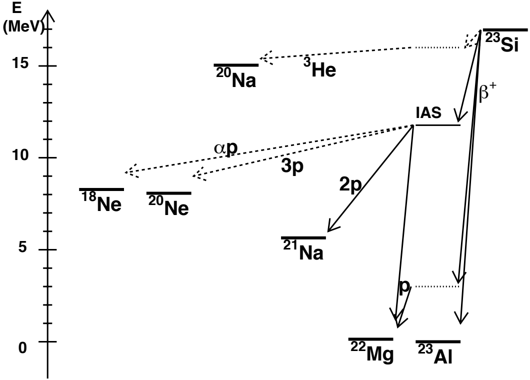


A. Kubiela, PhD thesis, University of Warsaw, in preparation

β-delayed multi-particle decays: light silicon isotopes

Region around ^{22}Si (Z=14, N=8):

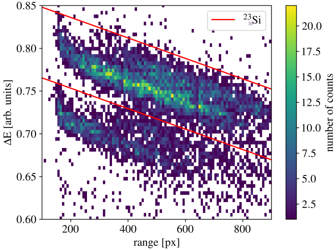
- ^{22}Si and ^{23}Si known to decay via β1p and β2p emission
- mostly through the IAS
- β3p, $\beta\alpha$p and β^3He channels (hitherto unobserved decay mode) open
- decay through other states than IAS not observed, nor the β3p

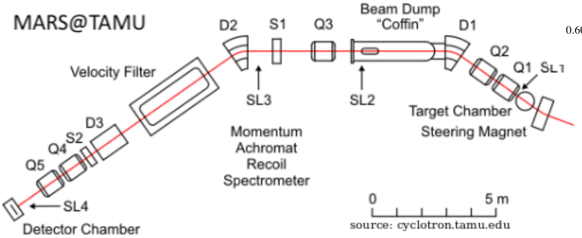


β-delayed multi-particle decays: light silicon isotopes

Experiment at the MARS spectrometer (Texas A&M University):

- fragmentation of a ^{28}Si beam @ 45 MeV/u on Ni target
- ion-by-ion identification
- selective triggering
- beam stopped upon good implantation



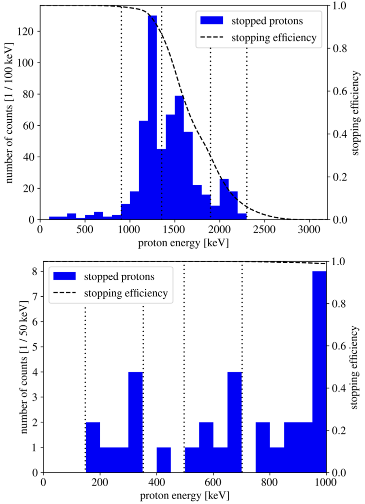


source: cyclotron.tamu.edu

New, exotic decay modes of ^{23}Si

β-delayed multi-particle emission from ^{23}Si

- about 7.5k implanted ^{23}Si ions
- branching ratios:
  $b_{\beta p} = 81.8(11)\%$ (lit. 71%)
  $b_{\beta 2p} = 7.73(35)\%$ (lit. 3.6%)
- new low-energy proton group observed



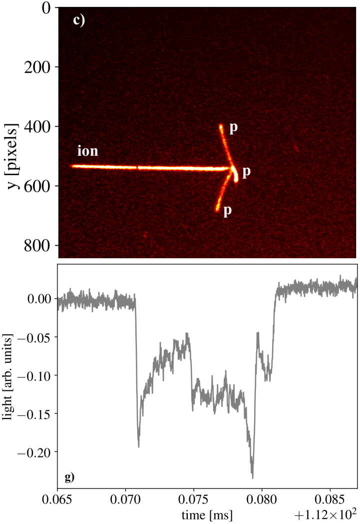
A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

New, exotic decay modes of ^{23}Si

β-delayed multi-particle emission from ^{23}Si

- first observation of β3p decay of ^{23}Si (2 evnts)
- $b_{\beta 3p}=2.9(^{+38}_{-19})\times 10^{-4}$
- E_{3p}= 3.65(35) MeV (# 1) and
  $E_{3p}\geq$2.7(7)-3.3(6) MeV (# 2)

  $\rightarrow$ compatible with decay through IAS or nearby states



A.A. Ciemny et al., submitted to Phys. Rev. C

A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

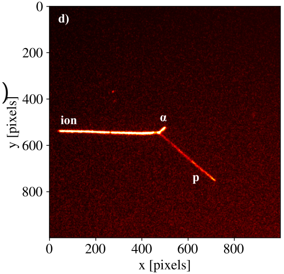
New, exotic decay modes of ^{23}Si

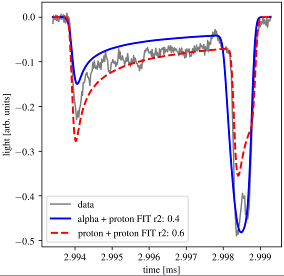
β-delayed multi-particle emission from ^{23}Si

- tentative identification of $\beta p\alpha$ decay of ^{23}Si (1 ev.)
- $b_{\beta p\alpha}=1.4(^{+33}_{-12})\times10^{-4}$
- Fit results:

  αp/pα $\rightarrow$ E_p=1.6(1) MeV and E_α=1.2(4) MeV (compatible with IAS decay)

  p+p $\rightarrow$ E_{p_1}=1.6(1) and E_{p_2}0.4(2) MeV (compatible with decay from state below IAS)





A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

New, exotic decay modes of ^{23}Si

β-delayed multi-particle emission from ^{23}Si: $\beta p\alpha/\beta\alpha p$ decay channel

- $\beta p\alpha$ or $\beta\alpha p$?
- barrier penetrability considerations with ℓ_α=0 favour p+α emission
- in literature βpα and $\beta\alpha$p observed in ^{17}Ne and ^{9}C, while βpα in ^{21}Mg

A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

New, exotic decay modes of ^{23}Si

β-delayed multi-particle emission from ^{23}Si: $\beta p\alpha/\beta\alpha p$ decay channel

- βpα/$\beta\alpha$p known cases (T_z=-3/2 ^{17}Ne, ^{9}C and ^{21}Mg) decay through α-conj. nucleus (^{16}O, ^{8}Be, ^{20}Ne)
- systematics of β-delayed multi-particle decay of $T_z \leq$-3/2 isotopes $\rightarrow$ presence of β3p and βpα/$\beta\alpha$p decay modes in $T_z \leq$-3/2 due to odd-even rather than α clustering effects (Lund et al., PLB750 (2015))
- observation in T_z=-5/2 ^{23}Si, ^{27}S, ^{31}Ar would support the conclusion
- discovery of β3p decay in ^{23}Si, ^{31}Ar and ^{43}Cr, and tentatively of βpα in ^{23}Si supports it

A.A. Ciemny et al., submitted to Phys. Rev. C

A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

β decay of ^{23}Si – DFT-NCCI calculations

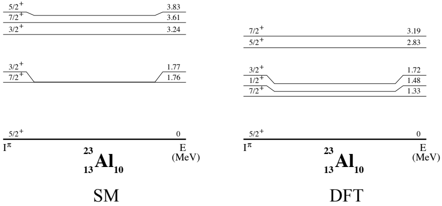
- State-of-the-art: shell-model
  $\rightarrow$ sufficiently accurate description of the low-energy spectrum of ^{23}Al
- Alternative approach: multi-reference density-functional-rooted (DFT-rooted) calculations
  $\rightarrow$ extension of conventional mean-field that restores angular momentum and treats properly isospin symmetry
- Aim: validate the new approach in the nucleus where benchmark SM results exist and test the properties of the underlying functional in this mass region without applying any local adjustment of its parameters.

A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

β decay of ^{23}Si – DFT-NCCI calculations

- Configuration-space and configuration mixing calculation → SV_{SO} density-ind. Skyrme interaction
- Low-energy spectrum compares relatively well with SM
- IAS predicted ~2.5 MeV lower than exp. and SM
  → need for better calibration of the symmetry energy strength in the functional
- GT for decay to states with E_x <3 MeV → GT mat. el. ≪1
- Shape difference predicted for ^{23}Si (weak def. obl.) and ^{23}Al (well def. prol.)
  → GT mat. el. hindrance + IAS dominance in decay pattern
- Difference between DFT-NCCI and SM predictions for E_x >3 MeV:
  still under investigations → will require better calibration of the functional

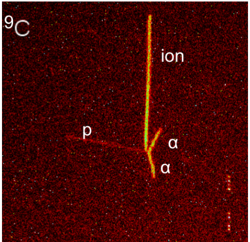
A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in prep.



Summary and outlook

OTPC used in connection with different ion-delivery systems:

- simple and very efficient tool to search for very rare decays and to investigate charged-particle decays obscured by β background
- it can provide precise branching ratios for β-delayed charged-particle channels
- low energies can be reconstructed (worse energy resolution than with Si detectors - complementarity!)
- most recent results include study of 2p decay of ^{54}Zn and βxp decay of ^{23}Si



A. Giska, BSc thesis (UW), 2018

Summary and outlook

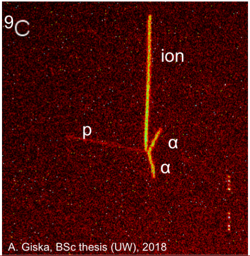
Limitations

- reconstruction of multi-particle decays (>2) difficult/impossible
- low counting rate ($\sim$2 Hz)
- long $T_{1/2}$ are very challenging
- limited range range of measurable energies
  (but complementary to Si-detector energy ranges)

New active target TPC with planar readout developed for nuclear astrophysics studies, but not only

OTPC experiments on the two-proton emitters ^{39}Ti and ^{48}Ni planned at GANIL and FRIB

Stay tuned!



thank you!

PHYSICAL REVIEW C **104**, 064610 (2021)

Production of the most neutron-deficient Zn isotopes by projectile fragmentation of ^{78}Kr

A. Kubiela,[1,*] H. Suzuki,[2] O. B. Tarasov,[3] M. Pfützner,[1,†] D.-S. Ahn,[2] H. Baba,[2] A. Bezbakh,[4] A. A. Ciemny,[1] W. Dominik,[1] N. Fukuda,[2] A. Giska,[1] R. Grzywacz,[5] Y. Ichikawa,[2,6] Z. Janas,[1] Ł. Janiak,[7] G. Kamiński,[4,8] K. Kawata,[2,9] T. Kubo,[2] M. Madurga,[5] C. Mazzocchi,[1] H. Nishibata,[2,6] M. Pomorski,[1] Y. Shimizu,[2] N. Sokołowska,[1] D. Suzuki,[2] P. Szymkiewicz,[4,10] A. Świercz,[4,10] M. Tajima,[2] A. Takamine,[2] H. Takeda,[2] Y. Takeuchi,[2,11] C. R. Thornsberry,[5] H. Ueno,[2] H. Yamazaki,[2] R. Yokoyama,[5] and K. Yoshida[2]

[1]*Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland*
[2]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Russia*
[5]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[6]*Department of Physics, Kyushu University, 744 Moto-oka, Nishi, Fukuoka, Fukuoka 819-0395, Japan*
[7]*National Centre for Nuclear Research, 05-400 Otwock, Świerk, Poland*
[8]*Heavy Ion Laboratory, University of Warsaw, 02-093 Warsaw, Poland*
[9]*Center for Nuclear Study, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[10]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 30-059 Krakow, Poland*
[11]*Department of Advanced Sciences, Hosei University, 3-7-2 Kajino-cho, Koganei, Tokyo 184-8584, Japan*

Beta-delayed charged-particle decay of ^{22,23}Si

A.A. Ciemny,[1,*] C. Mazzocchi,[1,†] W. Dominik,[1] A. Fijałkowska,[2,1] J. Hooker,[3,4] C. Hunt,[3,4] H. Jayatissa,[3,4] Ł. Janiak,[5,1] G. Kamiński,[6] E. Koshchiy,[3] M. Pfützner,[1] M. Pomorski,[1] B. Roeder,[3] G.V. Rogachev,[3,4] A. Saastamoinen,[3] S. Sharma,[1] N. Sokołowska,[1] W. Satuła,[1] and Jagjit Singh[1]

[1]*Faculty of Physics, University of Warsaw, Warsaw, Poland*
[2]*Rutgers University, New Brunswick, New Jersey*
[3]*Cyclotron Institute, Texas A&M University, College Station, Texas*
[4]*Department of Physics & Astronomy, Texas A&M University, 77843 Texas, USA*
[5]*National Centre for Nuclear Research, Otwock, Świerk, Poland*
[6]*Heavy Ion Laboratory, University of Warsaw, 02-093 Warsaw, Poland*

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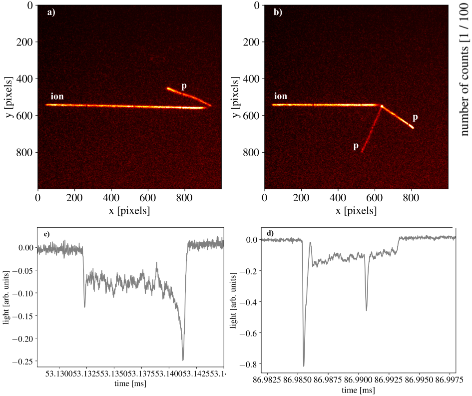
Back-up slides

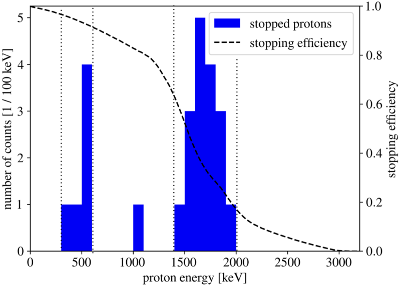
β-delayed multi-particle decays: ^{22}Si

- First observation in 1987, in ^{36}Ar fragmentation reaction.
- First $T_z = -3$ nucleus observed
- βp identified and energy spectrum measured in 1996
- β2p from IAS reported in 2017:
  - charged-particle group @ 5600(70) keV
  - BR = 0.7(3)% (5 events)

M.G. Saint-Laurent et al., PRL 59, 33, 1987
B. Blank et al., PRC 54, 572, 1996
X.X. Xu et al., PRL B 766, 312-316, 2017

β-delayed multi-particle decays: ^{22}Si





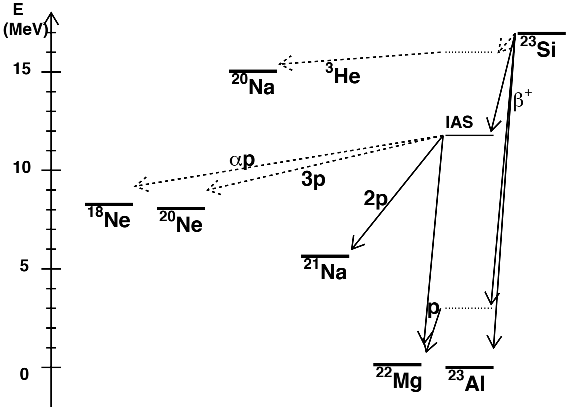
- 60 ions of ^{22}Si correctly implanted
- $b_{\beta p}=95(^{+14}_{-12})\%$
- $b_{\beta 2p}=3(^{+4}_{-2})\%$

A.A. Ciemny et al., submitted to Phys. Rev. C

A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

β-delayed multi-particle decays: ^{23}Si decay

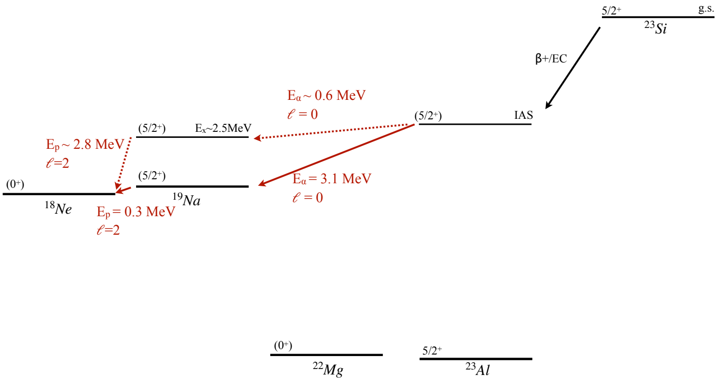
- First identification in 1986: ^{40}Ca fragmentation on Ni target
- First spectroscopic information in 1996: $b_{\beta p} = 71\%$ and $b_{\beta 2p} = 3.6\%$



M. Langevin et al., Nucl. Phys. A 455, 149, 1986
B. Blank et al., Z. Phys. A 357, 247-254, 1997

New, exotic decay modes of ^{23}Si

β-delayed multi-particle emission from ^{23}Si: $\beta p\alpha/\beta\alpha p$ decay channel



A.A. Ciemny et al., submitted to Phys. Rev. C

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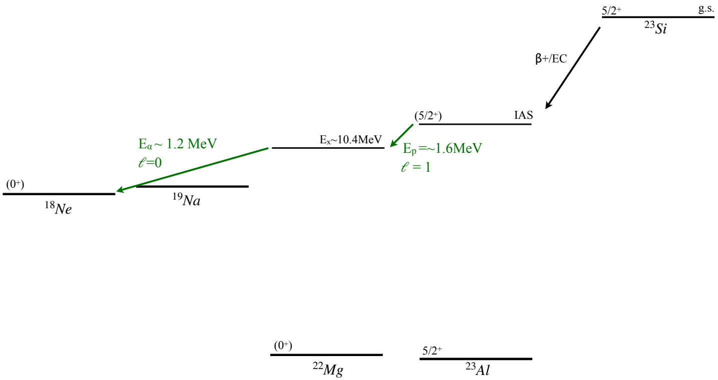
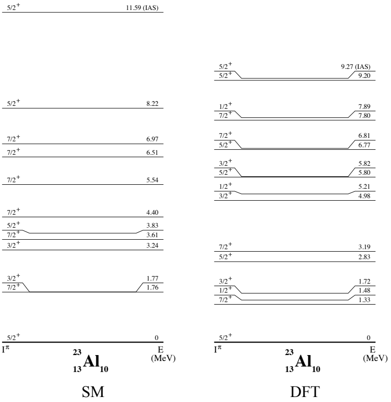


A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in preparation

β decay of ^{23}Si – DFT-NCCI calculations

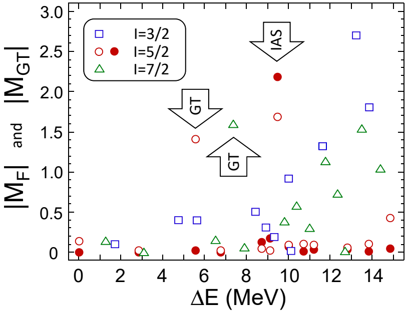
- Configuration space:
  g.s. and two lowest p-h config. in ^{23}Si
  + g.s.&13 excited configs in ^{23}Al
- E_{IAS}=9.27 MeV
  $|M_F| \approx \sqrt{4.9}$ and $|M_{GT}| \approx 1.5$
- GT predicted to populate mostly
  I^{π}=5/2$^+$ states at $E_x \sim$5.8 MeV
  ($|M_{GT}| = 1.3$) and
  I^{π}=7/2$^+$ states at $E_x \sim$7.8 MeV
  ($|M_{GT}| = 1.6$)
- results at variance with SM that
  predicts strong decay to
  I^{π}=5/2$^+$ at E_x =3.83 MeV and
  I^{π}=3/2$^+$ at E_x =3.24 MeV



A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in prep.

β decay of ^{23}Si – DFT-NCCI calculations

- Stability of the calculations verified by angular-momentum-projected calculations (AMP)
  $\rightarrow$ include more configurations + verify stability of low-en. spectra, wave funct. & β decay rates
  $\rightarrow$ 32 self-consistent mean-field solutions



A.A. Ciemny et al., submitted to Phys. Rev. C
A.A. Ciemny, PhD Thesis, University of Warsaw, in prep.