PHYSICS WITH HELIOS & IN-FLIGHT RADIOACTIVE BEAMS

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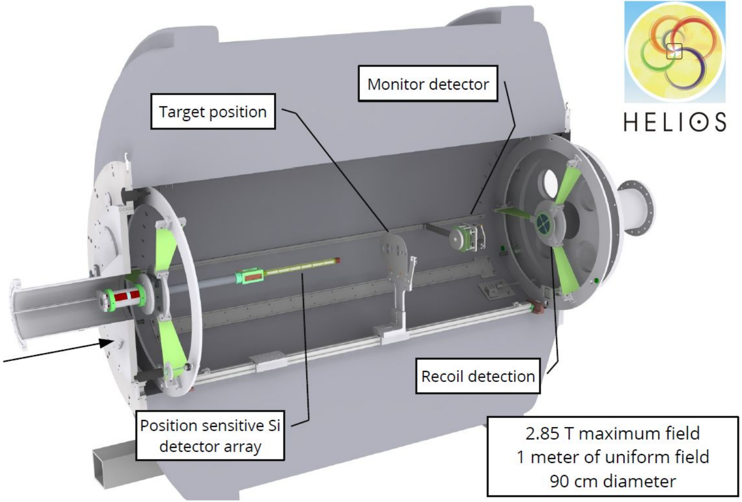
TALK OUTLINE

- overview of the device at ATLAS
- overview of in-flight beams
- details of in-flight production / tuning
- overview of measurements with in-flight beams
- a few physics examples
- new understanding from systematic data
- future & ongoing endeavors (AIRIS, Si Array, tracking, electronics, etc.)

HELIOS AT ARGONNE NAT. LAB.



HELIOS

Wuosmaa (2007), Lighthall (2010)

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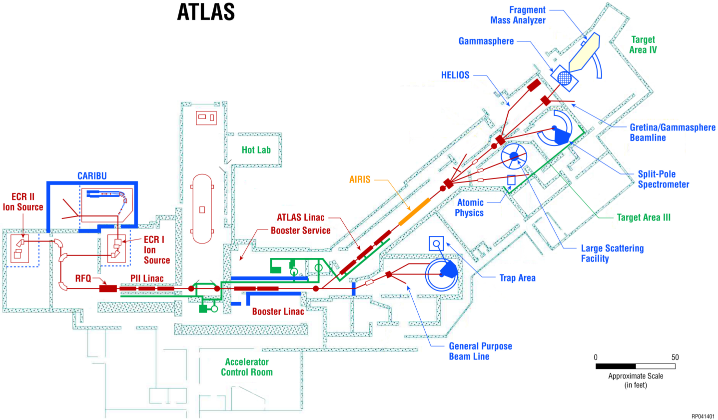
ATLAS ACCELERATOR LAYOUT

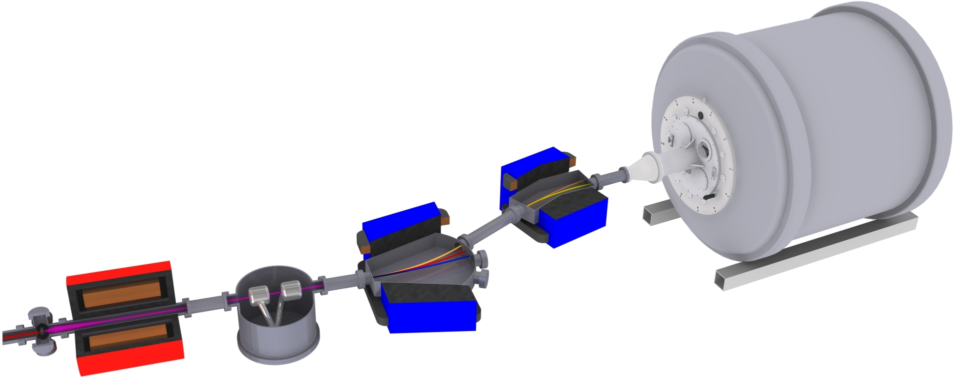
$p \rightarrow$ U, $<$ 15 MeV, few hundred pnA



www.phy.anl.gov/atlas

IN-FLIGHT BEAM PRODUCTION AT ATLAS

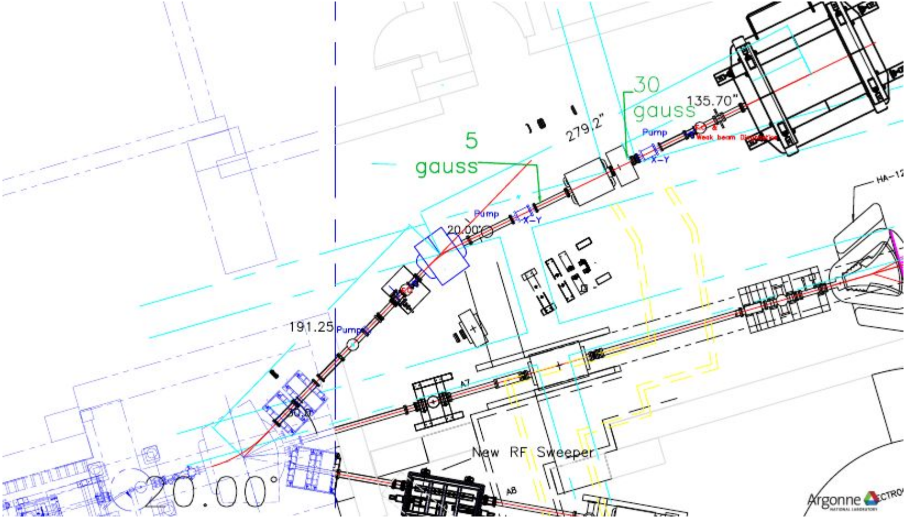
cryo-gas/Be target → solenoid → rebuncher → momentum selection



typically $<$100 pnA for gas target & up to 300 pnA for Be target

Harss (2000)

DRAWING OF ACTUAL BEAM LINE LAYOUT



BEAM TUNING PROCEDURE

typical procedure that has been used for in-flight beam tune to HELIOS

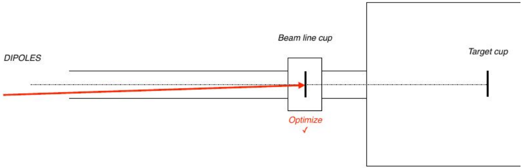
- tune primary stable beam (straight) onto the HELIOS target position
- insert production target to produce lower energy primary beam
  - identify q states
  - tune largest q state to HELIOS target
- scale optical elements to calculated in-flight $\sqrt{EA}/q$ value
- identify beam of interest via ΔE-TOF or other means, e.g., β decay
- optimize rate (not purity in most cases) manually

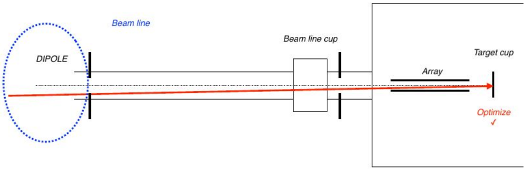
IMPACT OF BEAM TUNE ON HELIOS RESOLUTION

HELIOS requires a straight & centered beam tune

Beam offset (mm)	ΔE (keV), 5° c.m.	ΔE (keV), 15° c.m.	ΔE (keV), 30° c.m.
0	0	0	0
1	42	13	4
2	85	25	8
3	127	38	12
4	169	51	16
5	212	64	20
10	424	127	39

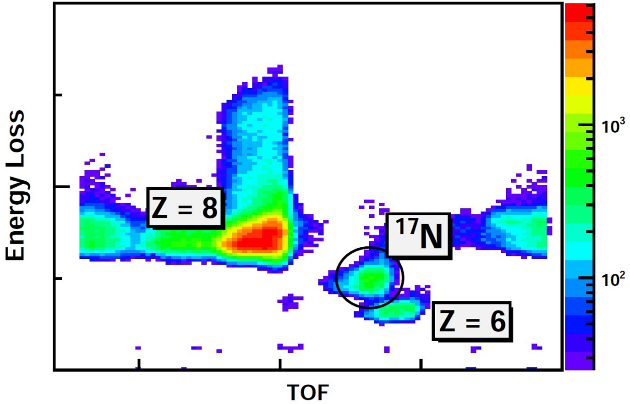
Angle (mrad, deg)	ΔE (keV), 5° c.m.	ΔE (keV), 15° c.m.	ΔE (keV), 30° c.m.
0, 0	(1.318 MeV)	(1.993 MeV)	(4.219 MeV)
1, 0.06	0.6	2.4	8.2
3, 0.17	1.7	7.2	24
5, 0.29	2.9	12	40
10, 0.57	5.7	24	79
15, 0.86	8.5	36	118
20, 1.15	11	47	156
25, 1.43	14	58	194





EXAMPLE OF IDENTIFICATION OF ^{17}N

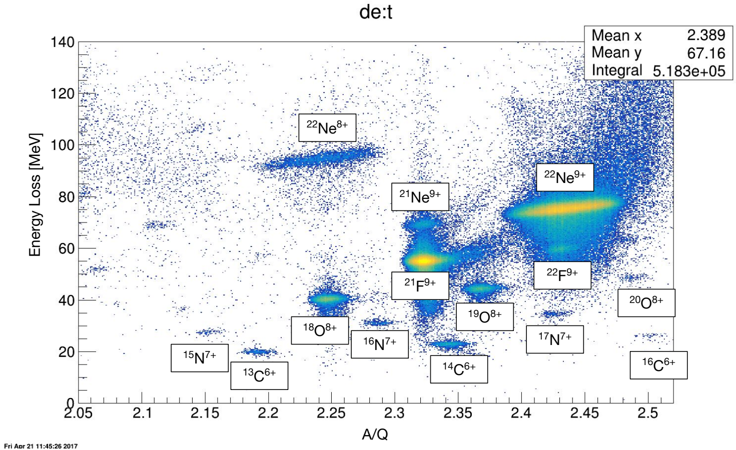
^{18}O + Be at $\sim$15 MeV/u, $>10^4$ pps, purity ranged from 1-20%



identification confirmed via γ-ray measurement of ^{17}N β decay

EXAMPLE OF IDENTIFICATION OF ^{21}F

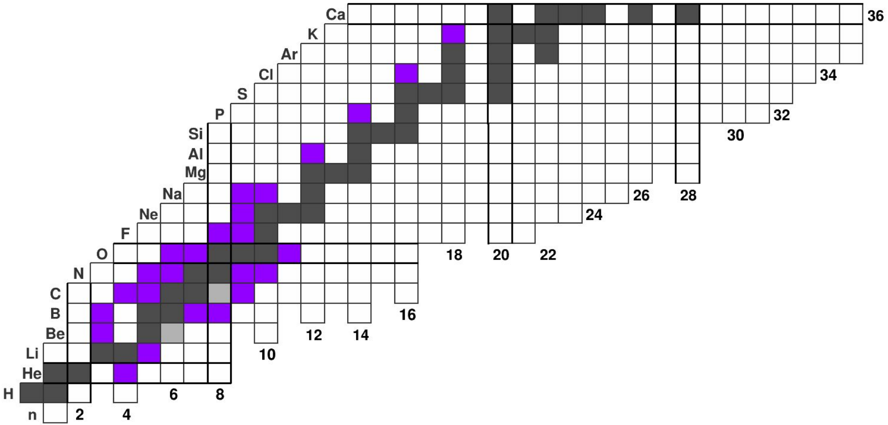
^{22}Ne + Be at $\sim$11 MeV/u, $>10^4$ pps, purity ranged from 0.1-80%



identification confirmed via γ-ray measurement of ^{21}F β decay

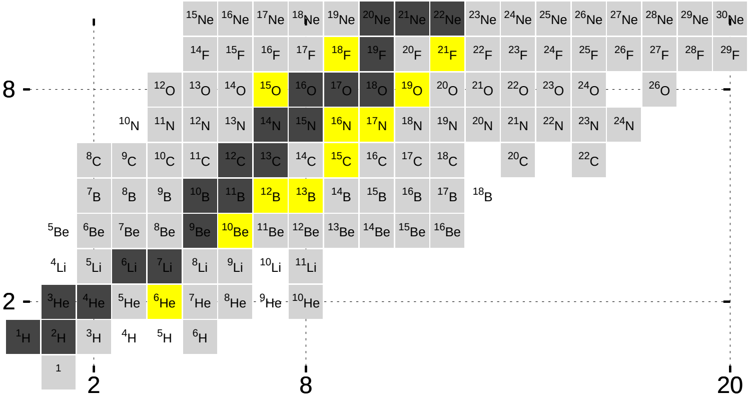
LIST OF IN-FLIGHT BEAMS USED AT ATLAS

nuclear reactions, astrophysics, structure, & fundamental symmetries



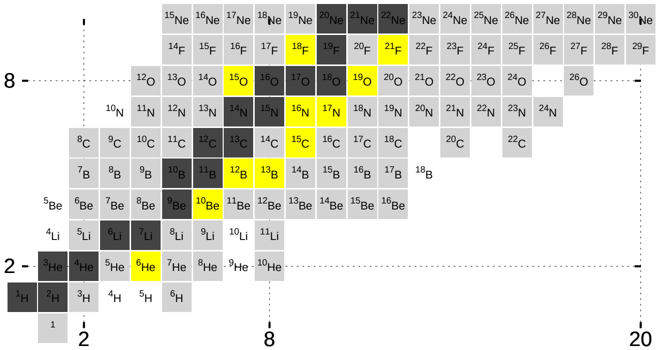
IN-FLIGHT BEAMS USED W/ HELIOS

spanning 2007 - present



rates from ~ 10^4-10^6 pps, newly realized capability for producing isomer beams

SUMMARY OF REACTIONS W/ IN-FLIGHT BEAMS

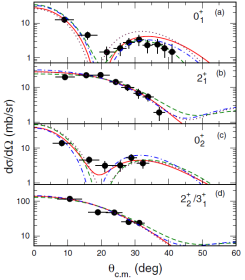


resolutions ranging from $\sim$ 100 keV - 350 keV
beam quality & target thickness dominate resolution

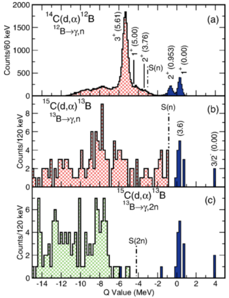
- neutron adding (d,p)
  - ^{12}B - Back [ANL/WMI/MAN] PRL (2010)
  - ^{13}B - Bedoor [WMI] PRC (2013)
  - ^{15}C - Wousmaa [WMI] PRL (2010)
  - ^{16g,m}N - Perdikakis [CMU]
  - ^{17}N - Hoffman [ANL] PRC (2013)
  - ^{19}O - Hoffman [ANL] PRC (2012)
  - ^{18g,m}F - Santiago [LSU/ANL]
  - ^{21}F - Chen [ANL]
- proton removal (d,^{3}He)
  - ^{13}B - Rogers [ANL/UMASS]
  - ^{14,15}C - Bedoor [WMI] PRC (2016)
- *pn* removal (d,α)
  - ^{14,15}C - Wuosmaa [WMI] PRC (2014)
  - ^{15}O - Wuosmaa [WMI/UCONN]
- other reactions
  - (t,p) - ^{12}B - Kuvin [UCONN]

SAMPLE OF PHYSICS RESULTS

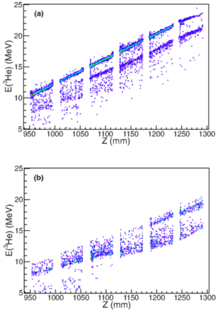
$^{15}C(d,p)^{16}C$



$^{14,15}C(d,\alpha)^{12,13}B$



$^{14,15}C(d,^{3}He)^{13,14}B$



- no exotic excitation modes in ^{16}C
- mixing between $0^+_{1,2}$ states agrees w/ USD interactions

- population of "stretched" configurations in B isotopes
- unique configurations test theory

- location of negative parity states in ^{13,14}B
- proton occupancy described by $p - sd$ interactions

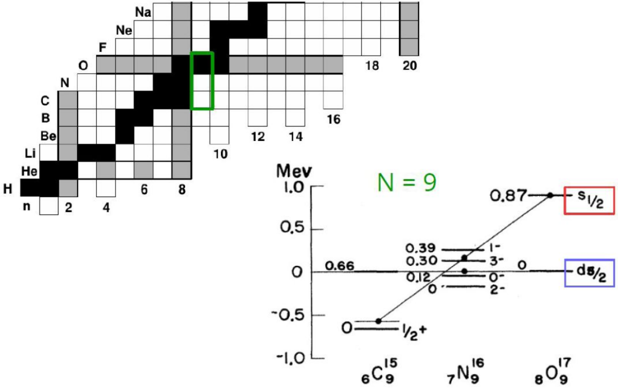
Wuosmaa (2010)

Wuosmaa (2014)

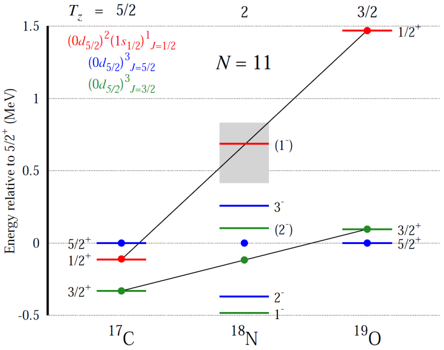
Bedoor (2016)

SD ORDERING IN LIGHT NUCLEI

well-known inversions of the $1s_{1/2}$-$0d_{5/2}$ neutron orbitals in N=9 isotones



^{17}N(d,p) reaction w/ HELIOS



similar trends identified in the N=9 & 11 isotones, same physics driving change?

Bedoor (2013), Hoffman (2013)

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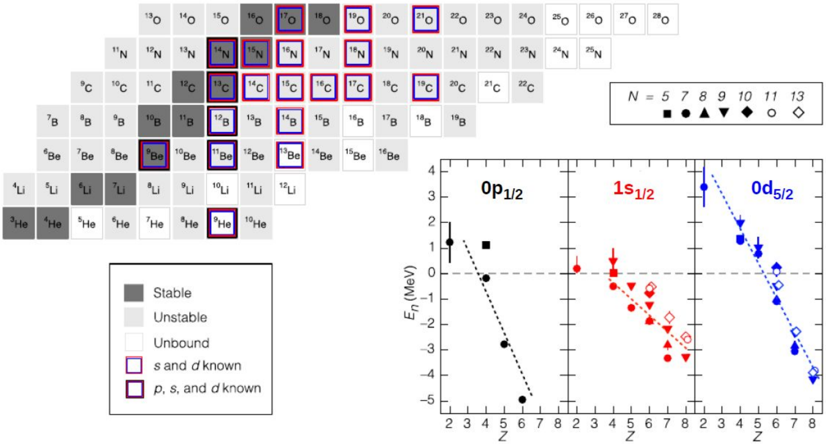
SD ORDERING IN LIGHT NUCLEI

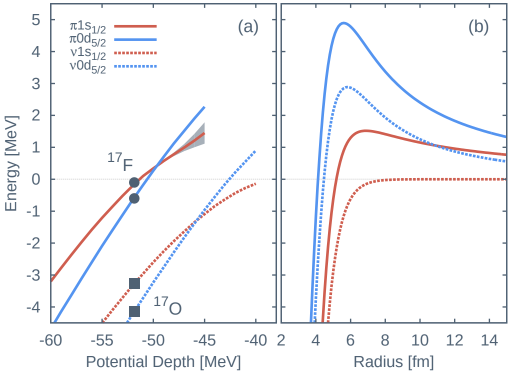
systematic investigation of single-neutron states in light nuclei



$E_n = E_x - S_n$ → Proximity of state to neutron separation energy

SD ORDERING IN LIGHT NUCLEI

ordering is primarily defined by proximity of *s*-orbital to threshold



Hoffman, Kay & Schiffer (2014,2016)

- Woods-Saxon calculations highlight change in $\ell = 0$ behavior near neutron threshold
- due to extended *s*-wave wavefunction $\rightarrow$ gives rise to nuclear halo (and other interesting phenomena)
- data also reproduced quantitatively
- threshold behavior is a global feature of all ℓ values near their potential barrier tops

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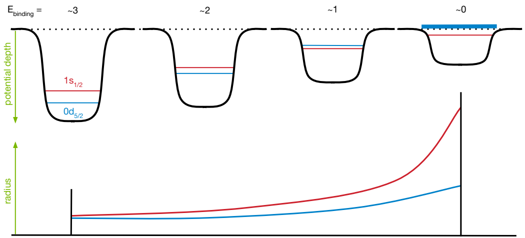

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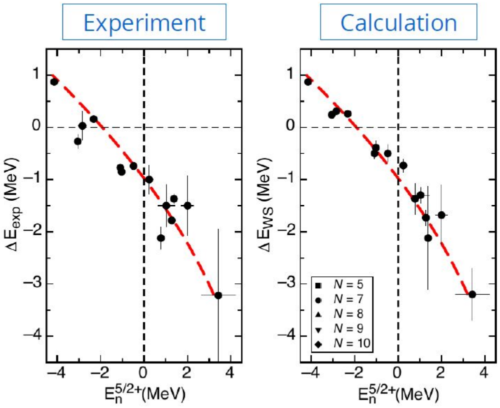

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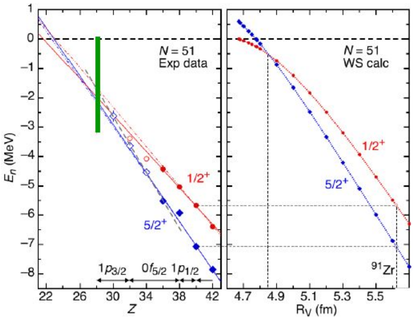
SD ORDERING OUTSIDE OF N=50 & 126

degeneracy of *sd* orbitals & possible halo in ^{79}Ni



Thomas (2007), Sharp (2013)

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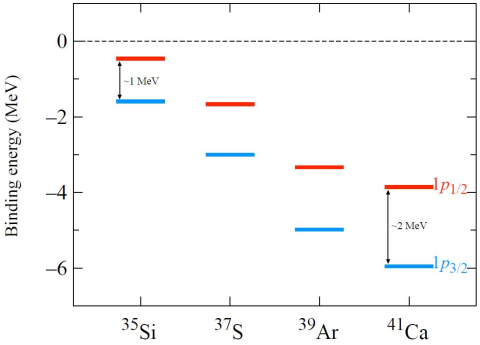
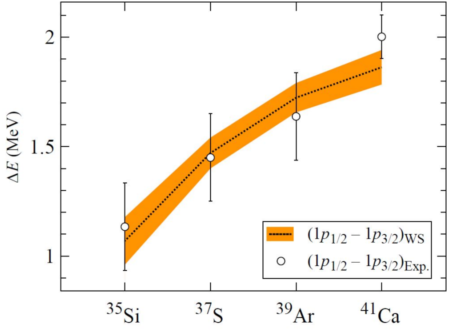
EVOLUTION OF THE N=21 S-O ENERGIES

spin-orbit energies between the $1p_{3/2}$ & $1p_{1/2}$ neutron orbitals



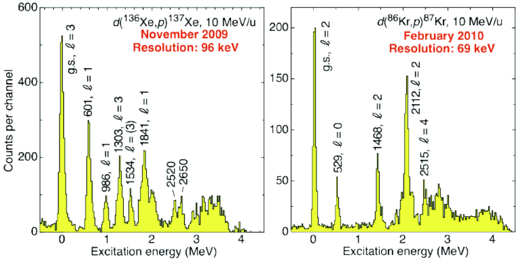


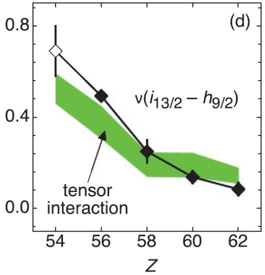
- various W-S parameters explored & trend is robust (orange band)
- weak binding effect can account for S-O energy splitting trend
- ^{34}Si "bubble" & reduced S-O potentials second order effects

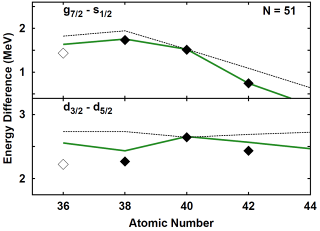
Burgunder (2014), Grasso (2009, 2015), Kay (2017)

SINGLE-PARTICLE STATES OUTSIDE N=50 & 82

systematic tests of the tensor force





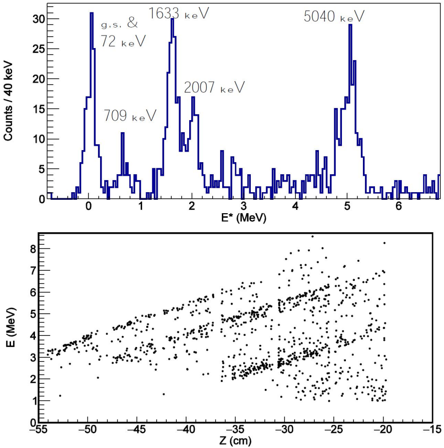


- inverse reactions w/ noble gas beams
  - $^{136}Xe(d,p)$ & $^{86}Kr(d,p)$
- <100 keV resolutions (target thickness)
- excellent agreement w/ expectation of *np* tensor force

Kay (2011), Sharp (2013), Talwar (2017)

ONGOING & FUTURE WORK

the ^{21}F(d,p)^{22}F reaction, ^{21}F produced at $>10^4$ pps



- ^{22}Ne + Be at 11 MeV/u [250 pnA]
- probes states belonging to:
  - $\pi(0d_{5/2})^1 \mathrm{x} \nu(0d_{5/2})^{-1}$
- compare with ^{18}F matrix elements
- first experiment utilizing digital daq upgrade

- ^{18g,m}F(d,p)^{19}F
  - single-particle nature of aligned $13/2^+$ state
- ^{6}He(d,d')
  - search for soft (low-lying) $E1$

Chen (in progress), Santiago (in progress)

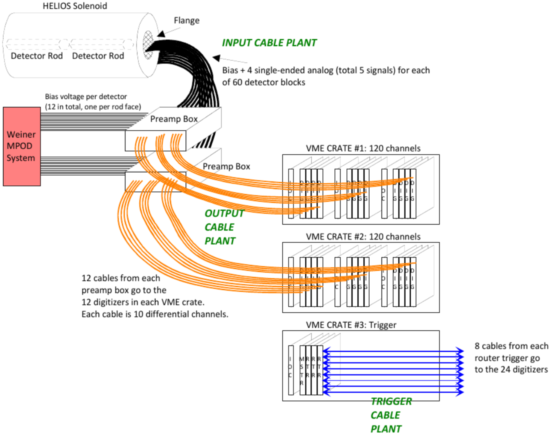
SUMMARY

- plethora of past & future physics opportunities w/ HELIOS at ATLAS utilizing in-flight short-lived beams
- transfer reaction production method allows for beam production at ideal energies for many direct reaction studies
- physics reaches from past and current measurements span specific case studies on, as well as global investigations of nuclear structure
- specifically, new insight on the evolution of orbitals & the role played by the threshold has been found in light nuclei
- the applicability of this new insight to other regions of the chart is an area of current & future research
- developments & improvements still underway on HELIOS device at ANL

Many thanks to all of the HELIOS collaboration members

DIGITAL DATA ACQUISITION

commissioned & used for an experiment in spring 2017



- comprised of Gretina digitizers & triggering hardware
- custom firmware written at Argonne
- μs of trace collected for each detectors
- opitmization of data analysis, reading of RF-Timing, and

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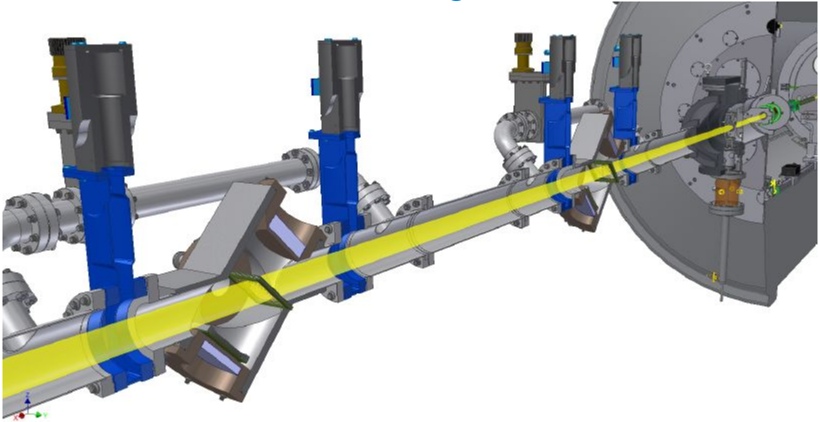
BEAM TRACKING W/ MULTIPLE MCP STATIONS

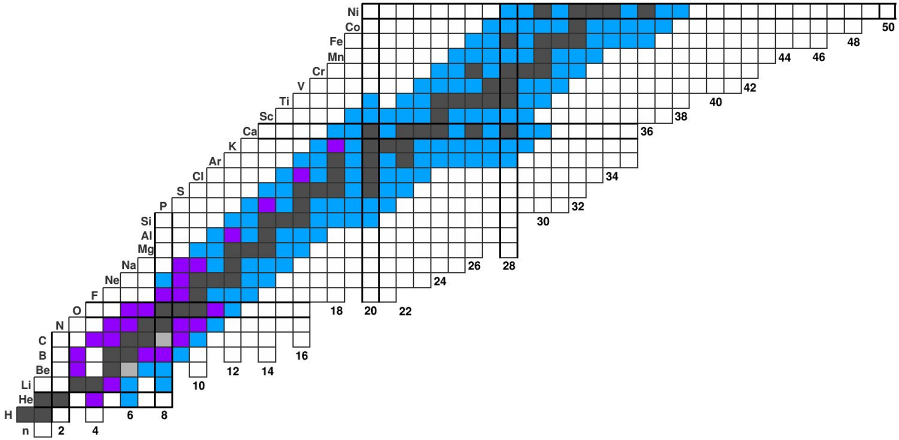
improve resolution & statistics w/ in-flight beams at ATLAS



event-by-event tof & position (angle) information on HELIOS target at rates up to 10^6 pps & energies around $\sim$10 MeV/u

LIST OF POSSIBLE IN-FLIGHT BEAMS W/ AIRIS

dedicated in-flight separator for ATLAS - CY2019



beams expected at $>10^2$ pps (x10 uncertainties for $\geq 2n$ away from stability)

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