Nuclear Astrophysics Facilities at TRIUMF

"Astrophysical Reactions Group"
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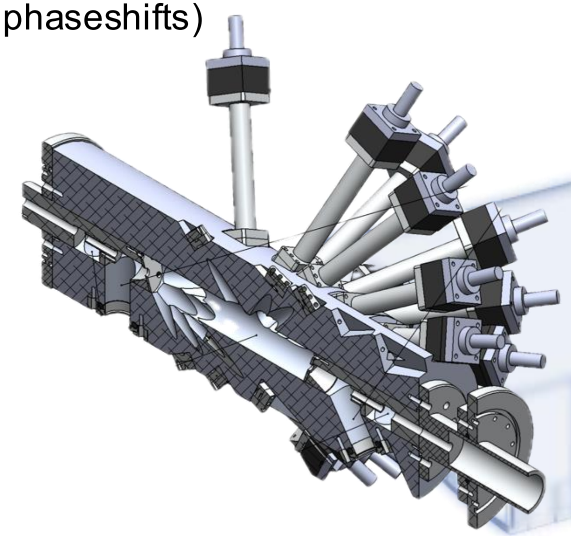
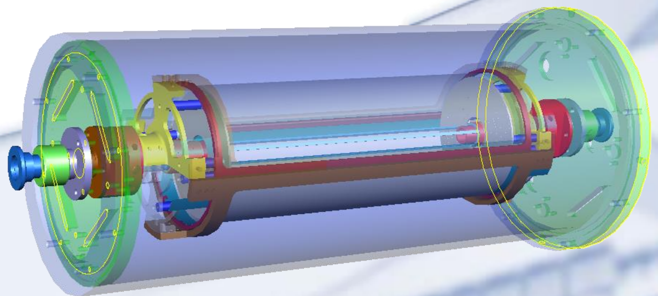
(+ TRIUMF Affiliates A. Laird, A. Hussein)

Other Canadian co-applicants: P. Navratil, N. Vassh (TRIUMF Theory); G. Christian, A. Psaltis (SMU), A. Chen (McMaster)

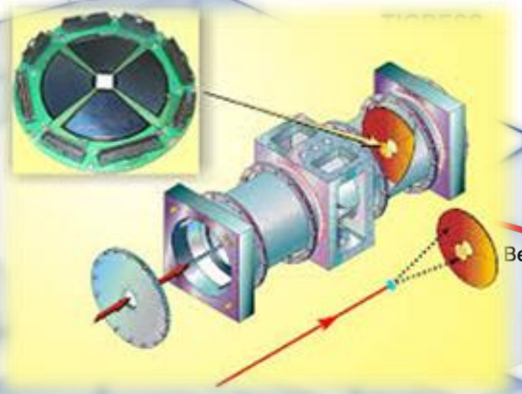
SONIK: extended gas scattering detector (precision low E elastic phaseshifts)



TACTIC: annular TPC for direct measurement of weakest (α,p) (p,α) reactions

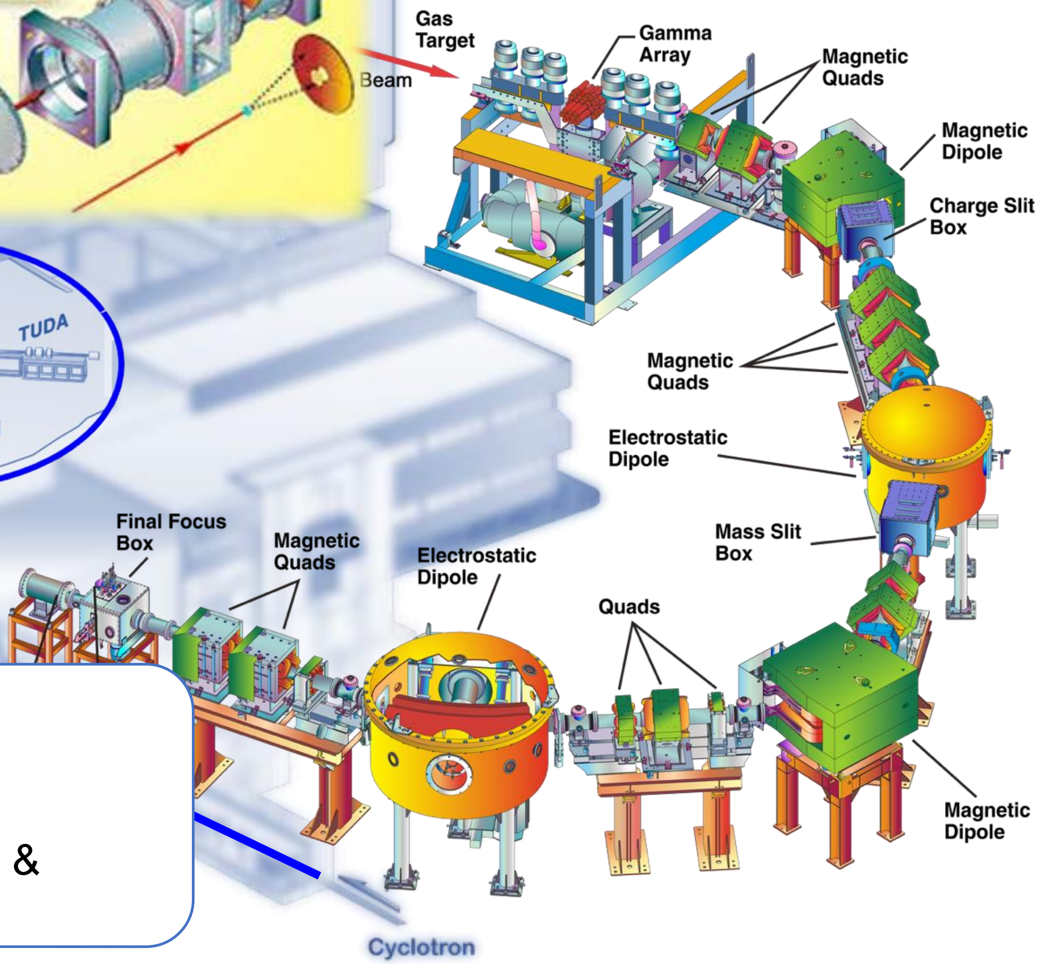


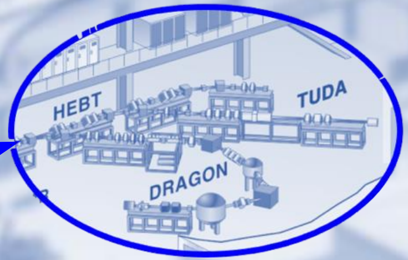
TUDA: charged particle direct measurements + sub barrier resonant elastic scattering

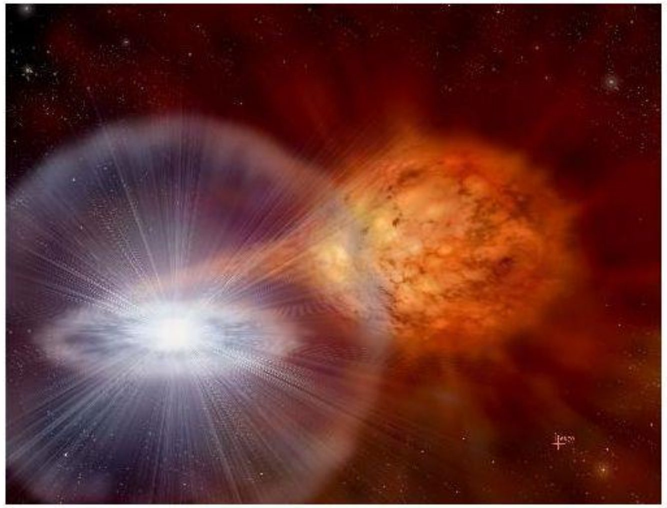


DRAGON:

Radiative capture







High Intensity →
High statistics (precision reactions & scattering)
High sensitivity (v. small cross sections & resonance strengths)

Reaction	**Motivation**	**Publication Status**
$^{21}\mathbf{Na}(p,\gamma)^{22}\mathbf{Mg}$	1.275 MeV line emission in O-Ne novae	PRL [3] + PRC [4] + 3 NPA [5] [6] [7]
$^{26g}\mathbf{Al}(p,\gamma)^{27}\mathbf{Si}$	Nova contribution to galactic ^{26}Al	PRL [8]
^{12}C$(\alpha,\gamma)^{16}$O	Helium burning in Red Giants	PRL [9]
^{12}C$(^{12}$C$,\gamma)^{24}$Mg	Nuclear cluster models	PRC [10]
^{40}Ca$(\alpha,\gamma)^{44}$Ti	Production of ^{44}Ti in SNII	PLB [11] + PRC [12]+ JPG [13] + NIMB [14
^{12}C$(^{16}$O$,\gamma)^{28}$Si	Nuclear cluster models	2 PRC [15] [16]
$^{23}\mathbf{Mg}(p,\gamma)^{24}\mathbf{Al}$	1.275 MeV line emission in O-Ne novae	PRC [17]
^{17}O$(\alpha,\gamma)^{21}$Ne	Neutron poison in massive stars	PRC [18] + PLB [19]
$^{18}\mathbf{F}(p,\gamma)^{19}\mathbf{Ne}$	511 keV line emission in O-Ne novae	PRL [20] + PRC [21]
^{33}S$(p,\gamma)^{34}$Cl	S isotopic ratios in presolar grains	PRC [22]
^{16}O$(\alpha,\gamma)^{20}$Ne	Stellar helium burning	2 PRC [23] [24]
^{17}O$(p,\gamma)^{18}$F	Explosive H burning in novae	PRC [25]
^{3}He$(\alpha,\gamma)^{7}$Be	Solar neutrino spectrum	NIMA [26]
^{58}Ni$(p,\gamma)^{59}$Cu	High mass tests (p-process, XRB)	EPJA [27]
$^{26m}\mathbf{Al}(p,\gamma)^{27}\mathbf{Si}$	SNII contribution to galactic 26Al	PRL [28]
^{34}S$(\alpha,\gamma)^{38}$Ar	Nucleosynthesis in massive stars and SNe	PRC [29]
$^{38g}\mathbf{K}(p,\gamma)^{39}\mathbf{Ca}$	Endpoint of nova nucleosynthesis	PRL [30] + PRC [31]
$^{19}\mathbf{Ne}(p,\gamma)^{20}\mathbf{Na}$	Fluorine detection in O-Ne novae	PRL [32]
^{34}S$(p,\gamma)^{35}$Cl	Nucleosynthesis in O-Ne novae	PRC [33]
^{22}Ne$(p,\gamma)^{23}$Na	Sodium production in AGB stars	PLB [34] + PRC [35]
^{6}Li$(\alpha,\gamma)^{10}$B	Proof-of-principle measurement	NIMA [36]
^{76}Se$(\alpha,\gamma)^{77}$Br	γ process in massive star explosions	PRC [37]
$^{7}\mathbf{Be}(\alpha,\gamma)^{11}\mathbf{C}$	νp process & pp-chain breakout	PRL [38] + PRC [39]
^{15}N$(\alpha,\gamma)^{19}$F	Synthesis of F in AGB stars	under analysis
^{14}N$(p,\gamma)^{15}$O	CN Cycle hydrogen burning	under analysis
^{30}Si$(p,\gamma)^{31}$P	Pollution of Globular Cluster	under analysis
^{39}K$(p,\gamma)^{40}$Ca	Pollution of Globular Cluster	under analysis
^{19}F$(p,\gamma)^{20}$Ne	Nucleosynthesis in the first stars	PRC [40] + in preparation
^{18}O$(\alpha,\gamma)^{22}$Ne	Stellar helium burning	under analysis
^{22}Ne$(\alpha,\gamma)^{26}$Mg	Weak r-process	under analysis
^{22}Ne$(\alpha,n)^{25}$Mg	Source of neutrons for s-process	under analysis
^{20}Ne$(p,\gamma)^{21}$Na	Proton Halo states and nucleosynthesis	PRC [41] + under analysis
$^{7}\mathbf{Be}(p,\gamma)^{8}\mathbf{B}$	Stellar neutrinos	under analysis
^{3}He$(\alpha,\alpha)^{3}$He	Big Bang Nucleosynthesis	PRC [42]
$^{7}\mathbf{Be}(\alpha,\alpha)^{7}\mathbf{Be}$	Big Bang Nucleosynthesis	under analysis

Table 1: Measurements completed or underway by the DRAGON Facility (top) and its SONIK ancillary system (bottom). Reactions in **bold** font denote radioactive beams. Journal acronyms: PRL = Phys. Rev. Lett., PRC = Phys. Rev. C, NPA = Nucl. Phys. A, PLB = Phys. Lett. B, JPG = J. Phys. G, NIMB = Nucl. Inst. Meth. B, NIMA = Nucl. Inst. Meth. A, EPJA = Eur. Phys. J. A

Reaction	**Motivation**	**Publication Status**
$^{21}\mathbf{Na}(p,p)^{21}\mathbf{Na}$	1.275 MeV line emission in O-Ne novae	2 PRC [43] [44]
$^{20}\mathbf{Na}(p,p)^{20}\mathbf{Na}$	1.275 MeV line emission in O-Ne novae	PRC [45]
$^{18}\mathbf{F}(p,p)^{18}\mathbf{F}$	511 keV line emission in O-Ne novae	PRC [46]
$^{18}\mathbf{F}(p,\alpha)^{15}\mathbf{O}$	511 keV line emission in O-Ne novae	PRC [47] + under analysis (2025 run)
$^{21}\mathbf{Na}(p,\alpha)^{18}\mathbf{Ne}$	Onset of Type 1 X-ray Bursts	PRL [48]
$^{7}\mathbf{Li}(^{8}\mathbf{Li},^{7}\mathbf{Li})^{8}\mathbf{Li}$	Big Bang Nucleosynthesis	PRC [49]
^{23}Na$(\alpha,p)^{26}$Mg	^{26}Al production in massive stars	PRL [50]
$^{26g}\mathbf{Al}(d,p)^{27}\mathbf{Al}$	^{26}Al production in massive stars	PRL [51] + EPJA [52]
$^{21}\mathbf{Na}(\alpha,p)^{24}\mathbf{Mg}$	nucleosynthesis in massive stars	in preparation

Table 2: Measurements completed or underway by the TUDA Facility. Reactions in **bold** font denote radioactive beams. Note some experiments related to nuclear structure and reaction dynamics studies have been omitted for brevity. Journal acronyms: PRL = Phys. Rev. Lett., PRC = Phys. Rev. C, EPJA = Eur. Phys. J. A

Number	**Reaction**	**Motivation**	**System**
S813LOI	$^{15}\mathbf{O}(\alpha,\gamma)^{19}\mathbf{Ne}$	Onset of Type 1 X-ray bursts	DRAGON
S870LOI	$^{18}\mathbf{Ne}(\alpha,p)^{21}\mathbf{Na}$	Onset of Type 1 X-ray bursts	TUDA
S922LOI	$^{25}\mathbf{Al}(p,\gamma)^{26}\mathbf{Si}$	Production of ^{26}Al in novae	DRAGON
S946LOI	$^{17}\mathbf{F}(p,\gamma)^{18}\mathbf{Ne}$	Hot CNO cycle	DRAGON
S996	$^{18}\mathbf{F}(p,\alpha)^{15}\mathbf{O}$	511 keV γ-ray line in novae	TUDA
S1289LOI	$^{44}\mathbf{Ti}(\alpha,p)^{47}\mathbf{V}$	^{44}Ti γ-ray line in core-collapse supernovae	TUDA
S1152LOI	$^{14}\mathbf{C}(\alpha,\gamma)^{18}\mathbf{O}$	Age of globular clusters	DRAGON
S1398	$^{11}\mathbf{C}(p,\gamma)^{12}\mathbf{N}$	*rap*-cycle in massive stars	DRAGON
S1425	$^{15}\mathbf{O}(\alpha,\gamma)^{19}\mathbf{Ne}$	511 keV γ-ray line in novae	DRAGON
S1690	$^{22}\mathbf{Na}(p,\gamma)^{23}\mathbf{Mg}$	1275 keV γ-ray line in novae	DRAGON
S1763	$^{11}\mathbf{C}(p,p)^{11}\mathbf{C}$	*ab-initio* theory benchmarking	TUDA
S1819	$^{18}\mathbf{Ne}(d,p)^{19}\mathbf{Ne}$	511 keV γ-ray line in novae	TUDA
S1880	^{20}Ne$(p,\gamma)^{21}$Na	Proton Halo states and nucleosynthesis	DRAGON+GRIFFIN
S1881LOI	$^{35}\mathbf{Ar}(p,\gamma)^{36}\mathbf{K}$	*rp*-process nucleosynthesis	DRAGON
S2013	$^{7}\mathbf{Be}(p,\gamma)^{8}\mathbf{B}$	Stellar neutrinos	DRAGON
S2018	$^{7}\mathbf{Be}(\alpha,\alpha)^{7}\mathbf{Be}$	Big Bang nucleosynthesis	SONIK
S2034	$^{7}\mathbf{Be}(p,p)^{7}\mathbf{Be}$	Stellar neutrinos and *ab-initio* theory benchmarking	SONIK
S2054LOI	^{29}Si$(p,\gamma)^{30}$S	Presolar grains	DRAGON
S2136LOI	$^{51}\mathbf{Mn}(p,\gamma)^{52}\mathbf{Fe}$	γ-ray lines in core-collapse supernovae	DRAGON
S2172	$^{6}\mathbf{He}(p,p)^{6}\mathbf{He}$	*ab-initio* theory benchmarking	TUDA
S2269	$^{10}\mathbf{Be}(p,\gamma)^{11}\mathbf{B}$	Structure of exotic ^{11}B state	DRAGON
S2294	$^{22}\mathbf{Mg}(\alpha,p)^{25}\mathbf{Al}$	αp-process in Type 1 X-ray bursts	TUDA
S2295	$^{39}\mathbf{K}(p,\alpha)^{36}\mathbf{Ar}$	αp-process in Type 1 X-ray bursts	TUDA
S2325	$^{37}\mathbf{Ar}(p,\gamma)^{38}\mathbf{K}$	Nova nucleosynthesis	DRAGON
S2344	$^{37}\mathbf{K}(p,\alpha)^{34}\mathbf{Ar}$	αp-process in Type 1 X-ray bursts	TUDA
S2379	^{38}Ar$(p,\gamma)^{39}$K	Nova nucleosynthesis	DRAGON
S2404	^{22}Ne$(\alpha,n)^{25}$Mg	*s*-process nucleosynthesis	DRAGON+DEMAND
S2408	$^{33}\mathbf{Cl}(p,\alpha)^{30}\mathbf{S}$	αp-process in Type 1 X-ray bursts	TUDA
S2417	^{20}Ne$(\alpha,\gamma)^{24}$Mg	Multiple stellar scenarios	DRAGON
S2421	^{16}O$(p,\gamma)^{17}$F	Quiescent stellar burning	DRAGON
S2442	$^{17}\mathbf{F}(\alpha,p)^{20}\mathbf{Na}$	Core-collapse supernovae and Type 1 X-ray bursts	TACTIC

Table 3: Accepted Proposals and Letters of Intent (LOI) for the Astrophysics Facilities. Reactions in **bold** font denote radioactive beams. This represents over 2,300 hours *each* of radioactive and stable beam experiments, not including the Letters of Intent which are beams yet to be developed.

Collaboration between TRIUMF Astrophysical Reactions Group & CNRS Researchers

- TRIUMF Affiliate Scientist Alison Laird (York, UK) has long-standing collaboration with N. de Sereville & F. Hammache (ICJLab - Orsay: Noyaux Exotiques StrucTure Astrophysique Réactions (NESTAR))– on several TRIUMF / other proposals

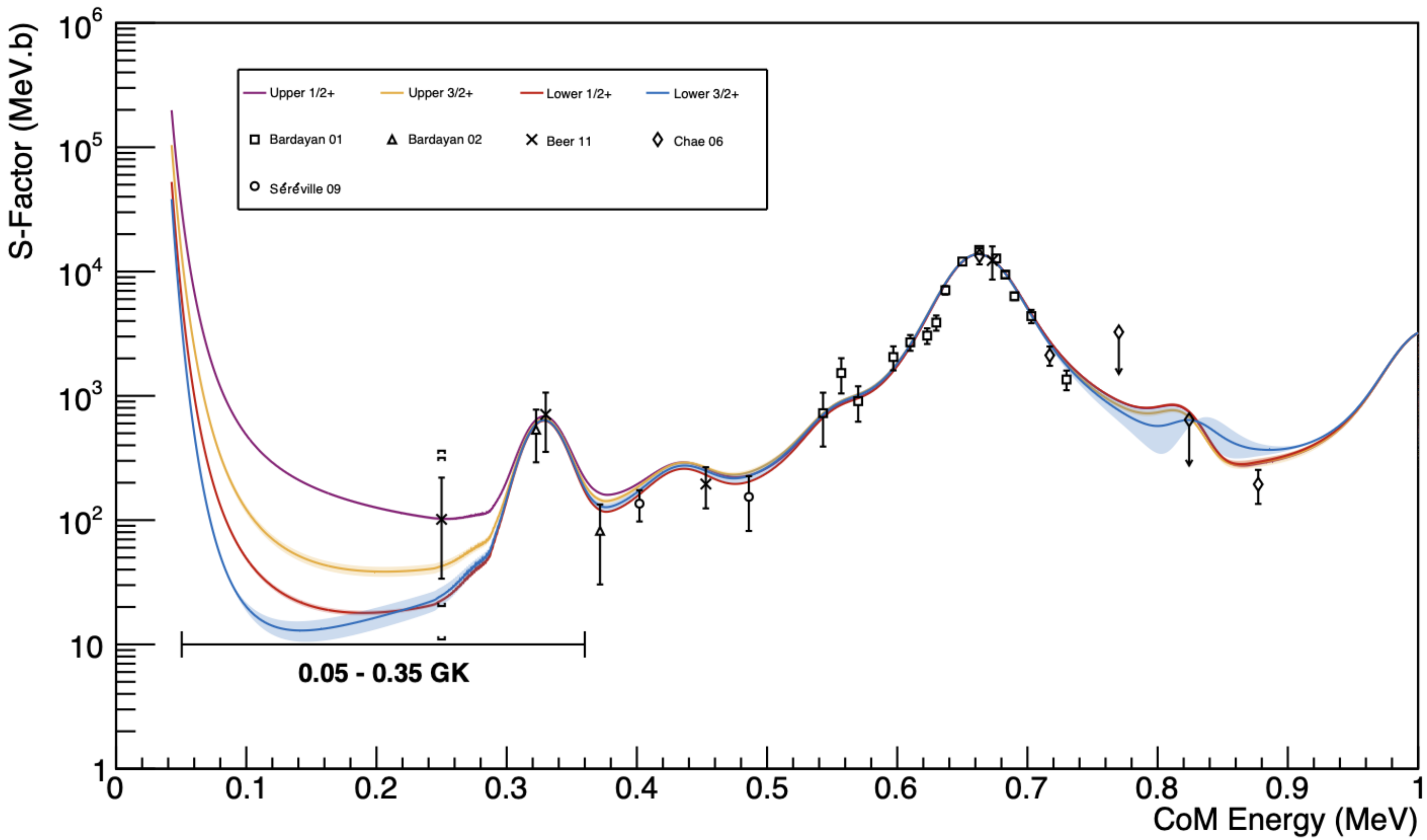


Figure 1: R-Matrix Calculations and existing experimental data for $^{18}F(p,\alpha)^{15}O$.
"Bardayan 15" = [7], "Bardayan 02" = [3], "Beer 11" = [4], "Chae 06" = [10], "Sereville 09" = [11]

Shared goals:
e.g. ^{18}F destruction/survival in novae

Reactions in novae, X-Ray Bursters, CCSNe, globular clusters

Understanding globular cluster abundances through nuclear reactions

P Adsley[1,2,3,4], M Williams[5], D S Harrouz[6], D P Carrasco-Rojas[2,7], N de Séréville[6], F Hammache[6], R Longland[8,9], B Bastin[10], B Davids[5,11], T Faestermann[12], C Fougères[10], U Greife[13], R Hertenberger[14], D Hutcheon[5], M La Cognata[15], AM Laird[16], L Lamia[15,17], A Lennarz[5], A Meyer[6], F d'Oliveira Santos[10], S Palmerini[18,19], A Psaltis[20], R G Pizzone[15], S Romano[15,17,21], C Ruiz[5,22], A Tumino[15,23], H-F Wirth[14]

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- C. Ruiz, collaborated with N. de Sereville & A. Parikh (UPC Barcelona) <10 years ago to come up with set of astrophysics measurements to target for TRIUMF and/or European Spectrometers (direct & indirect) – several became proposals & have been executed
- N. de Sereville, P. Adsley & group proposed & executed a set of DRAGON measurements for age of Globular Clusters
- IRL formed: ACTAR campaign at TRIUMF (inc. astro experiment)
- CNRS graduate student L. Denis participated in TUDA ^{18}F(p,α) experiment
- Future → highly encourage more direct collaboration between experiments / exchange of personnel

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e.g. ^{18}F destruction/survival in novae

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Measurement of ^{23}Na(α,p)^{26}Mg at Energies Relevant to ^{26}Al Production in Massive Stars

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