MEASUREMENT OF THE β ASYMMETRY PARAMETER IN ^{35}Ar DECAY WITH A LASER POLARIZED BEAM

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

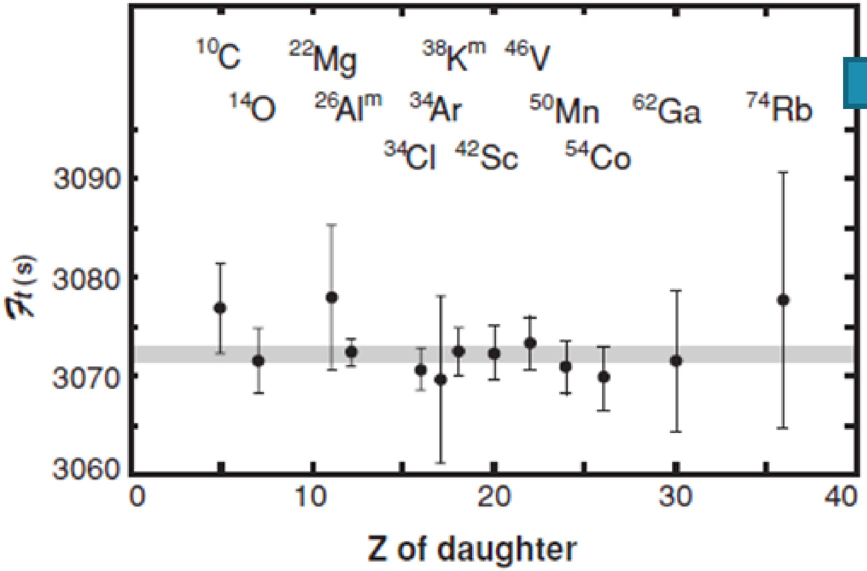
INTC Meeting - CERN, 5th November 2014

Philippe Velten

V_{ud} quark mixing matrix element & CKM unitarity

- From Ft value of $0^+ \rightarrow 0^+$ superallowed pure Fermi transitions:

$$\mathcal{F}t^{0^+\rightarrow 0^+} \equiv \underbrace{f_V t^{0^+\rightarrow 0^+}}_{\text{from experiment}} \underbrace{(1+\delta_{NS}^V-\delta_C^V)\,(1+\delta'_R)}_{\text{nucleus dependent corrections}} = \underbrace{\frac{K}{2G_F^2\,V_{ud}^2\,C_V^2\,(1+\Delta_R^V)}}_{\text{nucleus independent}}$$



$$\boxed{\mathcal{F}t^{0^+\rightarrow 0^+} = 3071.81(83)\ \text{s}}$$

Towner & Hardy, Rep. Prog Phys. 73 (2010) 046301

$$|V_{ud}| = 0.97425(22)$$

Hardy & Towner, PR C 79 (2009) 055502

$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99991(51)}$$

Strong limits on new physics in the weak interaction
(scalar currents, right-handed currents, heavy Z0 boson, …)

V_{ud} quark mixing matrix element & CKM unitarity

- From corrected Ft values of T = ½ mirror β transitions:

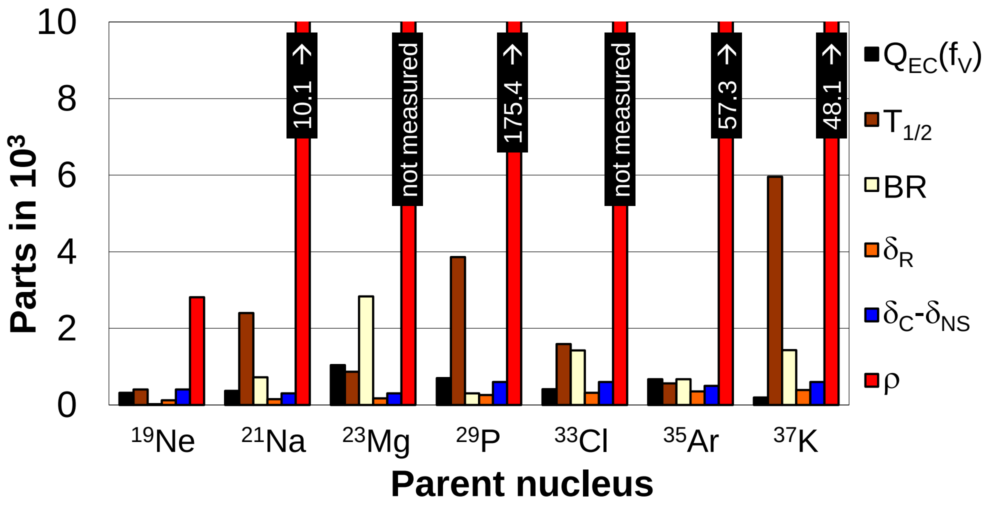
$$Ft^{mirror}\left(1+\frac{f_A}{f_V}\boxed{\rho^2}\right) = 2Ft^{0^+\rightarrow 0^+} = \frac{K}{G_F^2\ V_{ud}^2\ (1+\Delta_R^V)}$$

→ Requires measurement *of Q_{EC}, $T_{1/2}$, BR* **+ ρ**

O. Naviliat-Cuncic & N.S. , PRL 102 (2009) 142302

→ **$|V_{ud}| = 0.9719(17)$**

(Updated with 2014 data)



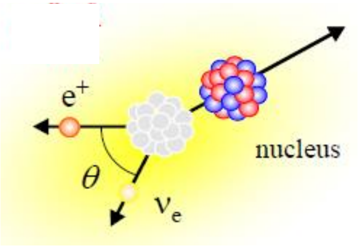
The GT/F mixing ratio: $\rho = \frac{C_A M_{GT}}{C_V M_F}$

- The least or **even not known quantity**!
- Precisely determined with **correlation measurements**

V_{ud} quark mixing matrix element from with correlation measurements of mirror β transitions

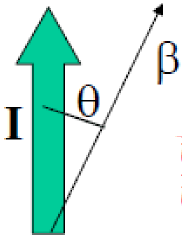
- β-ν correlation:

$$a = \frac{(1-\rho^2/3)}{(1+\rho^2)}$$



- β asymmetry:

$$A = \frac{\rho^2 - 2\rho\sqrt{J(J+1)}}{(1+\rho^2)(J+1)}$$



ΔV_{ud} for relative precision of 0.5% on $a_{\beta\nu}$ or A_β

		a			A	
Parent nucleus	ΔV_{ud}	$(\Delta V_{ud})^{\text{limit}}$	Factor $\Delta\mathcal{F}t$	ΔV_{ud}	$(\Delta V_{ud})^{\text{limit}}$	Factor $\Delta\mathcal{F}t$
^{3}H	0.0011	0.0010	2.1	0.0011	0.0009	2.3
^{11}C	0.0025	0.0016	4.0	0.0207	0.0207	0.3
^{13}N	0.0017	0.0017	1.0	0.0123	0.0123	0.1
^{15}O	0.0020	0.0016	2.4	0.0023	0.0020	1.9
^{17}F	0.0019	0.0013	3.1	0.0341	0.0341	0.1
^{19}Ne	0.0011	0.0010	1.5	0.0011	0.0011	1.5
^{21}Na	0.0022	0.0017	2.7	0.0036	0.0034	1.3
^{23}Mg	0.0025	0.0018	3.1	0.0034	0.0030	1.9
^{25}Al	0.0019	0.0018	1.7	0.0056	0.0056	0.5
^{27}Si	0.0029	0.0018	4.1	0.0068	0.0066	1.1
^{29}P	0.0026	0.0018	3.4	0.0024	0.0014	4.3
^{31}S	0.0038	0.0018	5.9	0.0068	0.0061	1.8
^{33}Cl	0.0021	0.0018	2.0	0.0013	0.0006	6.0
^{35}Ar	0.0019	0.0018	1.1	0.0007	0.0004	4.8
^{37}K	0.0034	0.0017	5.8	0.0050	0.0041	2.3
^{39}Ca	0.0024	0.0016	3.5	0.0032	0.0027	2.2
^{41}Sc	0.0029	0.0022	2.7	0.0299	0.0299	0.2
^{43}Ti	0.0076	0.0018	13.2	0.0167	0.0151	1.6
^{45}V	0.0112	0.0020	17.7	0.0115	0.0032	11.2

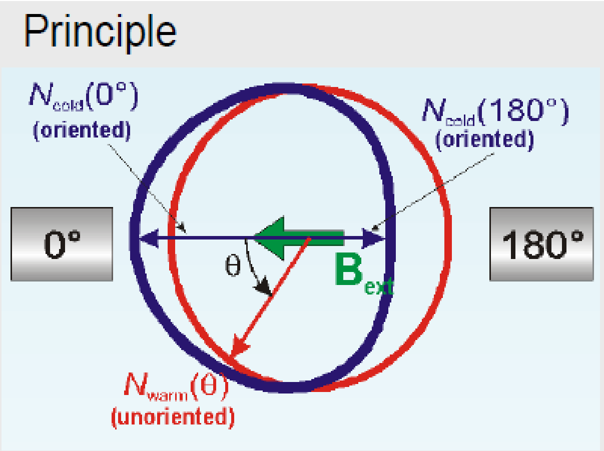
N.Severijns & O. Naviliat-Cuncic, Physica Scripta T152 (2013) 014018

A(^{35}Ar) is the best candidate:

- *ΔA/A=0.5%* → ΔV_{ud} = 0.0007 with present Ft value
- *ΔA/A=0.5%* → ΔV_{ud} = 0.0004 if Ft value is improved by factor 4.8 (requires Q_{EC}, $T_{1/2}$ and BR)

(<u>Note</u>: ΔV_{ud} (0+ → 0+) = 0.00022)

Measuring the β asymmetry parameter in nuclear β decay



- Transition rate of polarized nuclei:

$$W(\theta) = W_0 \left(1 + \frac{v}{c} J A cos(\theta)\right)$$

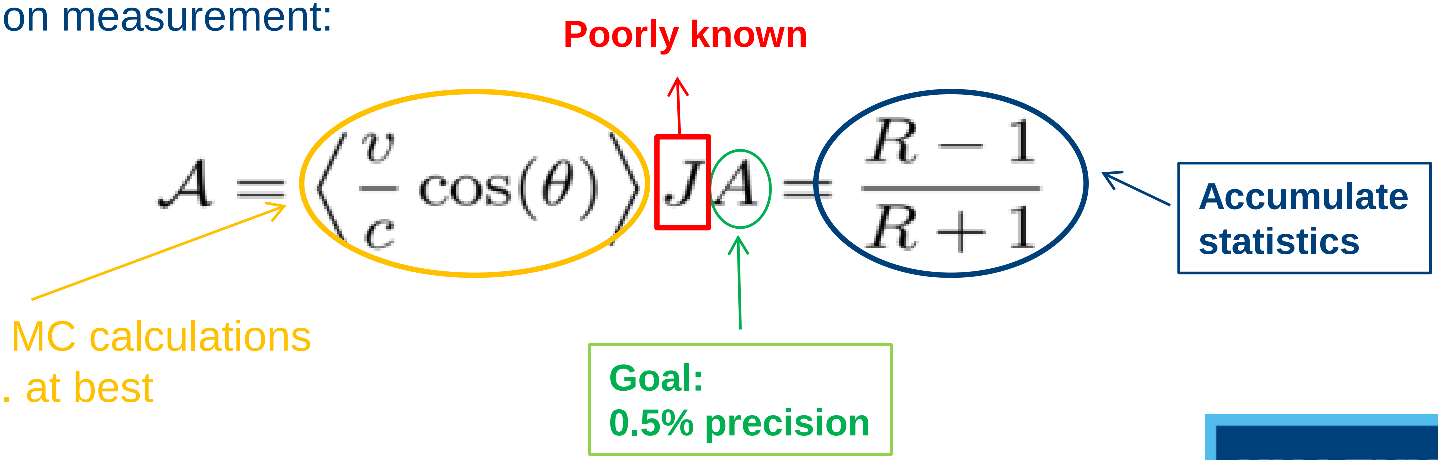
- Experimental asymmetry:

$$\mathcal{A} = \left\langle \frac{v}{c} \cos(\theta) \right\rangle JA = \frac{R-1}{R+1}$$

- Spin-flip:

$$R = \sqrt{\frac{N(0,+J)N(\pi,-J)}{N(0,-J)N(\pi,+J)}}$$

- High precision measurement:



Poorly known

$$\mathcal{A} = \left\langle \frac{v}{c} \cos(\theta) \right\rangle J A = \frac{R-1}{R+1}$$

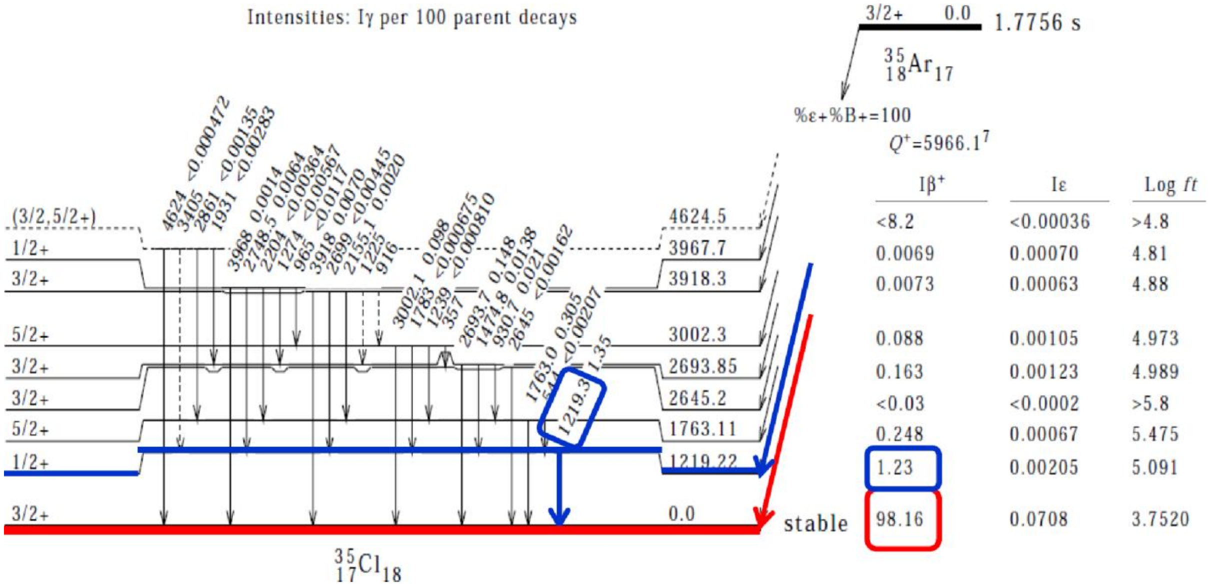
Accumulate statistics

requires adv. MC calculations
-> 1-2% pres. at best

Goal:
0.5% precision

Using the 1st excited state of 35Ar transition to reach high precision level

- Measurement of both ground & **first excited state** of ^{35}Ar:



		Iβ+	Iε	Log ft
(3/2,5/2+)	4624.5	<8.2	<0.00036	>4.8
1/2+	3967.7	0.0069	0.00070	4.81
3/2+	3918.3	0.0073	0.00063	4.88
5/2+	3002.3	0.088	0.00105	4.973
3/2+	2693.85	0.163	0.00123	4.989
3/2+	2645.2	<0.03	<0.0002	>5.8
5/2+	1763.11	0.248	0.00067	5.475
1/2+	1219.22	1.23	0.00205	5.091
3/2+	0.0	98.16	0.0708	3.7520

$$\frac{A_{gs}}{A_{ex}} = \frac{\left\langle \frac{v}{c}\cos(\theta)\right\rangle_{ex}}{\left\langle \frac{v}{c}\cos(\theta)\right\rangle_{gs}} \frac{A_{gs}}{A_{ex}}$$

=1
(pure GT)

measured

0.5% prec. should be ok
(study in progress)

Pros:

- **J cancels out**
- **Higher precision on kinematic&geometrical factor**

Con:

- **requires β-γ coincident detection**
- **statistical precision limited by excited state asymmetry since br = 1.23%**

Requirements to reach the 0.5% precision on A(^{35}Ar)

- Highly efficient β-γ coincident detection setup

→ Development in progress at IKS - KU Leuven

- Intense decay source of highly polarized ^{35}Ar

→ **VITO beamline at CERN-ISOLDE**

expected performance for the 35Ar beam:
- production rate: **I = ~1e6 ^{35}Ar/s**
- polarization: **P = 0.2 – 0.4**

→ **Implant 35Ar in a host lattice + magnetic field to maintain polarization**

Which crystal is the best suitable to implant ^{35}Ar and maintain polarization long enough to measure the β asymmetry (λ=1.8s) ?

→ Answering this question is the goal of the proposed experiments at COLLAPS

- Preliminary estimation: 0.5% statistical precision is achievable within few days of data taking time

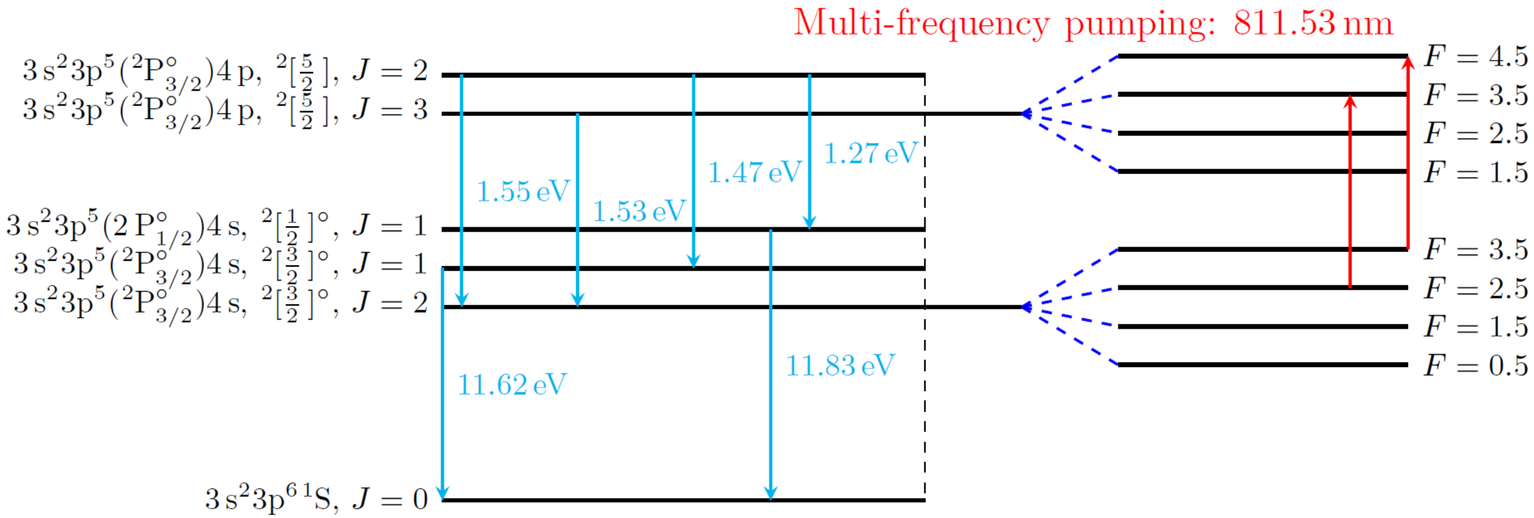
→ Depends strongly on the polarization level of the decay source:

Ex: if J= 0.4 → 0.2, the data taking time to reach a given stat. precision is **multiplied by 5**

KU LEUVEN

Polarization and crystal tests at COLLAPS

- **Scheme for the Ar beam polarization:**
  - Charge exchange with K results in 30-40% metastable $(3p_5 4s[3/2])_2$ state of neutral Ar
  - Optical pumping to J=3 state with cw Ti:Sa laser results in **30% polarization**



  - Characterize the ^{35}Ar hyperfine structure with β-NMR
    - **2% experimental asymmetry** is expected

      → **~30min. data taking duration** to gather enough statistics

Polarization and crystal tests at COLLAPS

- **Selection of host candidates:**
  - **KBr**:
    - Used as implant host in ^{35}Ar magnetic moment measurement with β-NMR
    - Cooled at 20K

      Matsuta K, et al. Nuc. Phys. A 701 383c (2002)
  - **NaF & CaF**:
    - NaF Used as catcher for β-NMR study of ^{23}Ne noble gas
    - Cooled at 15K
    - CaF: mass closer to Ar

      Ohtsubo T, et al. Hyp. Int. 180 85 (2007)
  - **NaCl & Si**:
    - Good implantation hosts for several elements

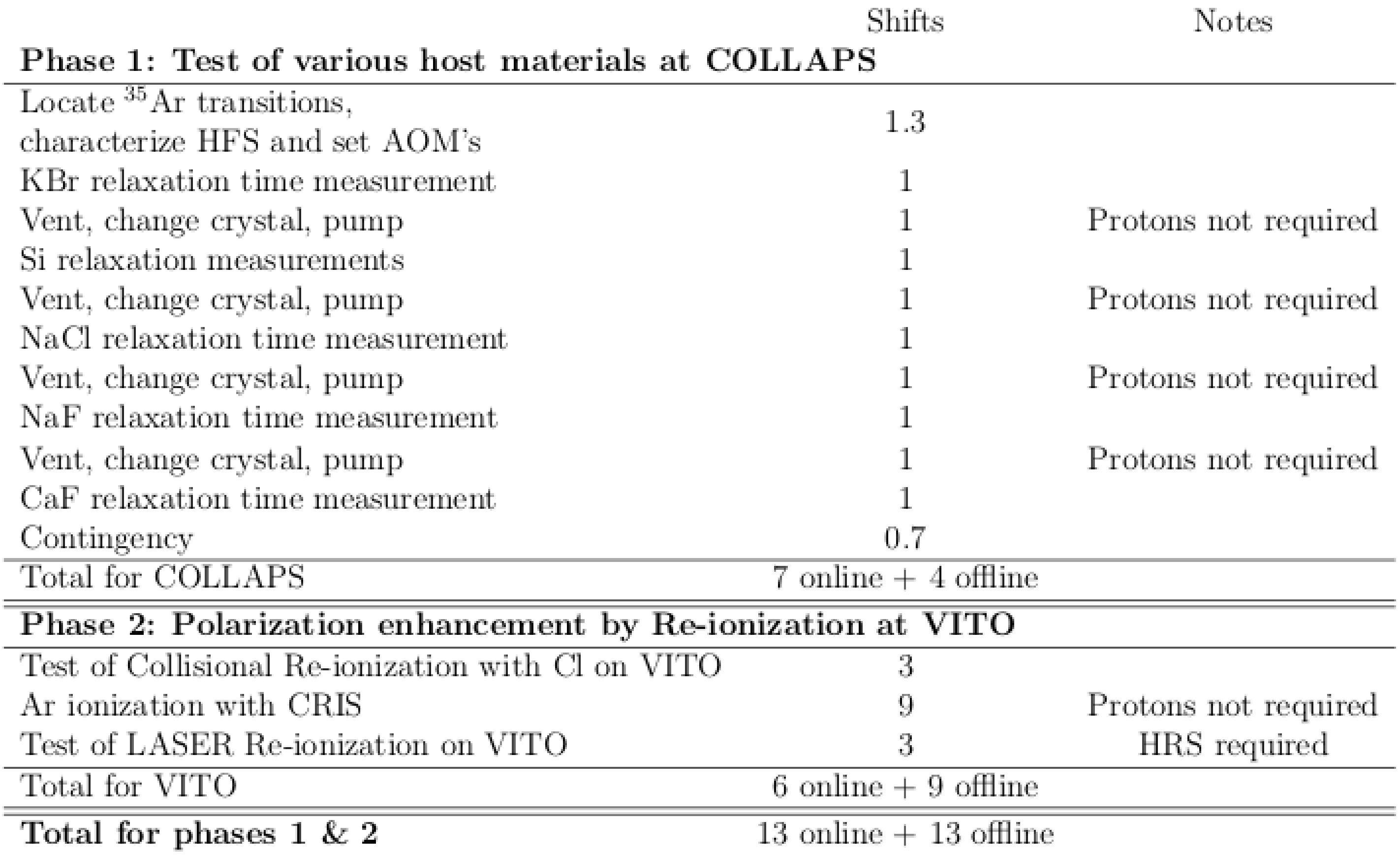
      Minamisono T, et al. Hyp. Int. 35 979 (1987),
      Borremans D, et al. Phys. Rev. C 72 044309 (2005)

- **Measurements with the existing detection setup at COLLAPS**:
  - Measure the polarization level + relaxation times with β-asymmetry setup
    - Use of acousto-optic modulators to provide maximum polarization
      → ~3h/relaxation time measurements
    - Measurement at different temperatures (ideally from 15K to room temp.)
      - Existing liquid nitrogen cooling at COLLAPS limited to **77K**

Polarization enhancement by reionization at VITO & CRIS

- Polarized part of the beam could be separated from the non-polarized beam by state-selective re-ionization:
  - ○ Collisional re-ionization with Cl could increase polarization by a **factor ~2**
    - Re-ionizing gas target will be installed at VITO (late 2015)
  - ○ Laser re-ionization:
    - Investigation of laser ionization scheme with CRIS (off-line)
    - 3 shifts on VITO to compare laser/collisional re-ionization

Beam time requirements for Phase 1 & phase 2



	Shifts	Notes
Phase 1: Test of various host materials at COLLAPS		
Locate ^{35}Ar transitions, characterize HFS and set AOM's	1.3	
KBr relaxation time measurement	1	
Vent, change crystal, pump	1	Protons not required
Si relaxation measurements	1	
Vent, change crystal, pump	1	Protons not required
NaCl relaxation time measurement	1	
Vent, change crystal, pump	1	Protons not required
NaF relaxation time measurement	1	
Vent, change crystal, pump	1	Protons not required
CaF relaxation time measurement	1	
Contingency	0.7	
Total for COLLAPS	7 online + 4 offline	
Phase 2: Polarization enhancement by Re-ionization at VITO		
Test of Collisional Re-ionization with Cl on VITO	3	
Ar ionization with CRIS	9	Protons not required
Test of LASER Re-ionization on VITO	3	HRS required
Total for VITO	6 online + 9 offline	
Total for phases 1 & 2	13 online + 13 offline	

Answers to INTC technical comments:

- Q: COLLAPS – does safety file for this configuration exist?
  A: The COLLAPS safety file includes the B-NMR (magnetic fields etc. are included in the document)

- Q: Safety file for VITO missing
  A: The VITO safety file is complete and submitted to EDMS. The files can be transmitted to the INTC if this is useful.

- Q: What is the required yield and purity vs 35Cl; same as WITCH?
  A: For COLLAPS test, any amount of 35Cl is ok. For laser re-ionization, less than **2pA contamination** would be required to limit space charge effects in ISCOOL

Thank you for your attention

Data taking time estimation

- Level of polarization impact greatly the data taking duration:

$$\Delta t = \frac{4}{\epsilon_{br}} \times \frac{1}{I_{dcy}} \times \underbrace{\frac{1}{\epsilon_{\gamma}} \times \frac{1}{\epsilon_{\beta}^{>E_{\mathrm{th}}}}} \times (1 + 2/\mathrm{SB}) \times \underbrace{\frac{R}{(R-1)^2}} \times \left(\frac{\Delta\mathcal{A}}{\mathcal{A}}\right)^{-2}$$

Statistical precision on exp. asymmetry

Decay source intensity

S/B ratio

G(A, J, θ) = Asymmetry setting factor

Particle detection efficiencies

Data taking time estimation

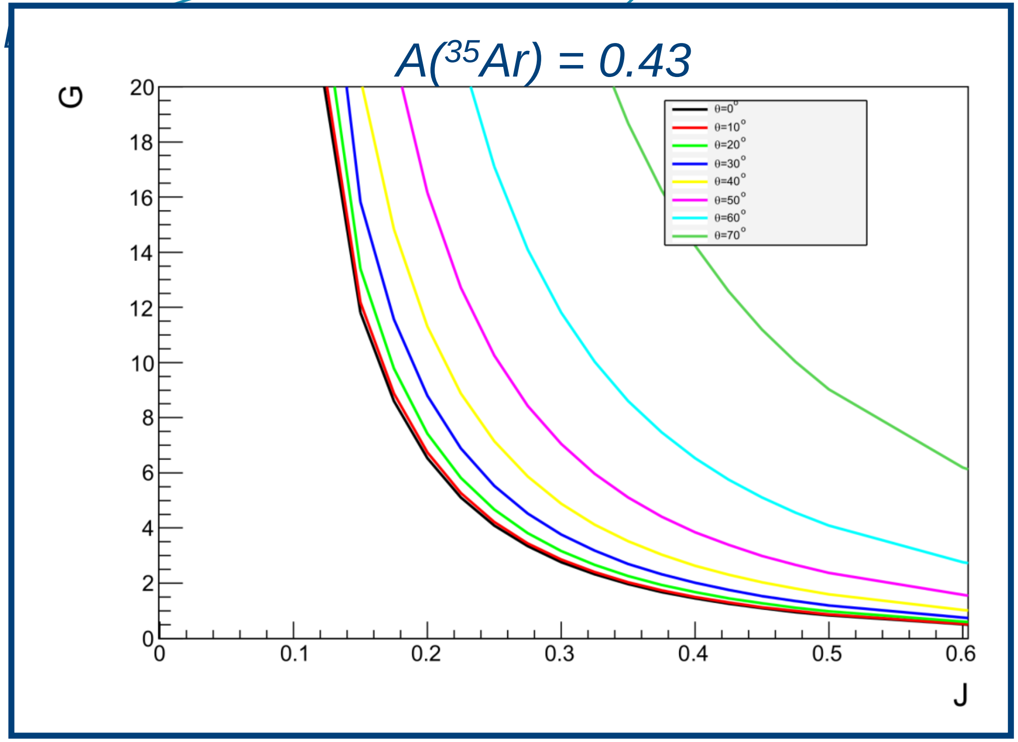
- Level of polarization impact greatly the data taking duration:

$$\Delta t = \frac{4}{\epsilon_{br}} \times \frac{1}{I_{dcy}} \times \underbrace{\frac{1}{\epsilon_{\gamma}} \times \frac{1}{\epsilon_{\beta}^{>E_{\mathrm{th}}}}}_{} \times (1+2/\mathrm{SB}) \times \underbrace{\frac{R}{(R-1)^2}}_{} \times \left(\frac{\Delta\mathcal{A}}{\mathcal{A}}\right)^{-2}$$

Statistical precision on exp. asymmetry

G(A, J, θ) = Asymmetry setting factor

A: asymmetry parameter
J: polarization of the source
θ: position of the detectors



Polarization enhancement by reionization at VITO & CRIS

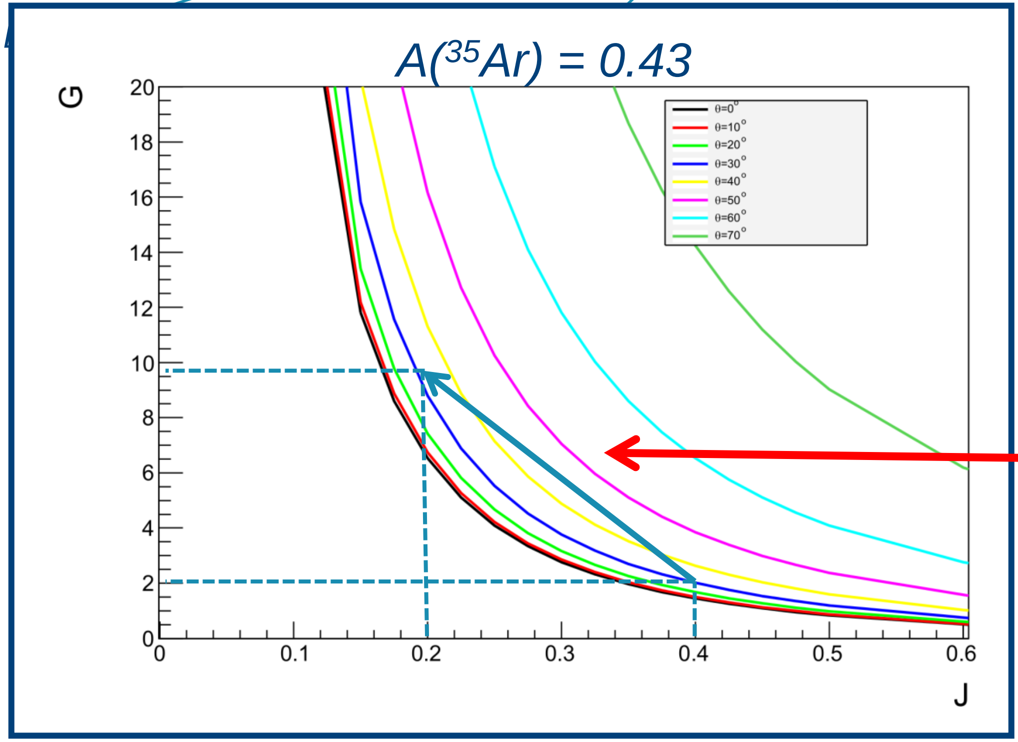
- Level of polarization impact greatly the data taking duration:

$$\Delta t = \frac{4}{\epsilon_{br}} \times \frac{1}{I_{dcy}} \times \underbrace{\frac{1}{\epsilon_{\gamma}} \times \frac{1}{\epsilon_{\beta}^{>E_{\mathrm{th}}}}}_{} \times (1+2/\mathrm{SB}) \times \underbrace{\frac{R}{(R-1)^2}}_{} \times \left(\frac{\Delta\mathcal{A}}{\mathcal{A}}\right)^{-2}$$

Statistical precision on exp. asymmetry

G(A, J, θ) = Asymmetry setting factor

A: asymmetry parameter
J: polarization of the source
θ: position of the detectors



J: 0.4 → 0.2
→ Δt x5

Data taking time estimation

$$\Delta t = \frac{4}{\epsilon_{br}} \times \frac{1}{I_{dcy}} \times \frac{1}{\epsilon_\gamma} \times \frac{1}{\epsilon_\beta^{>E_{\rm th}}} \times (1 + 2/{\rm SB}) \times \frac{R}{(R-1)^2} \times \left(\frac{\Delta\mathcal{A}}{\mathcal{A}}\right)^{-2}$$

Parameter	Nominal	Pessimistic scenario
$\frac{\Delta\mathcal{A}}{\mathcal{A}}$	0.5%	idem
v/c	0.96	idem
θ (degree)	35	idem
$E_{\rm th}$ (MeV)	1.4	idem
$\epsilon_\beta^{>E_{\rm th}}$ (count/decay)	2×10^{-2}	idem
ϵ_γ (count/decay)	4.7×10^{-2}	idem
$\epsilon^{\rm coinc}$ (count/decay)	1.16×10^{-5}	idem
S/B	4.7	idem
Q	1.43	idem
J	0.3	0.2
$\mathcal{A}_{ex}$	0.24	0.16
R	1.62	1.37
G	4.24	9.86
$N_2^{\rm tot}$	7.4×10^5	1.89×10^6
I (decays/s)	10^6	0.5×10^6
$\frac{dN_{\det\beta}}{dt}$ (counts/s)	3.7×10^4	1.85×10^5
$< \frac{dN_{\rm CsI\ block}}{dt} >$ (counts/s)	2.3×10^4	1.15×10^4
Δt (s)	83680	388888

PRELIMINARY

Nominal -> Pessimistic:

- 50% reduction in decay source
- Polarization: J= 0.2 instead of 0.3

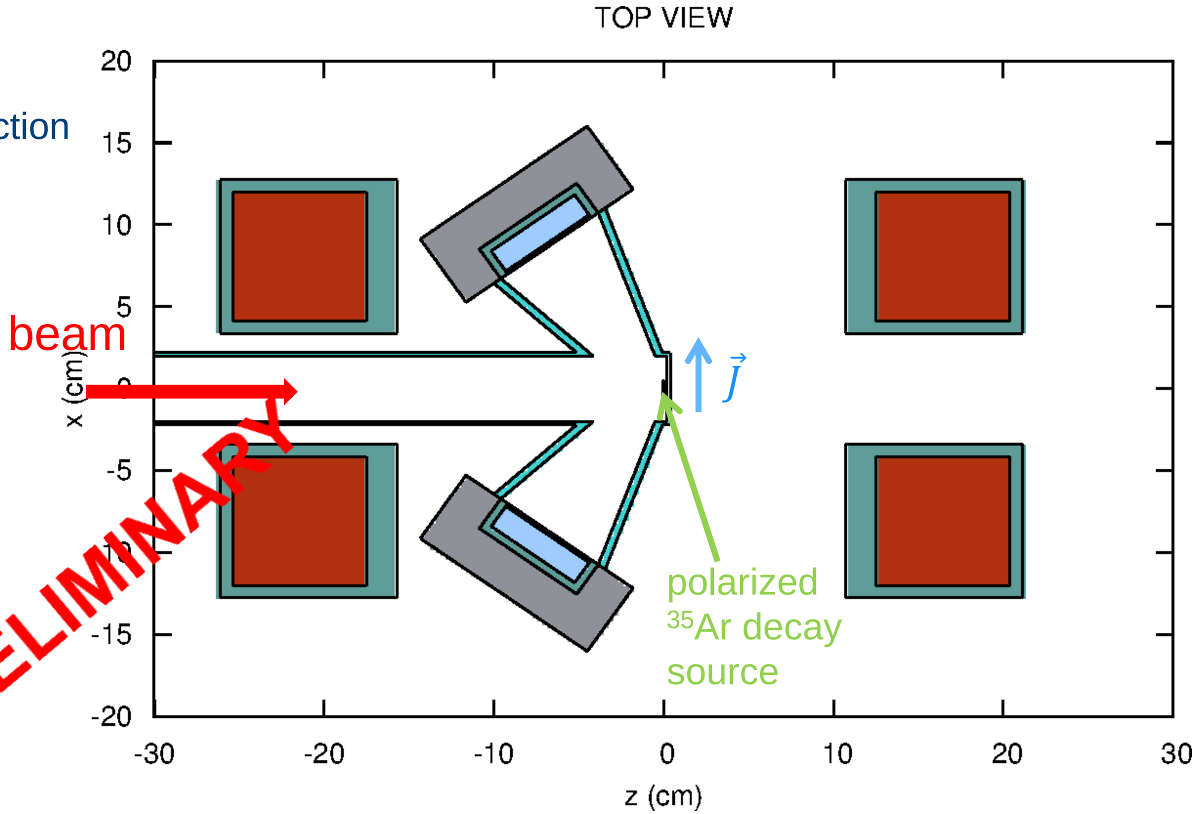
← 4.5 days instead of 24h

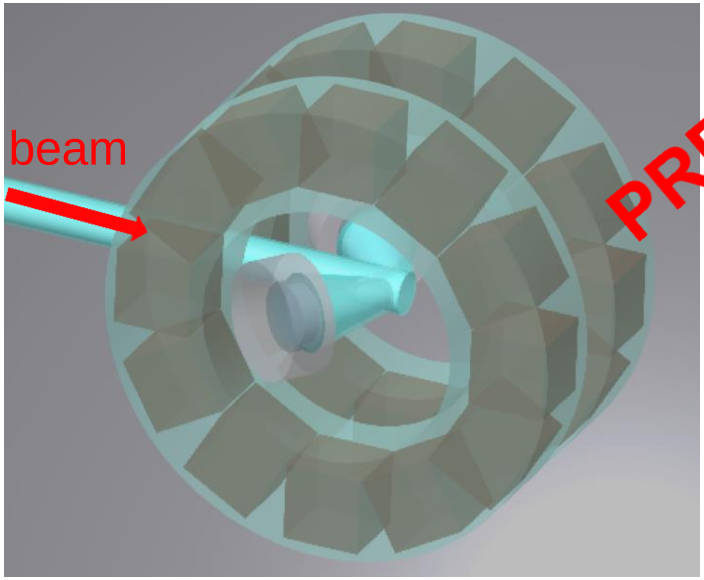
(Possible) detection setup for the A(^{35}Ar) measurement

2x ΔE-E telescopes for β+ detection
2x CsI rings for γ-ray @1.219 MeV detection

Main features:

- Left-Right symmetric layout
- Maximize detection solid angle



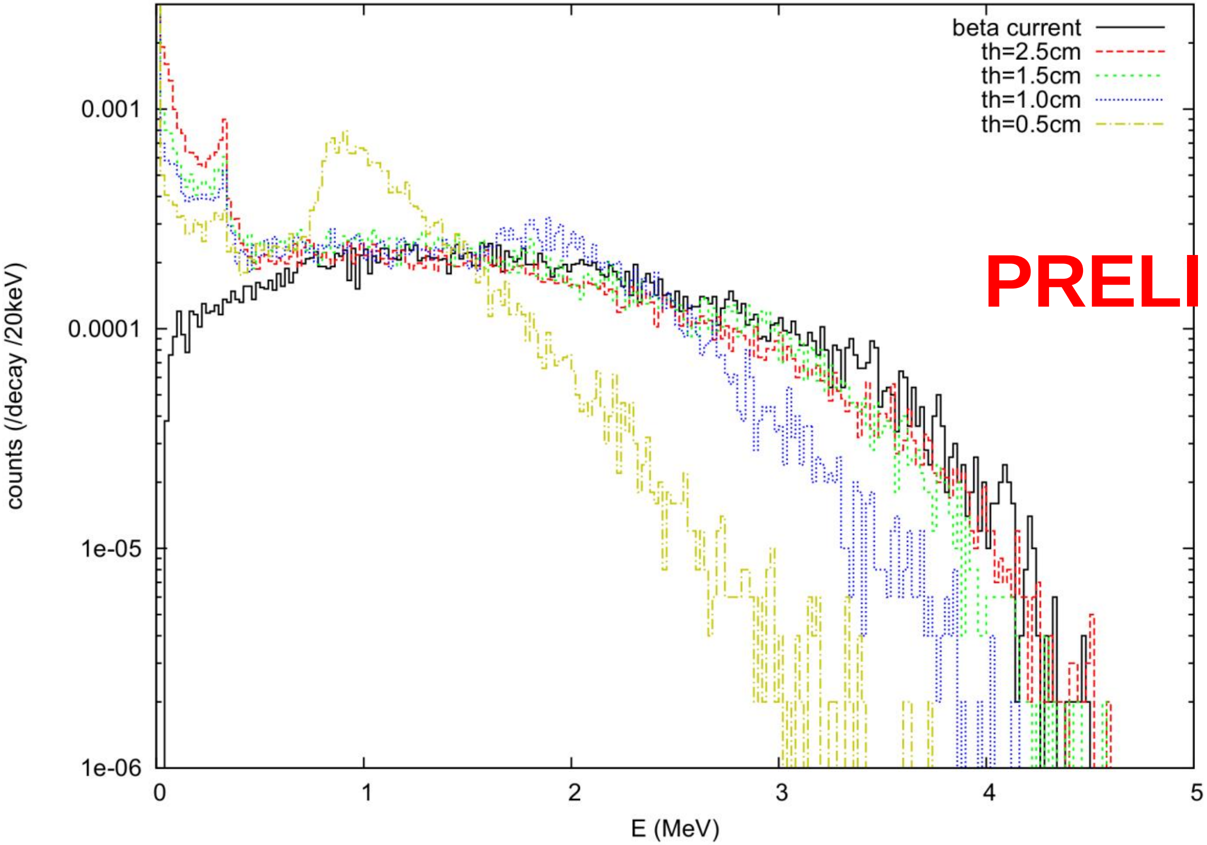


MC simulations has been initiated to

- Optimize detection efficiency
- Study systematic effects (β scattering, etc.)

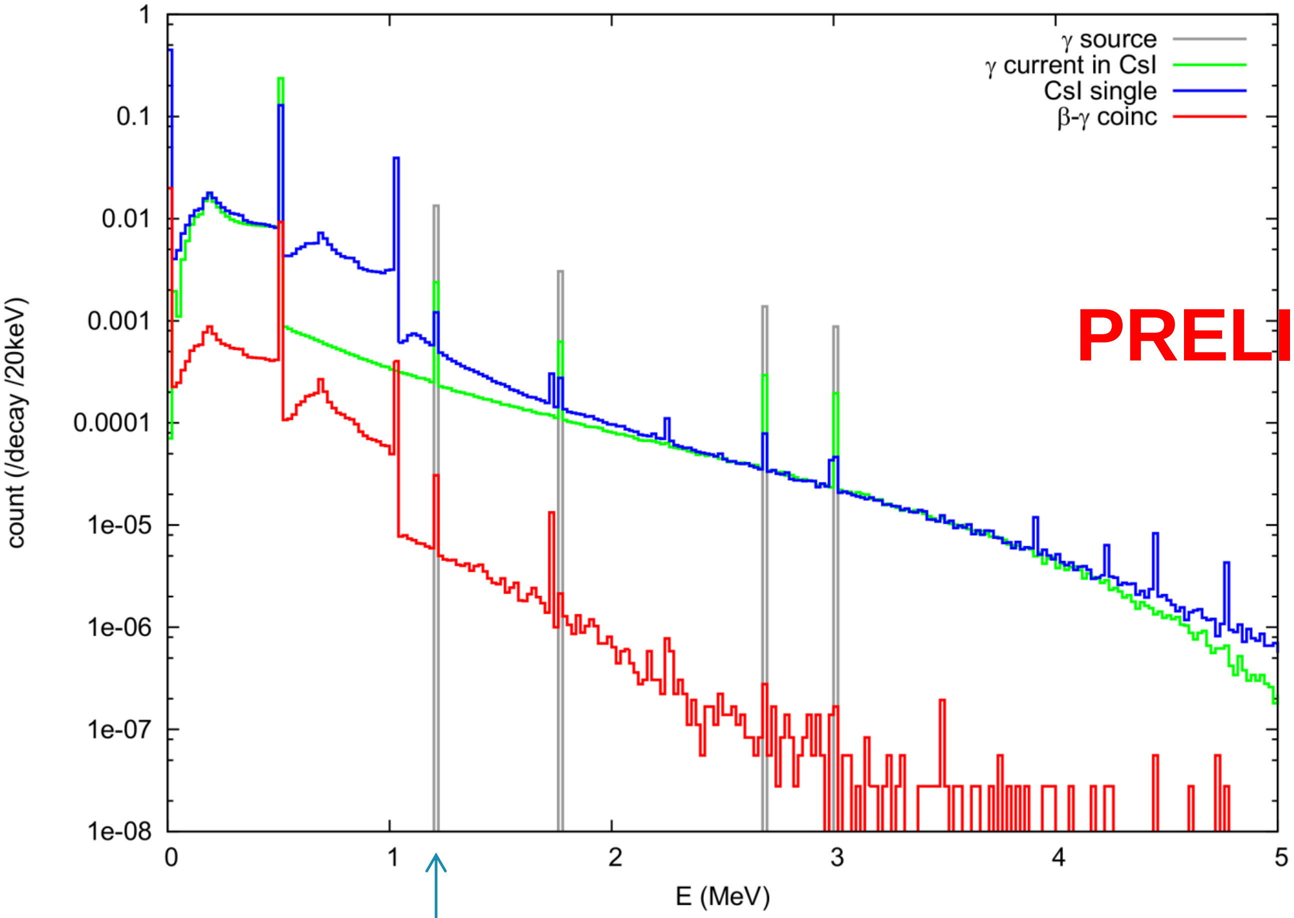
Positron detection

- Energy deposition from 35Ar decay in detection volumes generated by MC simulations with FLUKA



PRELIMINARY

Gamma detection



PRELIMINARY

1st excited state γ-ray