Neutrino, Dark Photon and Axion signals in Liquid Argon Detectors

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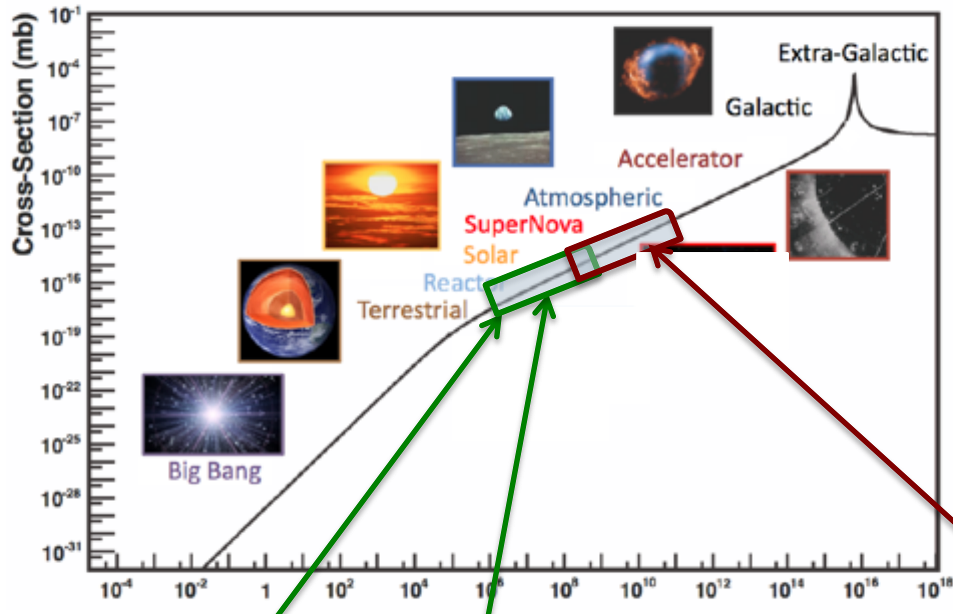
Neutrino-Nucleus Scattering Experimental Data Falls into three main Energy Regions



Exclusive Final States 1+, 1-, 2+, 2-, …

Giant Resonances, Continuum

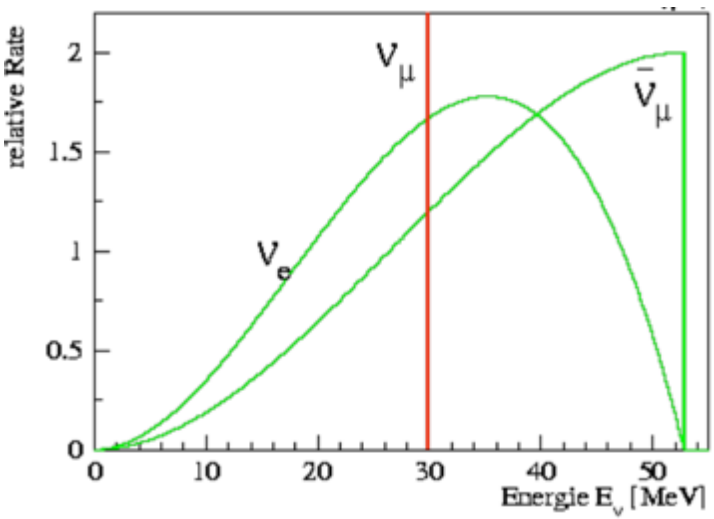
Quasi Elastic, Delta Resonance, DIS

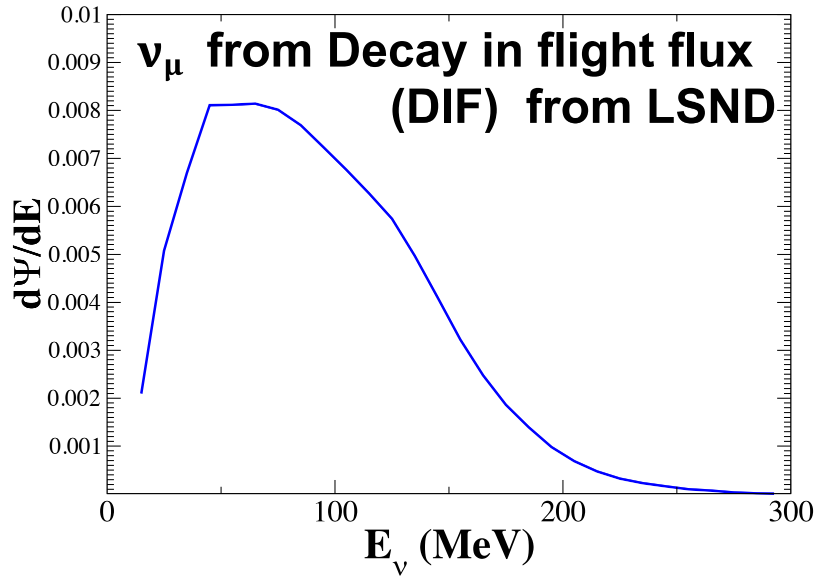
^{12}C

^{12}C is the most studied nucleus via Electroweak Interactions

Accelerator neutrino neutral and charged-current, (e,e'), (γ,γ'), β-decay, and μ-capture data available.

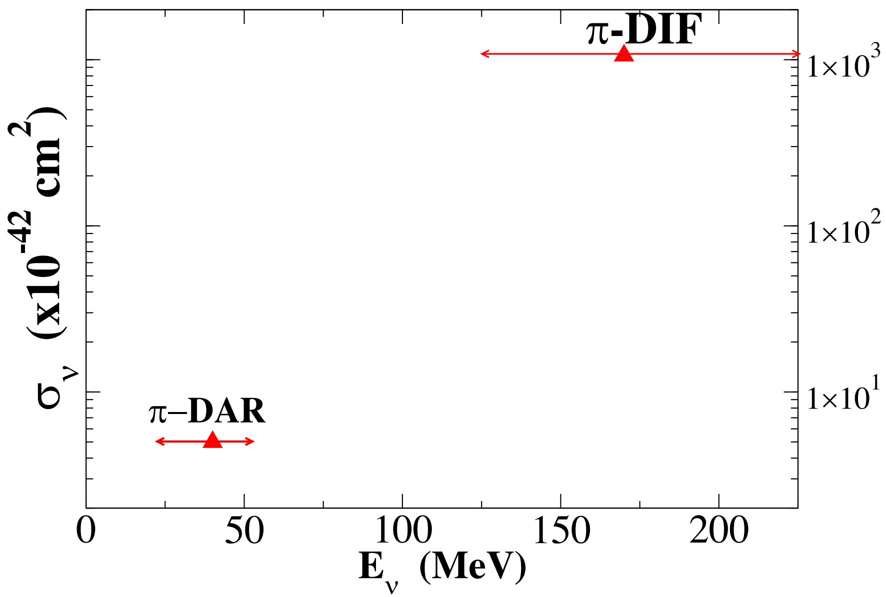
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

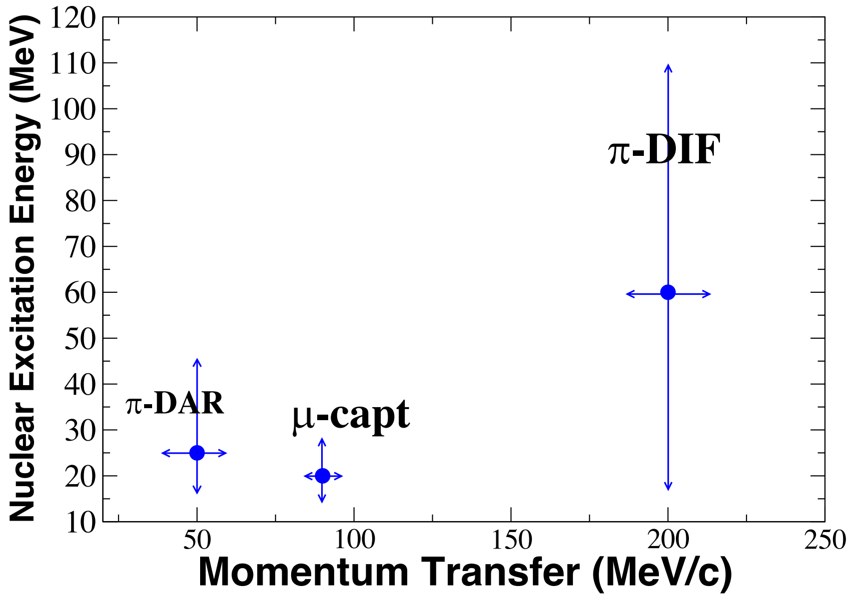




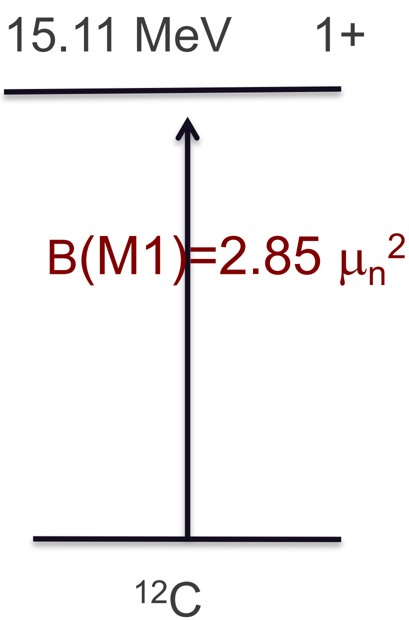
KARMEN and LSND experiments measured a set a cross sections with E_ν=0-200 MeV, Q=50-110 MeV/c.

Many details of the $^{12}C(\mu-,\nu)^{12}B$ reaction were studied at TRIUMF and Double Chooz recently provided high-accuracy μ-capture rates on ^{12}C.

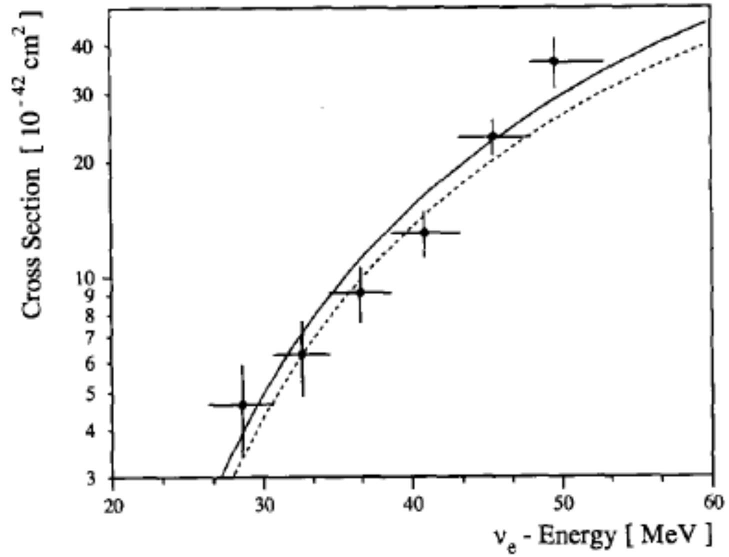




The 1+ T=1 transition in A=12 involves the largest GT transition in nuclear physics. Almost pure GT from comparisons between photon and β-decay



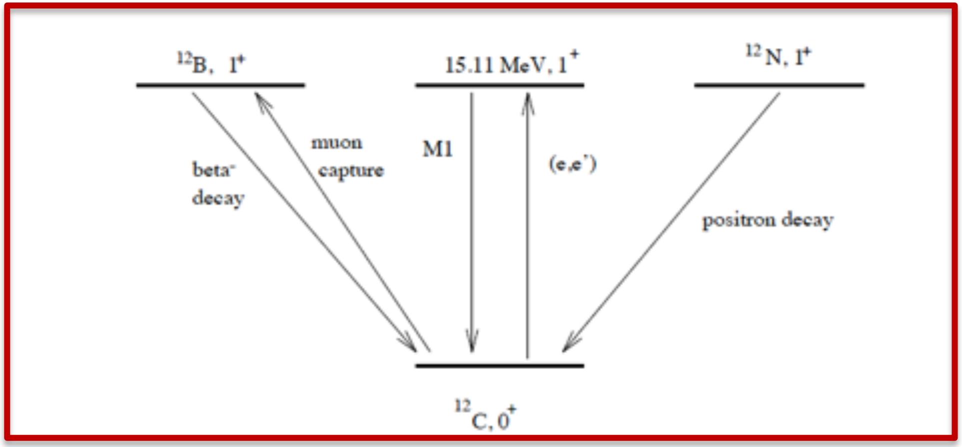
KARMEN $^{12}C(\nu_e,e-)12N$g.s.

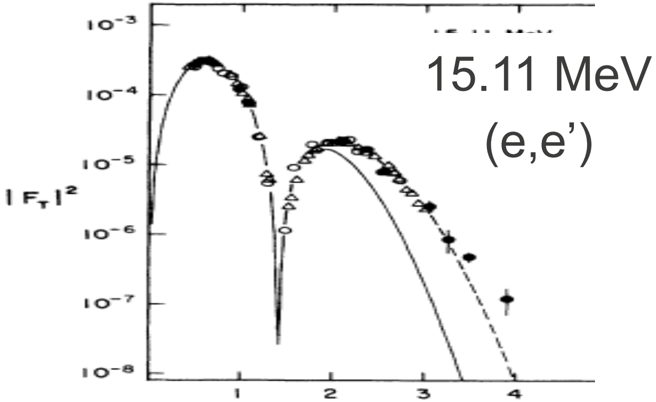


Predictions using electroweak data reproduce the KARMEN neutrino data.

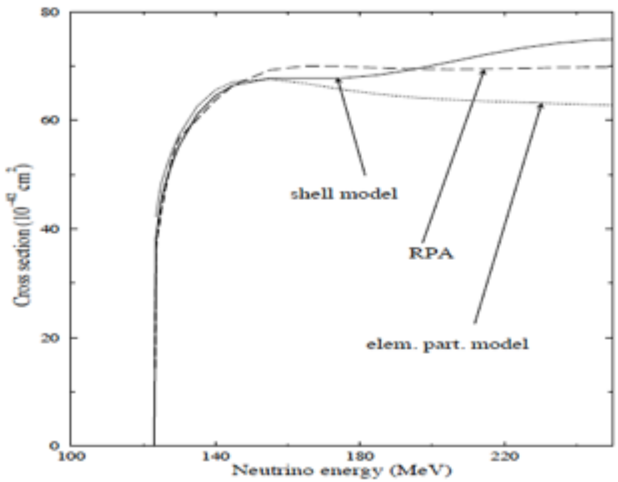
Fukugita at al. PLB 212 (1988) 139; Mintz PRC 40 ((1989)2458

The triad of 1+ states in A=12 is the best known example of well constrained neutrino cross sections.

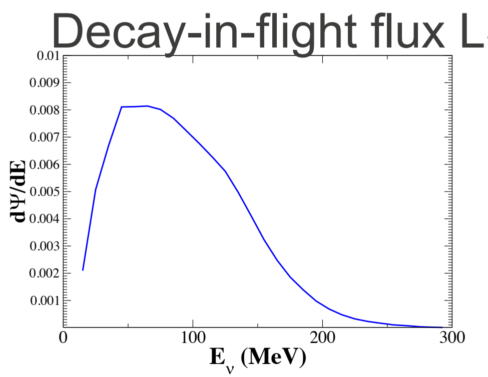


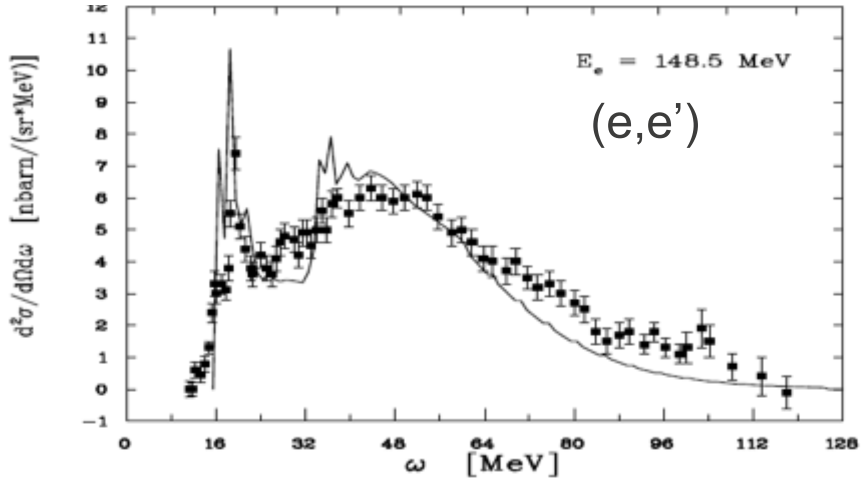


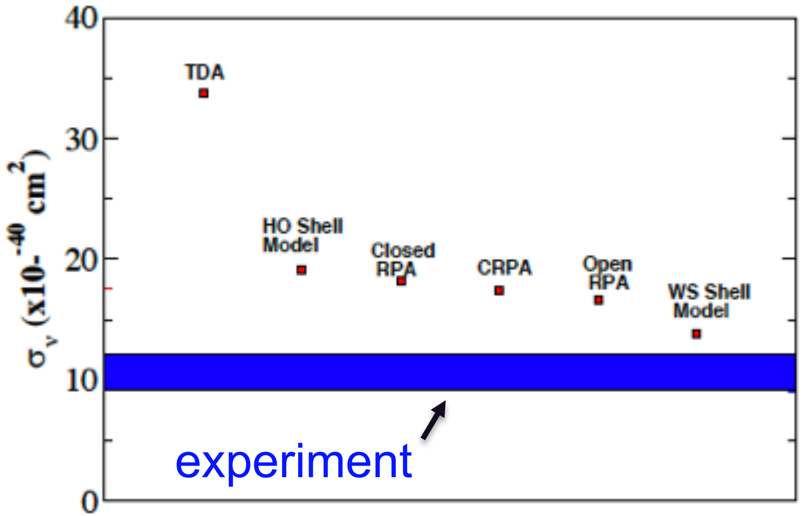
The neutrino reactions are approximately model independent up to E_ν=150 MeV: Usingthe measured M1, μ-capture, β-decay strengths, and the (e,e') form factor.



But, in general, we do not have enough information to constrain fully neutrino cross sections







- Even with a reasonable reproduction of the electron scattering data, models disagree on the neutrino cross-section.
- Many multipoles and operators are involved.
- The treatment of nuclear correlations was found to be very important in calculations

LAr

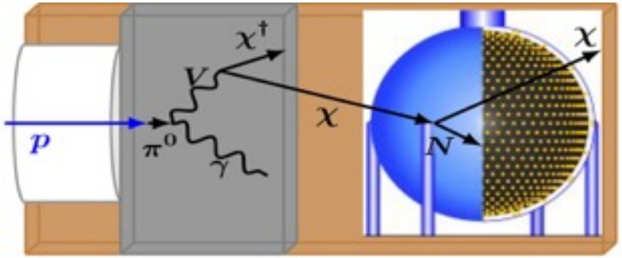
There are a number of low-energy neutrino and dark sector studies planned for LAr detectors

- **Supernova neutrino detection**
  - neutral current with the emission of γ-rays

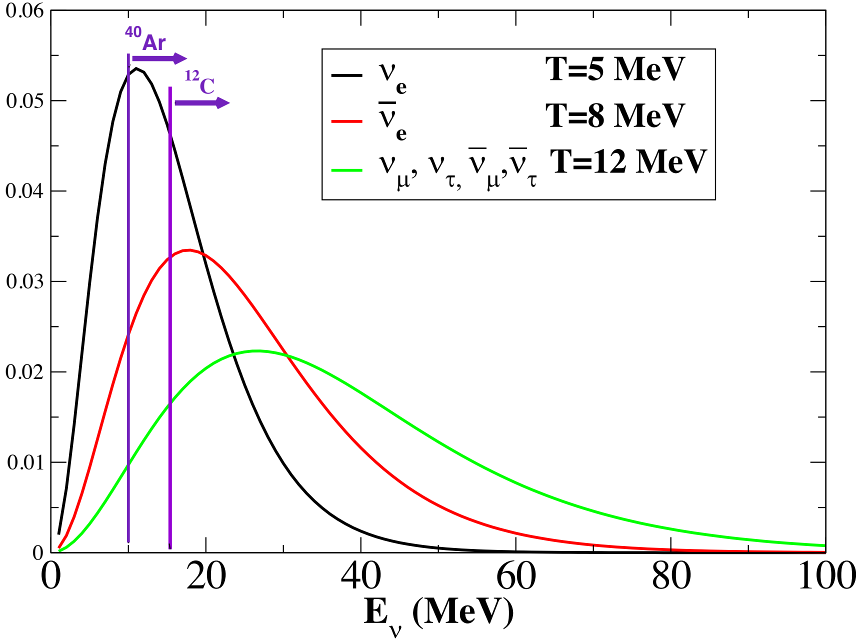
  → total incoming neutrino flux.
  - charged current - determines the ν_e flux $^{40}Ar(\nu_e,e^-)^{40}K$

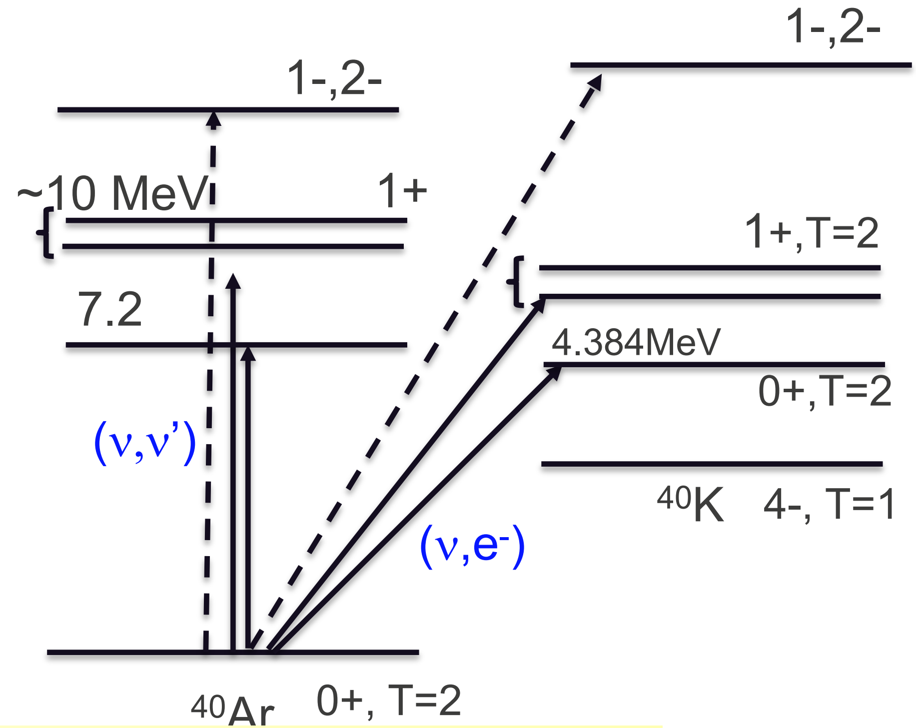
- **Coherent neutrino scattering**

  - searches for: sterile neutrinos and dark photons, or axions



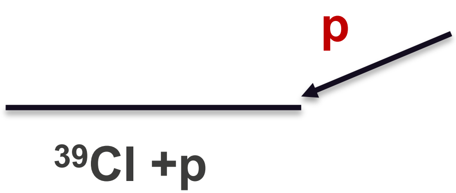
E_ν<100 MeV, excitations of ^{40}Ar are dominated by F(0+) and GT(1+),
(and a small amount from FF(1-,2-) ,with nuclear breakup by particle emission)

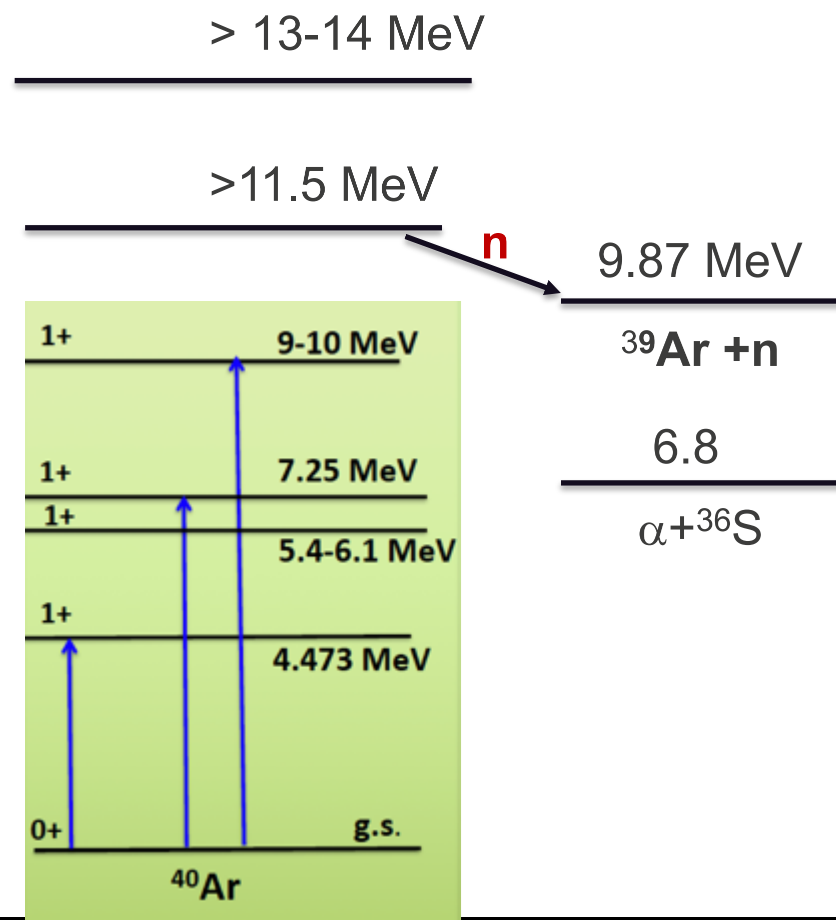




^{40}Ar has lower energy excitations than ^{12}C,
and more γ-rays of different energies are emitted.

The Neutral Current



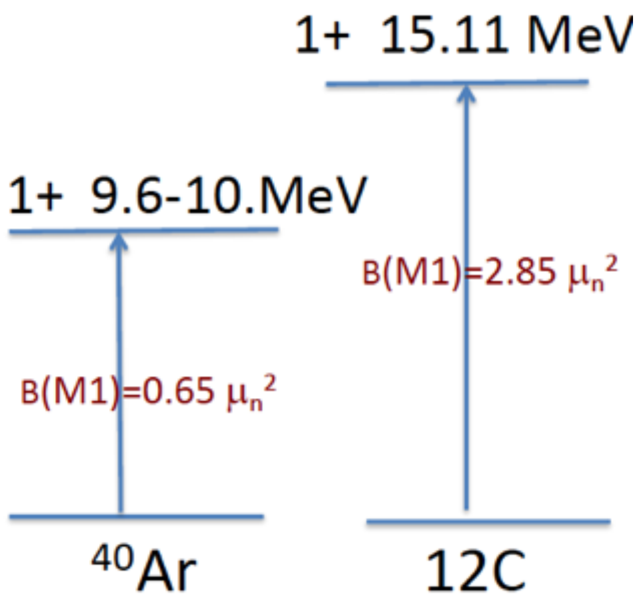


Below 10 MeV excitation:
All states decay by γ-decay

Above 11 MeV:
n-emission

Above 14 MeV:
p-, n- emission

Lowest energy contribution to the (ν,ν') cross section is determined by the Gamow-Teller strength, B(GT), which is related to the B(M1)strength



q→0 limit:

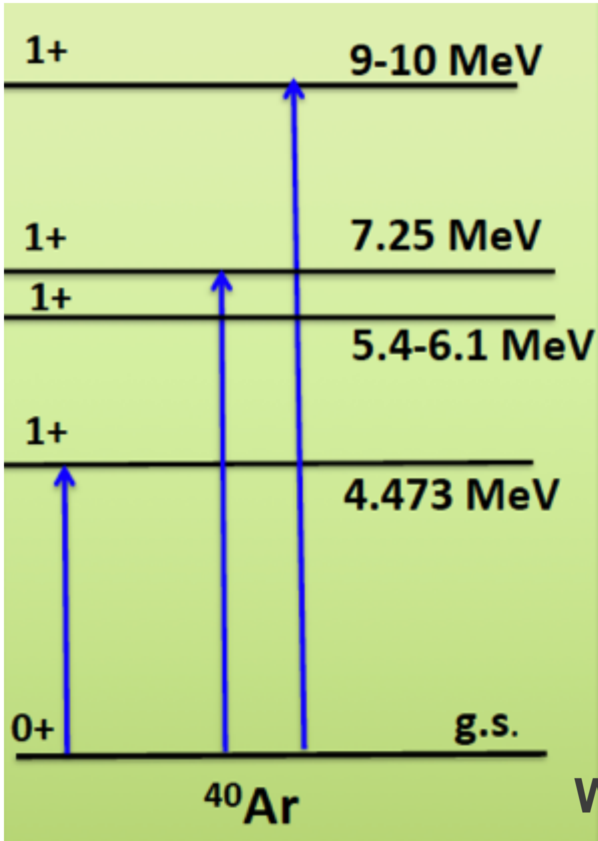
$$\sigma = G_F^2 V_{ud}^2 (E-\omega)^2 B(GT)/\pi$$

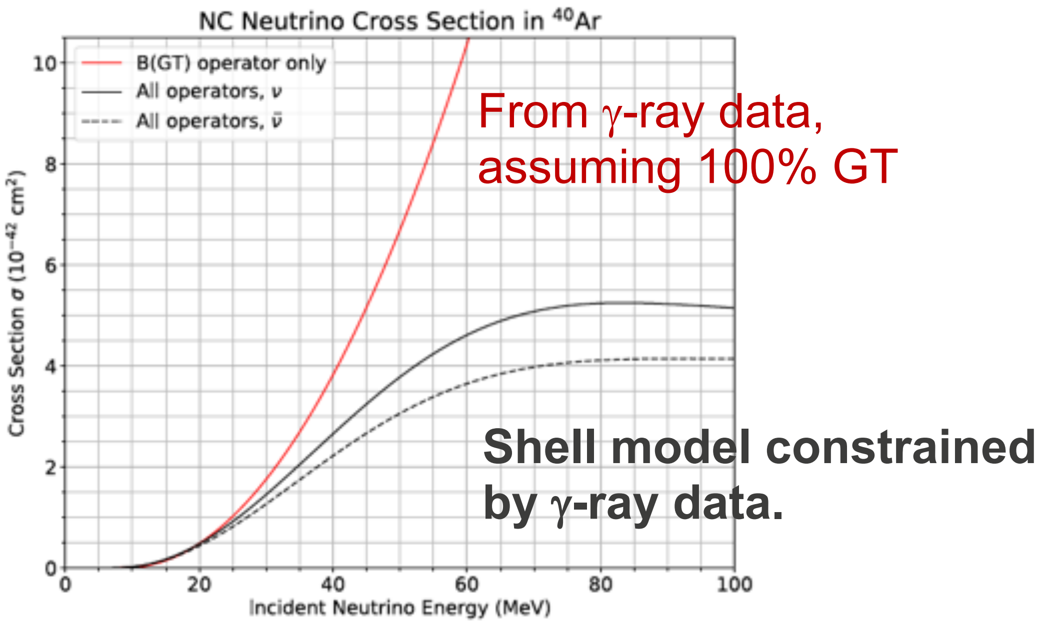
$$B(GT) = \frac{1}{2}\langle \sigma\tau \rangle^2$$

$$B(M1) = \frac{3}{4\pi}\left\{ g_l^{IS}\langle \ell \rangle + \frac{g_s^{is}}{2}\langle \sigma \rangle + \frac{g_s^{IV}}{2}\langle \ell\tau \rangle + \frac{g_s^{IV}}{2}\langle \sigma\tau \rangle \right\}^2 \mu_n^2$$

To relate the B(M1) to the B(GT) requires a model. For ^{12}C this can be done model independently. But ^{40}Ar it is model dependent, hence larger uncertainty.

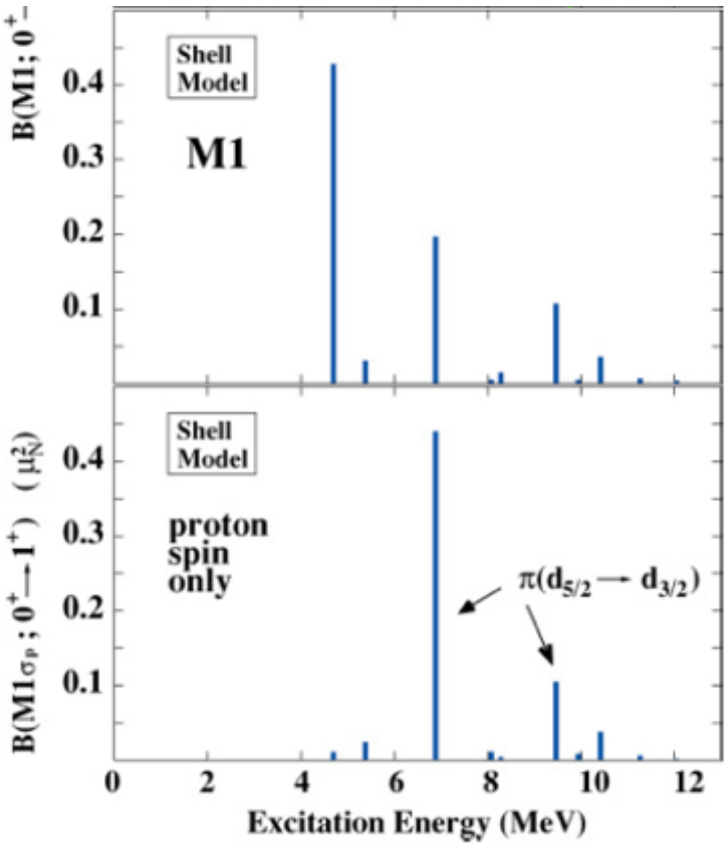
Neutral current cross section from M1 transitions





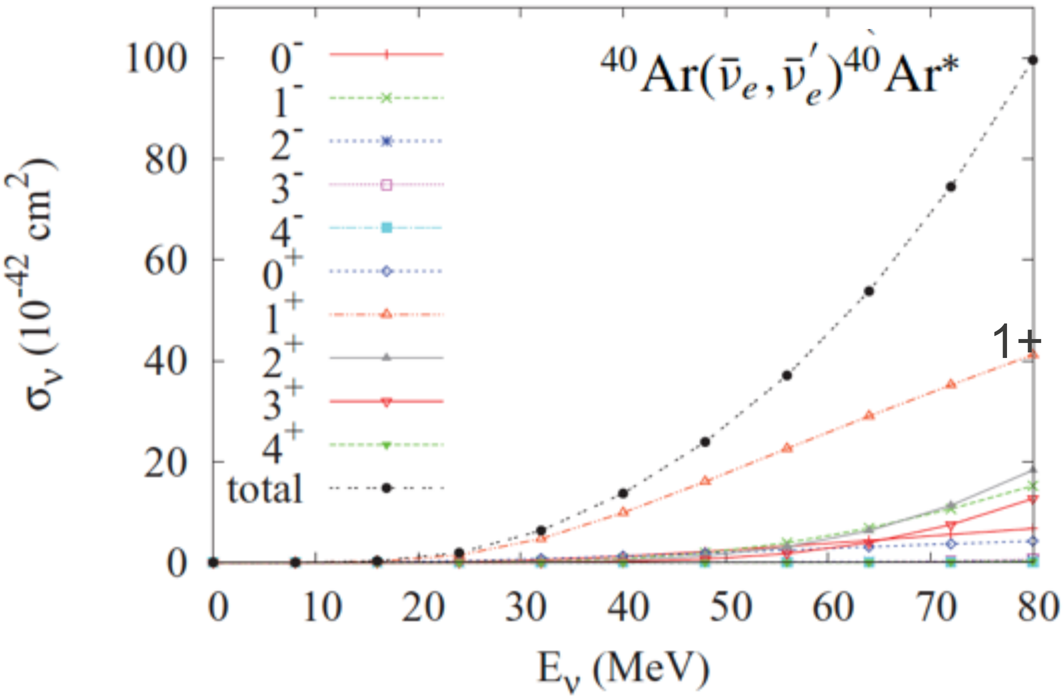
Would greatly benefit from (e,e') form factor measurements to determine the important operators.

Main difference between shell model and simple B(GT) model is that the transitions are not 100% GT. This is especially true for the 4.47 MeV state.



- This <u>needs</u> to be checked using a DAR flux and observing the emitted γ-rays from neutral current.
- Requires an ability to see 4- 10 MeV γ-rays in a LAr detector.
- Such an experimental capability would determine the ratio of γ-rays emitted from (ν,ν').
- Would be an ideal neutral current signal for supernova neutrinos

QPRA calculations predict a 1+ neutral cross section ~10 times bigger. This includes states above particle threshold.



Myung-Ki Cheoun, et al. PRC, 83, 028801 (2011)

Currently trying to understand the difference between these calculations and the estimates using measured B(M1) values.

QRPA also predicts a very high CC cross section to ^{40}Cl, compared to other calculations.

The Charged Current

11.7 MeV

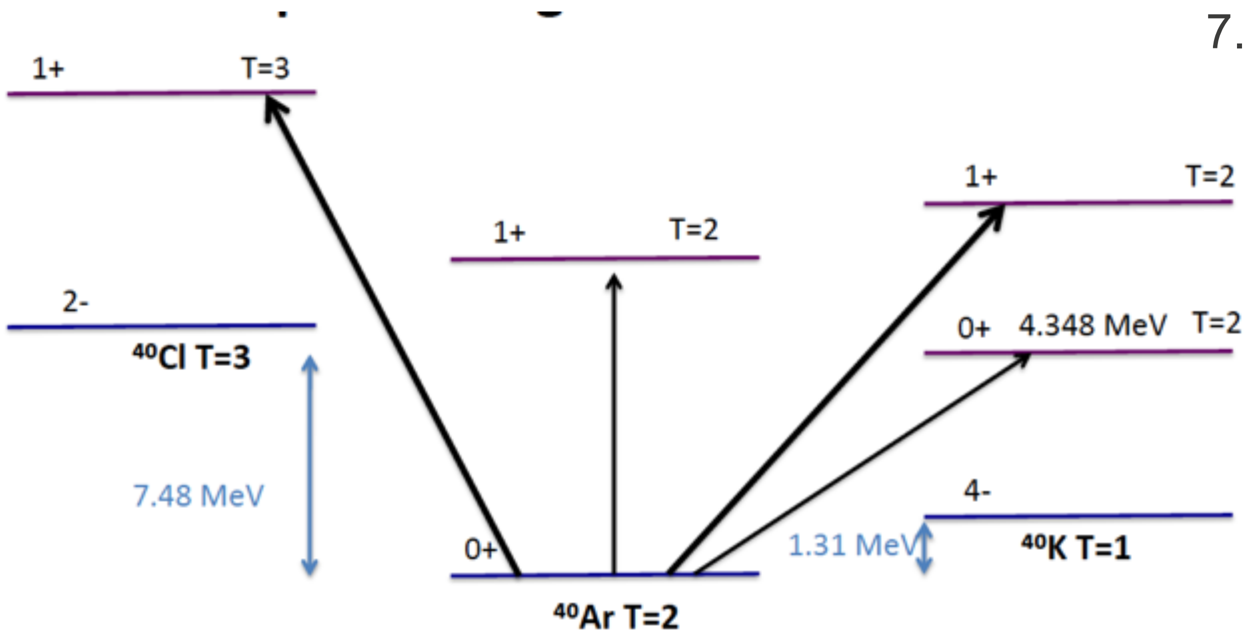
$p+^{38}S$

5.83 MeV

$n+^{38}Cl$

7.8 MeV, 7.6 MeV

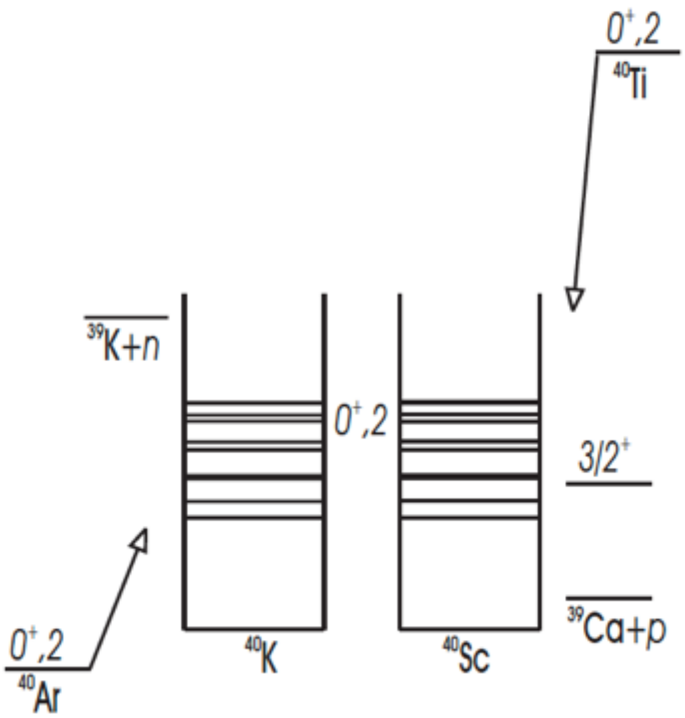
$n+^{39}K$, $p+^{39}Ar$



Charged-Current cross sections on ^{40}Ar can be constrained by β-decay of ^{40}Ti, (p,n), and μ-capture or (n,p) to ^{40}Cl

- The β-decays of ^{40}Ti → ^{40}Sc are assumed to be the isobaric analogs of the the equivalent ^{40}Ar→^{40}K transitions.

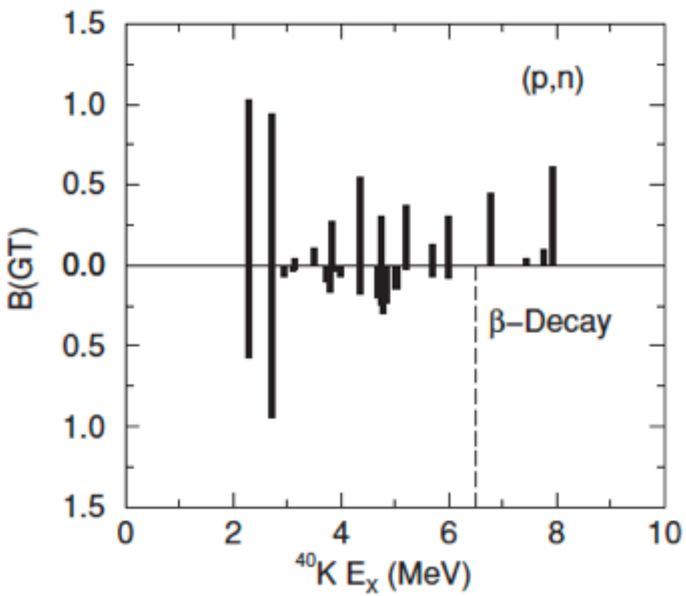
- The forward angle θ=0° (n,p) cross section can be related to the B(GT) values.
  (Note that: Haxton et al. have suggested that other operators complicate this analysis in ^{71}Ge.)

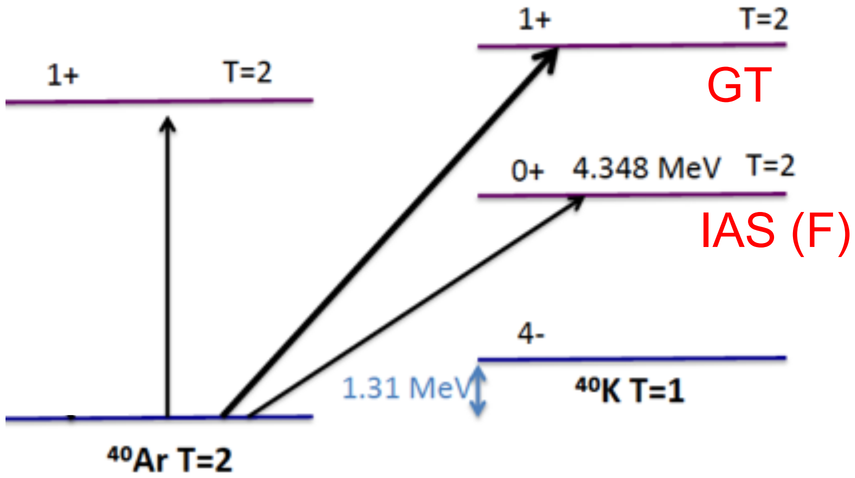


The β-decay technique is limited in the excitation energy probed, while the (p,n) technique involves some uncertainty on whether operators other GT enter.

To leading order the cross section is dominated by the Fermi transition to the IAS and the B(GT) to the 1+ states

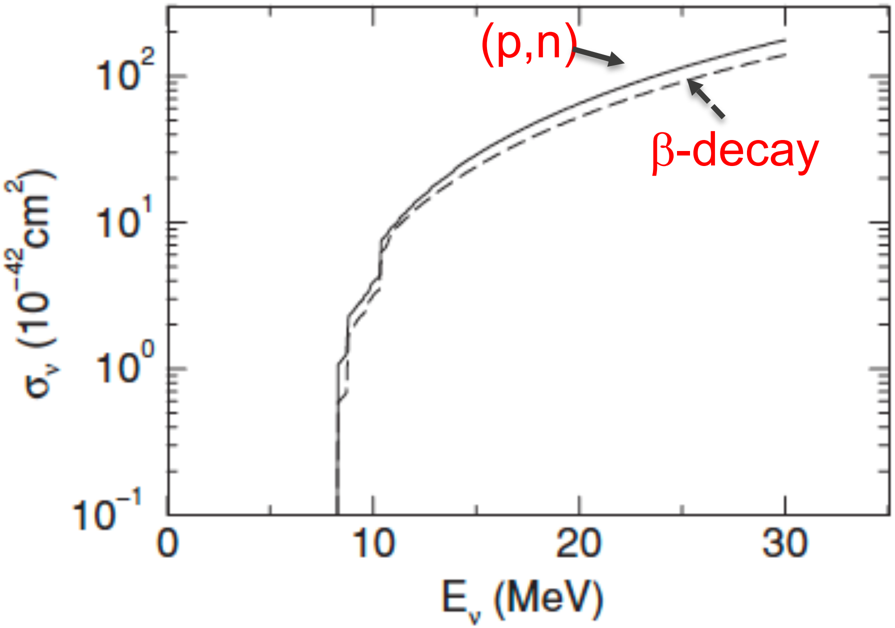
$$\sigma(E_\nu) = \frac{G_F^2 \cos^2\theta_{ud}}{\pi\hbar^4 c^3} \sum_i p_i W_i F(Z, W_i)[B_i(\mathrm{GT}) + B_i(F)]$$



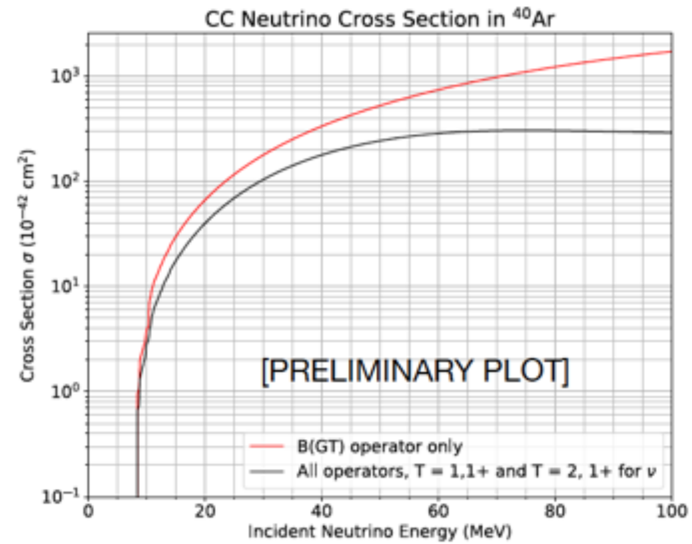


The B(GT) values for discrete states in ^{40}K for the charged current are an order of magnitude bigger than for the neutral current in ^{40}Ar*.

The (p,n) X-section analysis is higher but close to that from β–decay. At SN energies 2- states become important.



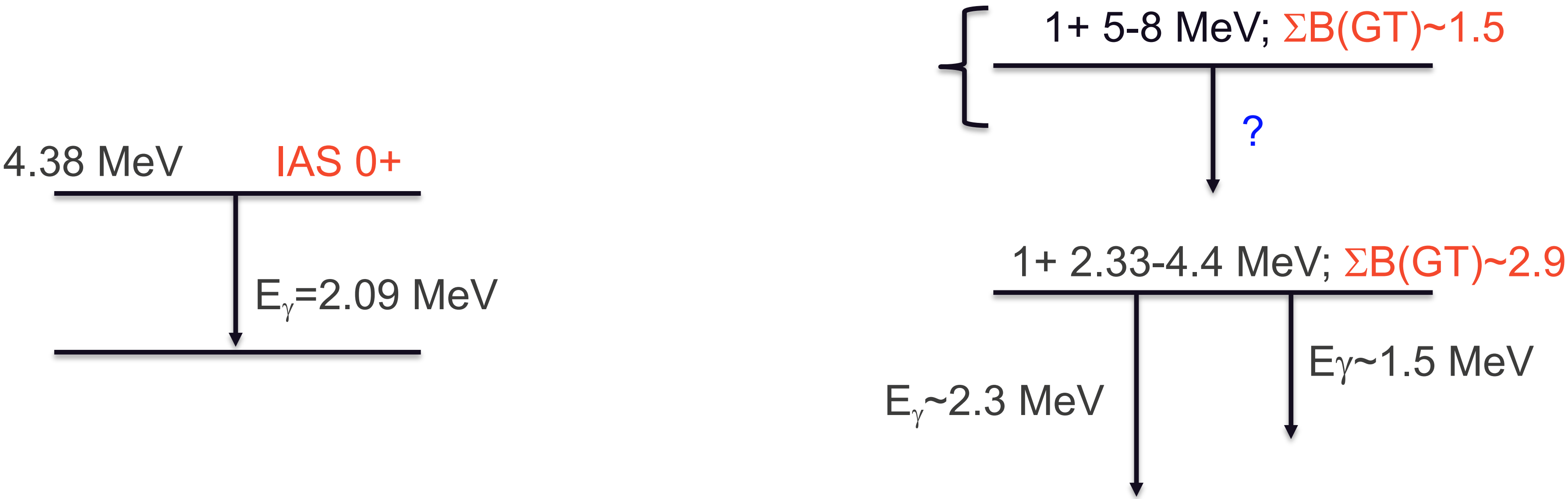
M. Bhattacharya, et al.,
PRC **80**, 055501 (2009)



Shell model constrained to fit B(GT) values.
Higher order operators tend to lower the cross section.

D. Newmark and A.H.

Known γ-ray signals from the CC excitation of ^{40}K are ~1-2 MeV. States above 5 MeV have unknown decay schemes.



Although the cross section is much larger, the CC γ-ray signals are much lower in energy that for the NC signal.
The decay schemes of the higher lying states needs to be studied.

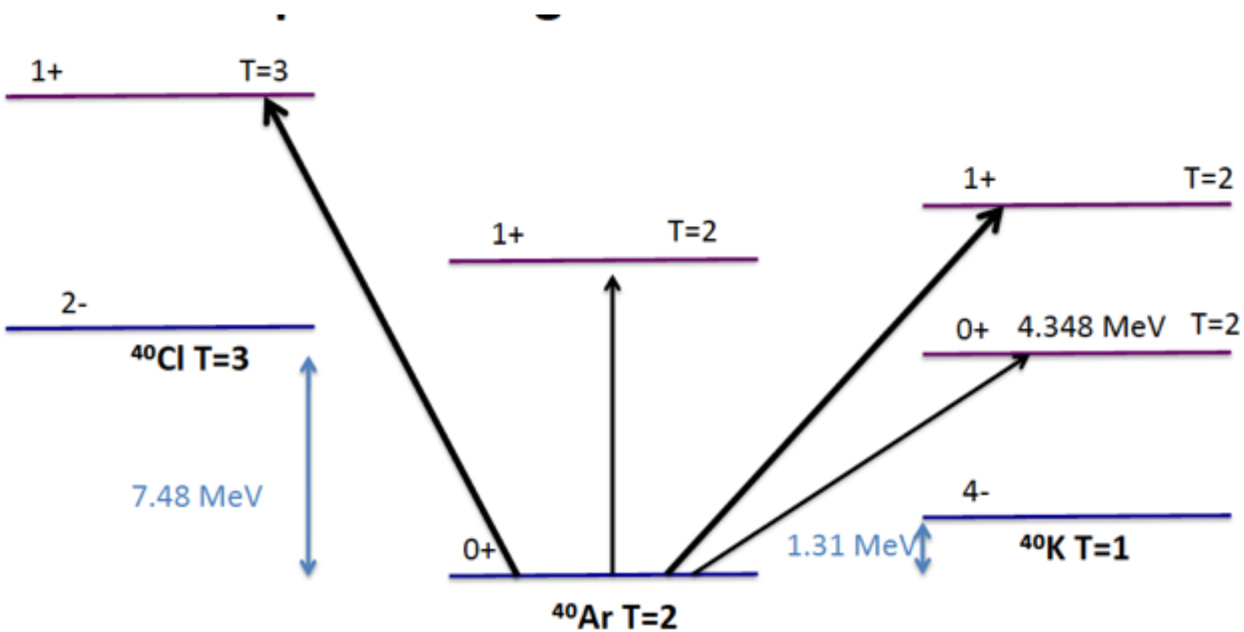
11.7 MeV

$p+{}^{38}S$

5.83 MeV

$n+{}^{38}Cl$

^{40}Cl

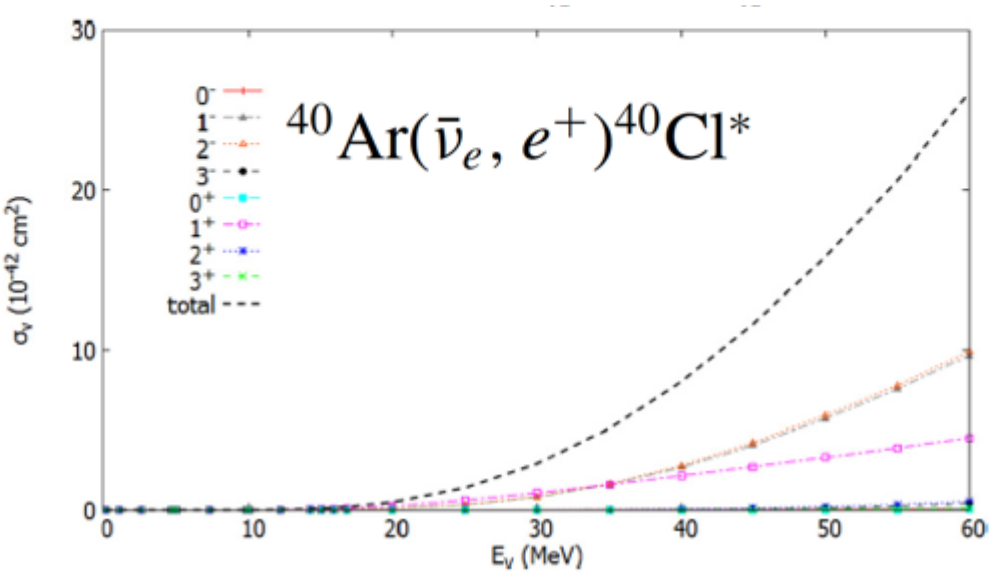


The γ–rays from muon capture on ^{40}Ar have been measured E_γ=0.66-5.9 MeV. The CC $\overline{\nu}$ cross section is relatively small.

$$(Z, A) + \mu^- \rightarrow (Z-1, A) + \nu_\mu$$

Isotope	Energy, keV	Line intensity
^{40}Cl	660	2.5
	881	2.6
	1063	2.3
	1746	2.7
	1797	2.2
	2219	7.0
	2523	2.0
	2621	14.7
	2839	28
	3918	3.9
	5879	4.1

A. V. Klinskikh, et al., Bull Russian Acad Sci. 2008, 72, 735

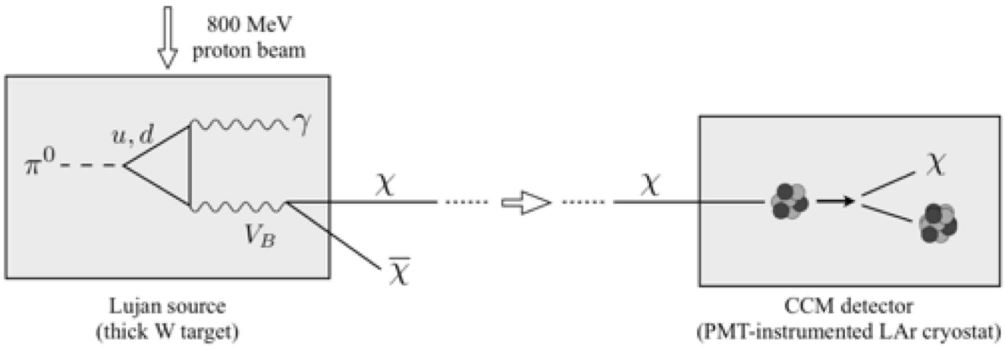


. Kostensalo et al. PRC 97, 034309 (2018)

Searches for physics BSM via coherent neutrino scattering

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \frac{Q_W^2}{4} F^2(Q^2) \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right]$$

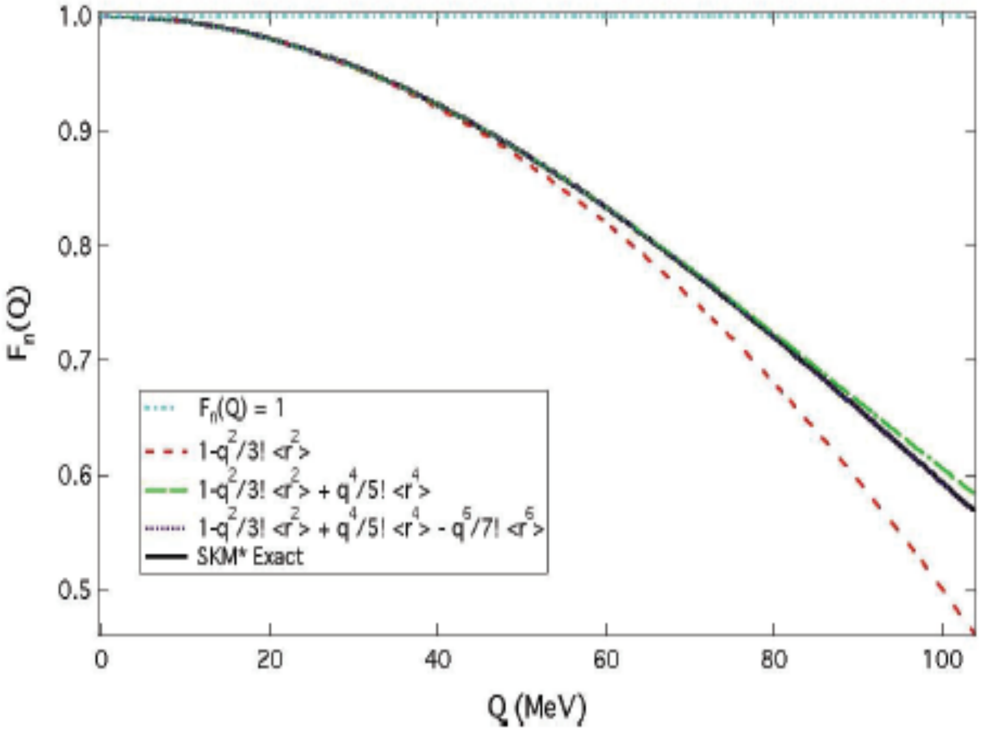
Well understood, except for small uncertainty in the weak form factor.



BSM searches for larger than expected nuclear recoil.

Decay-in-flight $\pi^o \rightarrow \chi$

The Weak form factor

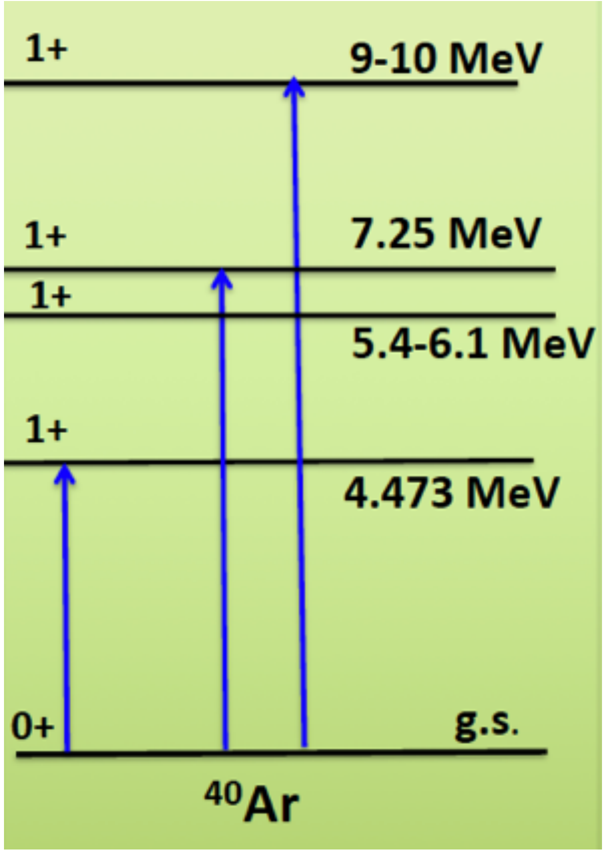


$$F(Q^2) = \frac{1}{Q_W}\int r^2 dr \frac{\sin(Qr)}{Qr} \times [\rho_n(r) - (1-4\sin^2\theta_W)\rho_p(r)]$$

For ^{40}Ar, he Coulomb field is relatively small, so that $\rho_n(r)$ is not hugely different from $\rho_p(r)$.

CCM already set an interesting limit.

Alternate (nutty?) method to search for DM candidates



- DM candidates can couple through the vector current only or the axial current only, depending the their production mechanism.
- This would change the ratio of the different γ-rays emitted.
- Need to be able to see this difference above the neutrino induced γ-ray ratios.
- Of course, need to measure the γ-rays from (ν,ν') first.

D. Alves and AH. preliminary

Summary:

- The triad of 1+ T=1 states in ^{12}C is the classic example of neutrino cross sections being constrained by other observables. This is not as well known for inclusive DIF cross sections on ^{12}C.
- Several γ-rays will be produced in $^{40}Ar(\nu,\nu')$ reaction but the ratio and magnitude of these partial cross sections need to be measured. These could be constrained with (e,e') form factors.
- In CC on ^{40}Ar, the γ-rays emitted are relatively low in energy. The cross section is probably lower than that predicted by β-decay or (p,n).
- Elastic and inelastic neutral current cross sections could possibly set limits for dark matter searches.