Proton spectral function from the Ar&Ti(*e,e'p*) cross sections

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for the Jlab E12-14-012 experiment

NuINT22, Oct.24-30, 2022

E12-14-012:Reminder

- **Primary Goal:** Extraction of the spectral functions of Argon and Titanium through Ar-Ti *(e,e′p)* reactions
  - Data Collected (Feb-March 2017):
    - Ar/Ti/C/Dummy/Optical *(e,e′p)* reactions for five different kinematic set-ups
    - Ar/Ti/C/Dummy (*e,e′*) reactions for one kinematic set-up

- **Primary Motivation**: To help improve the accuracy of the measurement of the neutrino-oscillation parameters, including the *CP violation in leptonic sector* (one of the top priority of the US particle physics community), in the future neutrino experiments, mainly DUNE, by:

- The spectral function of argon (~ initial momentum and energy distributions of nucleons bound in argon) can directly be used in the reconstruction of neutrino energies (currently the major source of uncertainty in neutrino experiments).

- Using the extracted argon spectral functions to further develop (extend) a fully consistent parameter-free theoretical (neutrino-nucleus) model that can be used in (every step of) the analysis of long baseline neutrino experiments.

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Research associate - SLAC

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Outline

Neutrino Oscillation Experiments - DUNE

- Importance of cross sections in oscillation results
- Connection between electron and neutrino cross section

Experimental setup

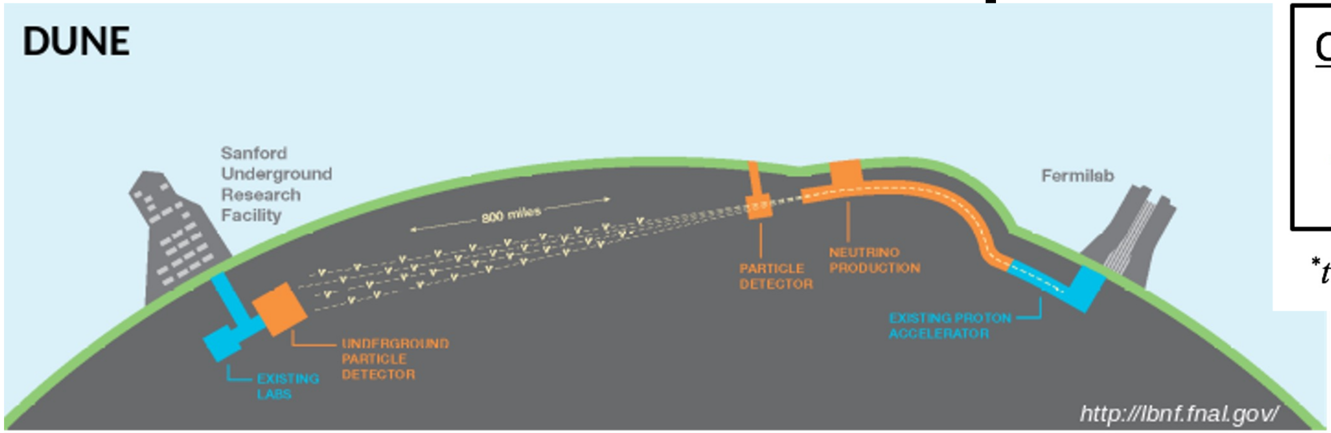
- Jefferson Lab – Hall A
- E12-14-012
    - Motivations and goals
    - Target
    - Kinematic configurations
    - Publications

E12-14-012 - Exclusive analysis

- Analysis strategy
- Missing Energy and Missing momentum fits
    - Ar
    - Ti

Summary

DUNE Experiment



Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

two neutrino flavors, for simplicity

Experiments measure event rates which, for a given observable topology, can be naively computed as:

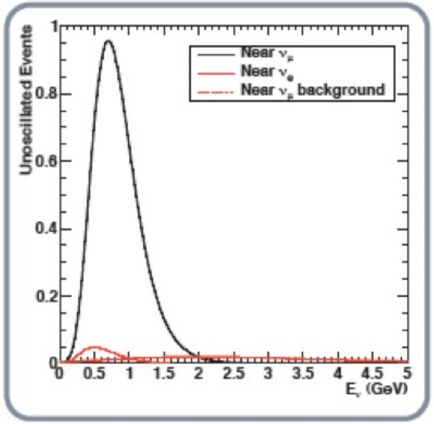
Event Rate at near detector:

$$N^\alpha_{\mathrm{ND}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma^i_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

Event Rate at far detector:

$$N^{\alpha\to\beta}_{\mathrm{FD}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

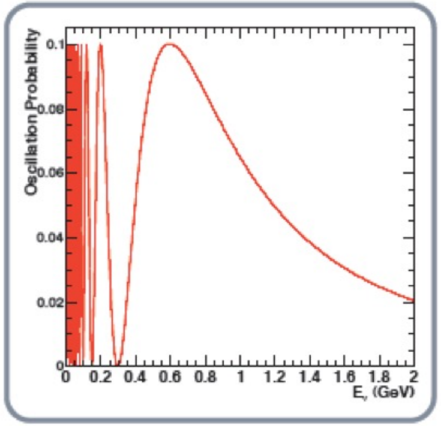
Near detector



measure # events = flux x cross section

×

Oscillation probability



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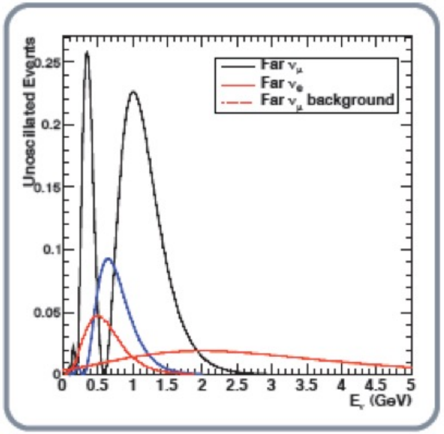
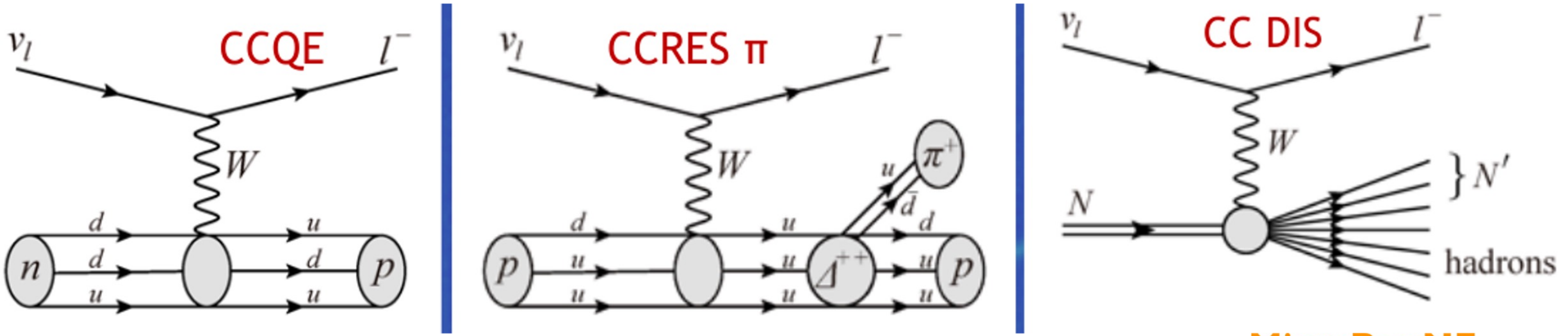
Far detector

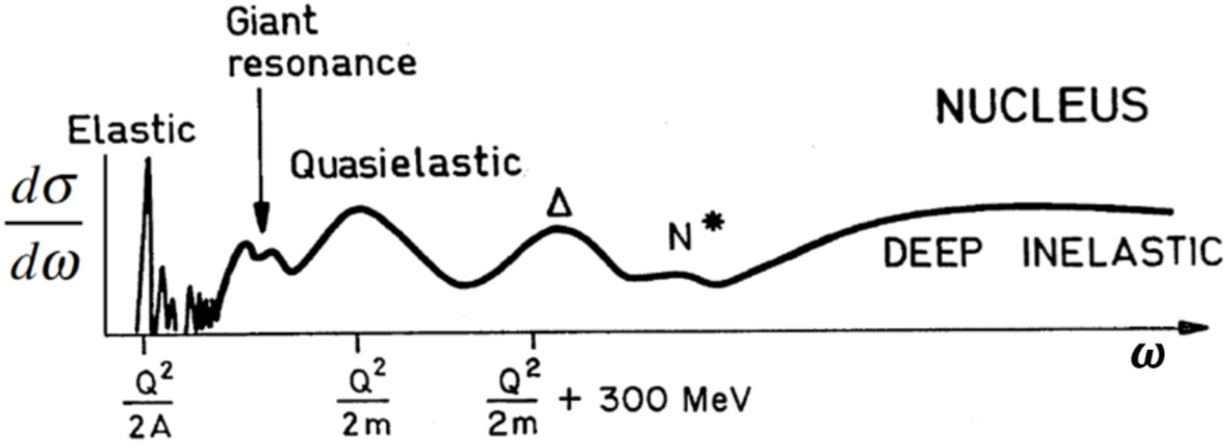


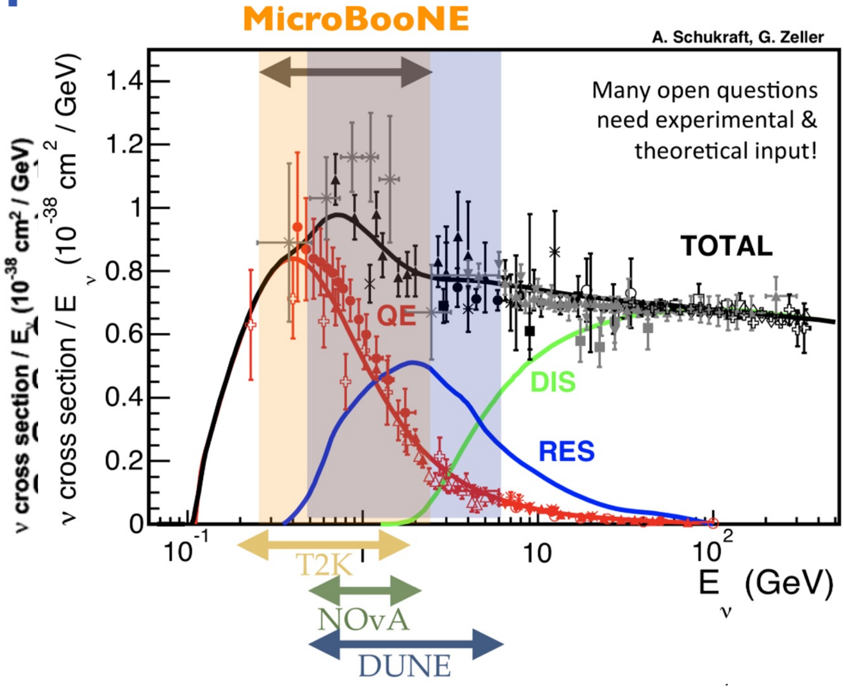
Black curve: ν_μ disappearance
Blue curve: ν_e appearance
Red curve: intrinsic ν_e/ν_μ bkg

Beam between Near and Far detector is not the same: divergence

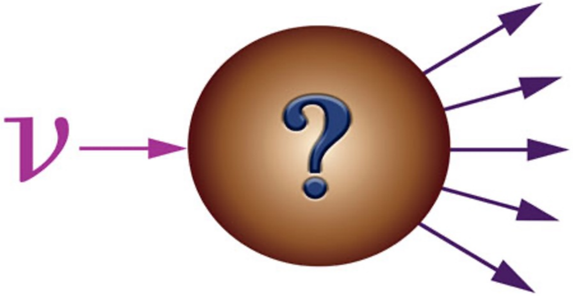
Neutrino Interactions

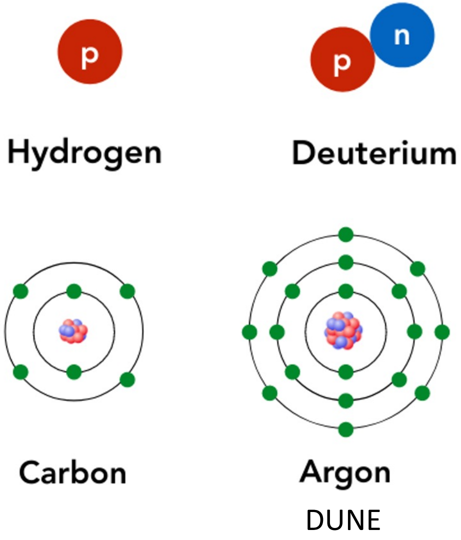






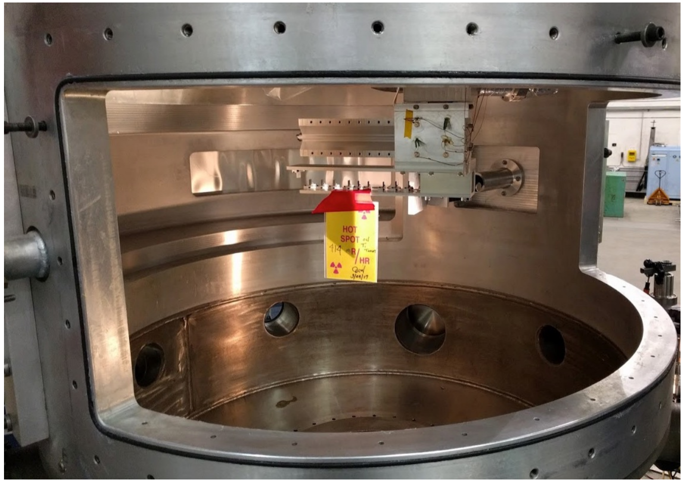
Nuclear Effects

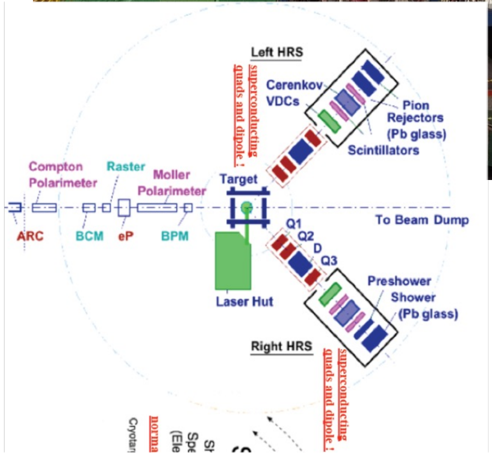


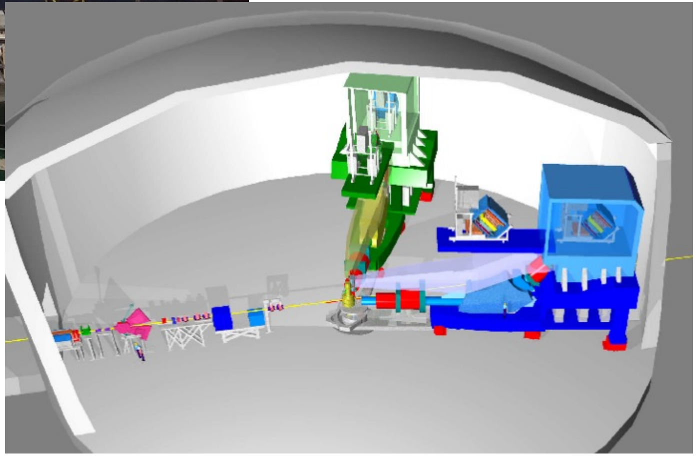


- 1970-1990’s
  - Hydrogen/deuterium filled bubble chambers:
    - Experiments: ANL (hydrogen), BNL (hydrogen and deuterium)
    - Test the V-A nature of weak interactions
    - Measure nucleon axial vector form factor
- 1990-present
  - Complex nuclei as targets: C, Fe, **Ar**
  - Z ≠ N in Argon, neutrino and anti-neutrino QE could be different (arXiv: 1603.01072)
  - **Heavier targets have more complex nuclear effects**

Hall A at Jefferson Lab

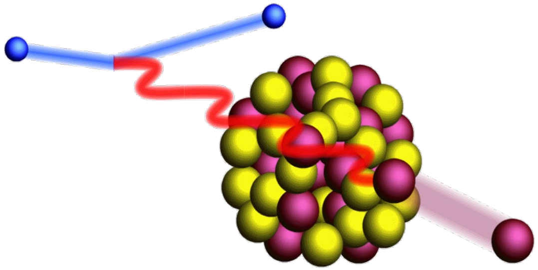






E12-14-012: (*e,e'*) and (*e,e'p*) on Ar and Ti

Aim: Obtaining the experimental input indispensable to construct the argon spectral function, thus paving the way for a reliable estimate of the neutrino cross sections in DUNE. In addition, stimulating a number of theoretical developments, such as the description of final-state interactions.
[Benhar *et al.*, arXiv:1406.4080]



$E_e = 2.222$ GeV

	E'_e (GeV)	θ_e (deg)	$\lvert\mathbf{p}'\rvert$ (MeV)	$\theta_{p'}$ (deg)	$\lvert\mathbf{q}\rvert$ (MeV)	p_m (MeV)	E_m (MeV)
kin1	1.777	21.5	915	−50.0	865	50	73
kin2	1.716	20.0	1030	−44.0	846	184	50
kin3	1.799	17.5	915	−47.0	741	174	50
kin4	1.799	15.5	915	−44.5	685	230	50
kin5	1.716	15.5	1030	−39.0	730	300	50

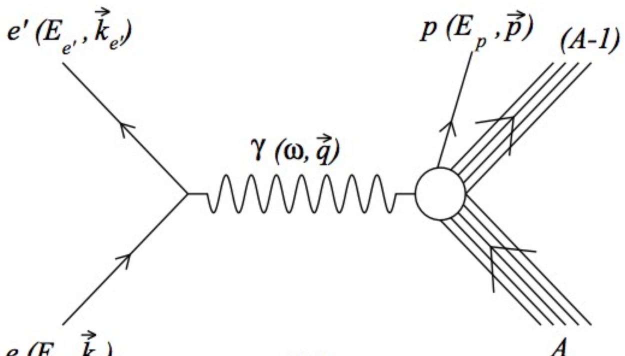
Exploratory analysis of the full dataset

(e,e’) and (e,e’p) processes

(e, e’p) process (exclusive):

Both outgoing electron and proton are detected

$$e + A \rightarrow e' + p + (A-1)$$

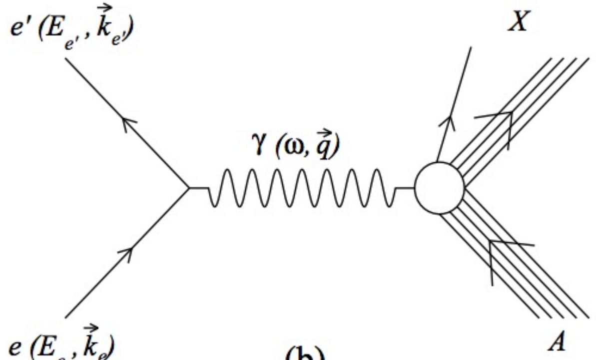


(a)

(e, e’) process (inclusive):

Only scattered electron is detected

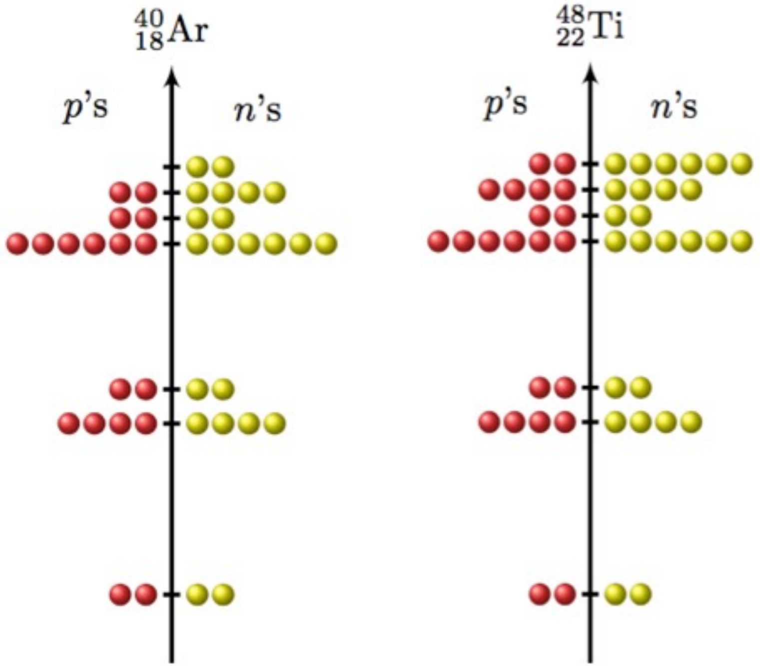
$$e + A \rightarrow e' + X$$



(b)

Why Titanium?

The shell model structure of the **protons in Ti** is nearly identical to that of the **neutrons in Ar**



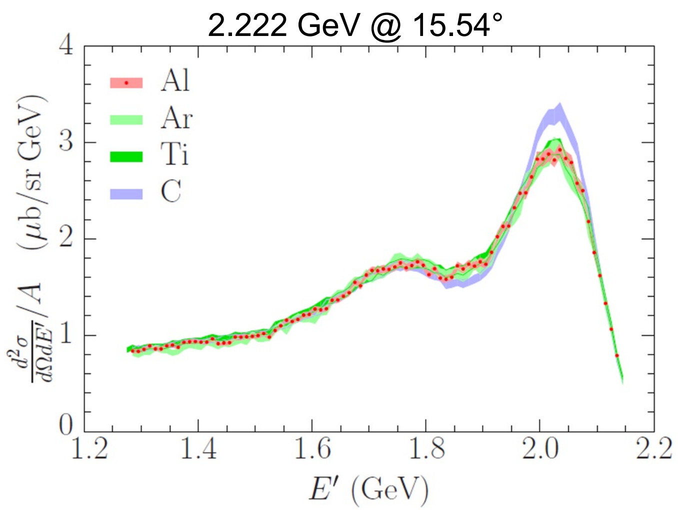
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

$$\nu_l + n \rightarrow l^- + p$$

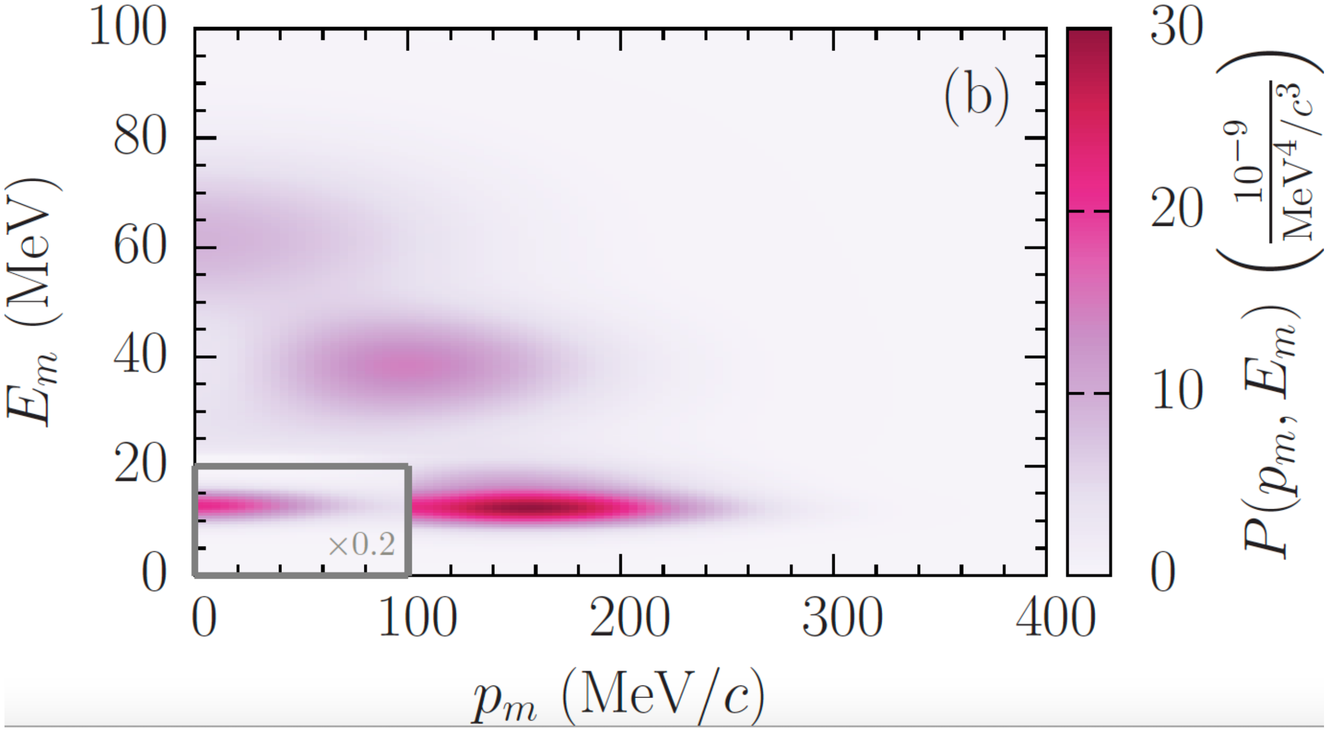
Ar(e,e'p)->SF of protons in Ar nucleus	Ti(e,e'p)->SF of neutrons in Ar nucleus

Publications

- Inclusive cross sections for C and Ti,
  [Dai *et al.*, PRC 98, 014617 (2018)]
- Inclusive cross section for Ar,
  [Dai *et al.*, PRC 99, 054608 (2019)]
- Inclusive cross section for Al-7075, Ar, C and Ti of all (*e,e'*) data
  [Murphy *et al.*, PRC 100, 054606 (2019)]
- Exclusive Ar & Ti cross sections for a single kinematics, p_m ~ 50–60 MeV, E_m ~ 50–70 MeV
  [Gu *et al.*, PRC 103, 034604 (2021)]
- Exclusive Ar cross sections for all kinematics, p_m ~ 50–350 MeV/c, E_m ~ 10–70 MeV
  [Jiang *et al.*, PRD 105, 112002 (2022)]

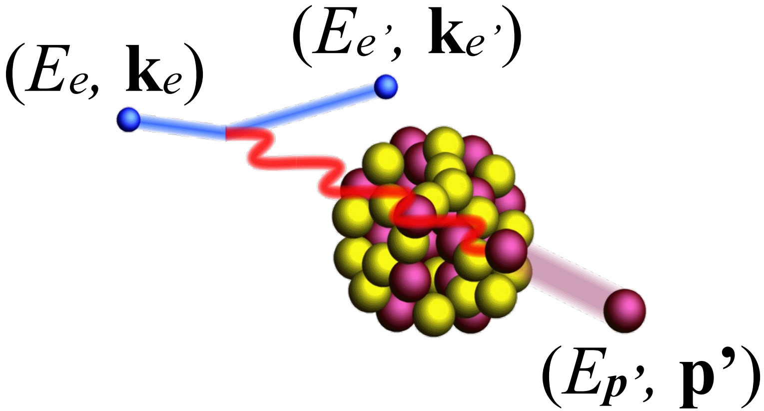


Extraction of the spectral function



Universal property of the nucleus, independent of the interaction.

Missing momentum $\mathbf{p}_m$ and missing energy E_m



$$E_e + M - \underline{E_m} = E_{e'} + E_{p'}$$

known

$$\mathbf{k}_e + \underline{\mathbf{p}_m} = \mathbf{k}_{e'} + \mathbf{p'}$$

(*e*,*e'p*) cross section

elementary cross section

nuclear transparency

$$\frac{d^6\sigma_{\rm IA}}{d\Omega_{e'}dE_{e'}d\Omega_{p'}dE_{p'}} \propto \sigma_{ep}\, S(p_m, E_m)T(E_{p'})$$

spectral function

Analysis procedure

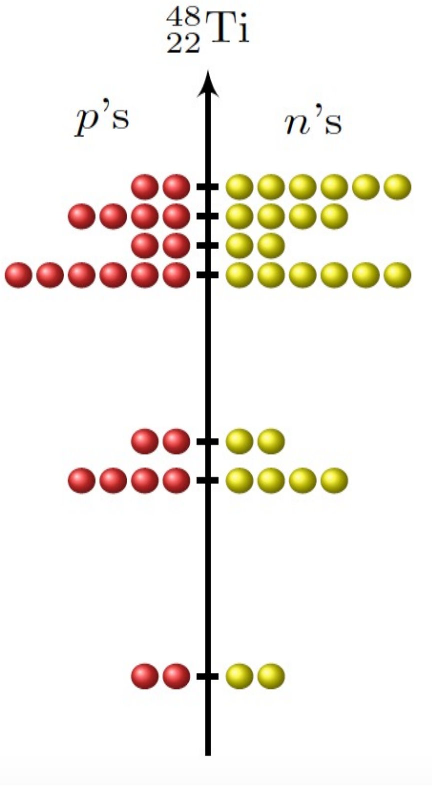
1) Extract of the (*e,e’p*) cross section

2) Using σ_{cc1} of de Forest and nuclear transparency, obtain the reduced cross sections as a function of (a) p_m and (b) E_m.

3) Find the parameters of the spectral function (*i.e.*, spectroscopic factors) from the fits to the reduced cross sections as a function of p_m.

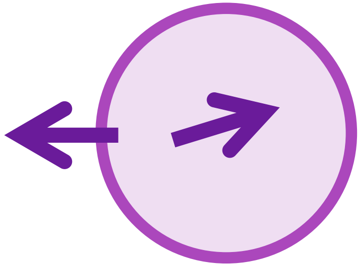
4) Using the priors from Step 3), find the parameters of the spectral function (*i.e.*, spectroscopic factors, peak positions, distribution widths) from the fits to the reduced cross sections as a function of E_m. Correct for transparency.

Test spectral function: 80% mean-field + 20% *NN* correlations



Independent-particle shell model

+



Convolution model of the correlated spectral function

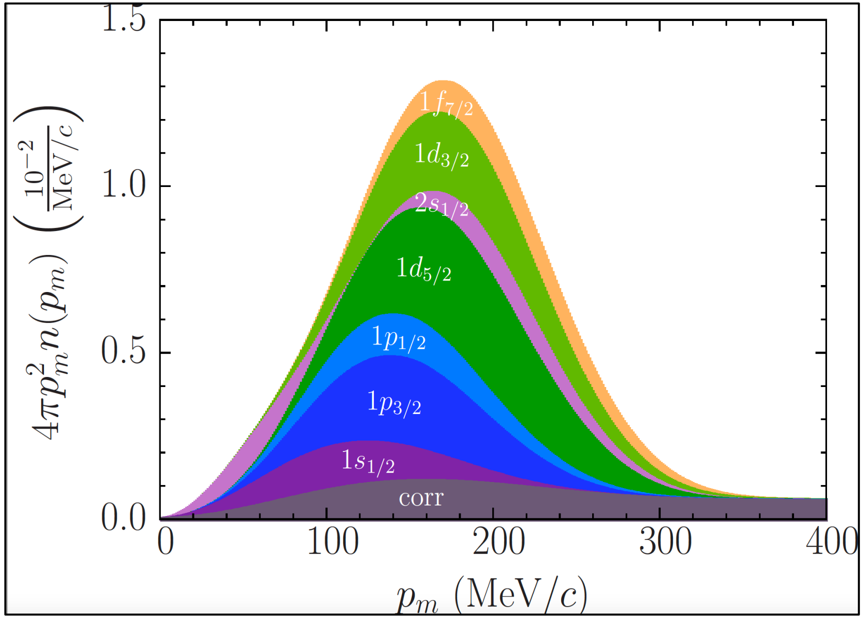
Mean-field part of the spectral function

spectroscopic factor

energy distribution

$$P_{\mathrm{MF}}(p_m, E_m) = \sum_{\alpha} S_{\alpha} |\phi_{\alpha}(p_m)|^2 f_{\alpha}(E_m)$$

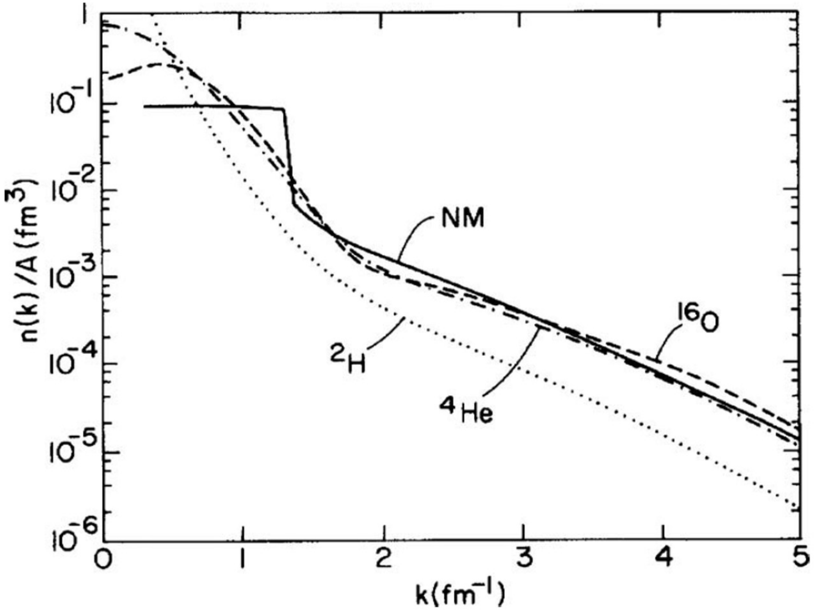
wave function in momentum space



Relativistic MF calculations by C. Giusti

Correlated part of the spectral function

Benhar *et al.*, RMP **80**, 189 (2008)



Ciofi degli Atti and Simula, PRC **53**, 1689 (1996)

- Correlated nucleons form quasi-deuteron pairs, with the relative momentum distributed as in deuteron.
- *NN* pairs undergo CM motion (Gaussian distrib.)
- Excitation energy of the (A − 1)-nucleons is their kinetic energy plus the *pn* knockout threshold

Fit procedure and minimization

For each bin in the spectra of missing energy (100 bins between 1 and 100 MeV) and missing momentum (40 bins with momentum range changing between kinematics), we determined the product of the reduced MC cross section and the ratio of the data to simulation yield

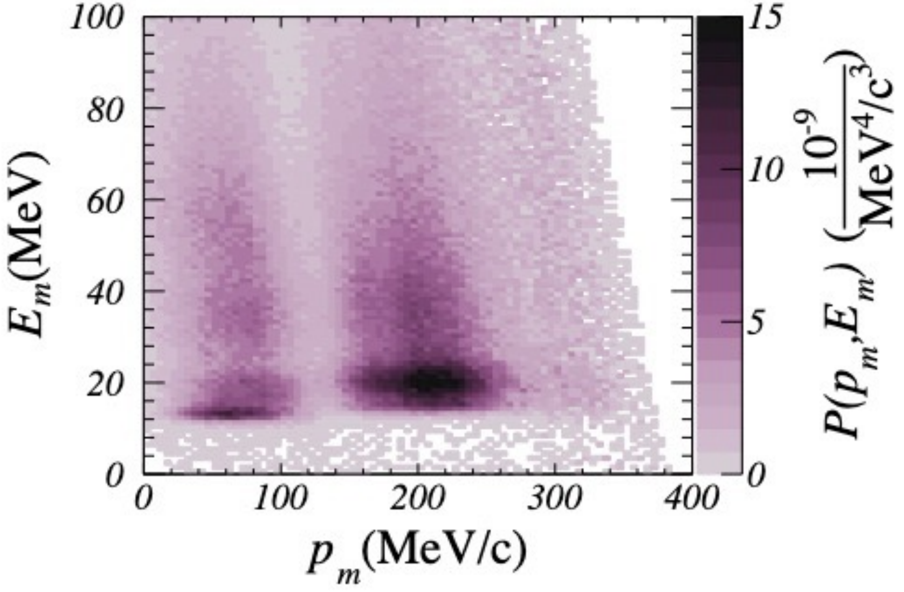
$$\frac{d^2\sigma^{\text{red}}_{cc1}}{d\Omega dE'} = \left(\frac{d^2\sigma^{\text{red}}_{cc1}}{d\Omega dE'}\right)_{\text{MC}} \times \frac{Y(E',\theta)}{Y_{\text{MC}}(E',\theta)}$$

The fit performs a χ^2 minimization using the TMinuit package available in root.

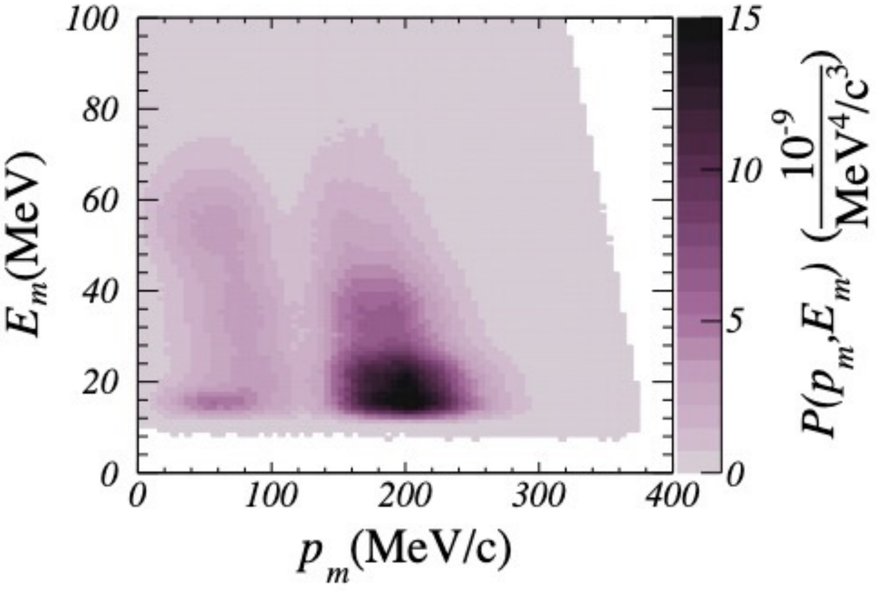
The index i labels the missing momentum(energy) bin, α is the orbital index, $f^{pred}_{\alpha}(i)$ is the parametrized prediction evaluated at bin i in the missing momentum spectra for orbital α, S_α is the spectroscopic factor.

$$\chi^2 = \sum_i \chi_i^2 = \sum_i \left(\frac{\sigma_i^{\text{red, obs}} - \sum_\alpha S_\alpha f_\alpha^{\text{pred}}(i)}{\sigma_{\sigma_i^{\text{red, obs}}}} \right)^2$$

Ar (e,e'p) – Phys. Rev. D 105, 112002, (2022)

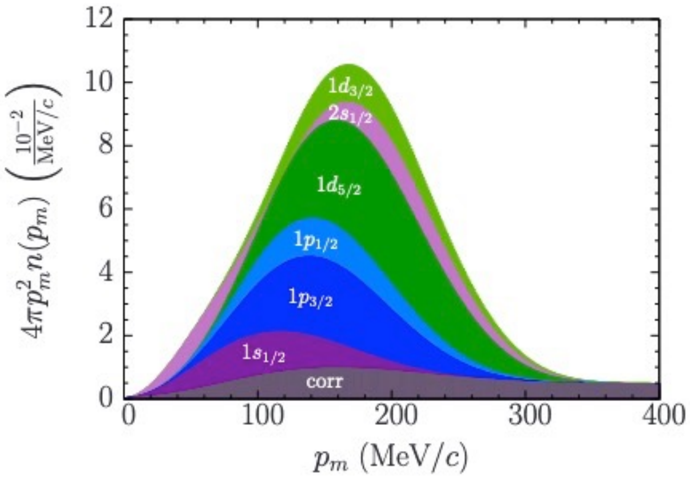


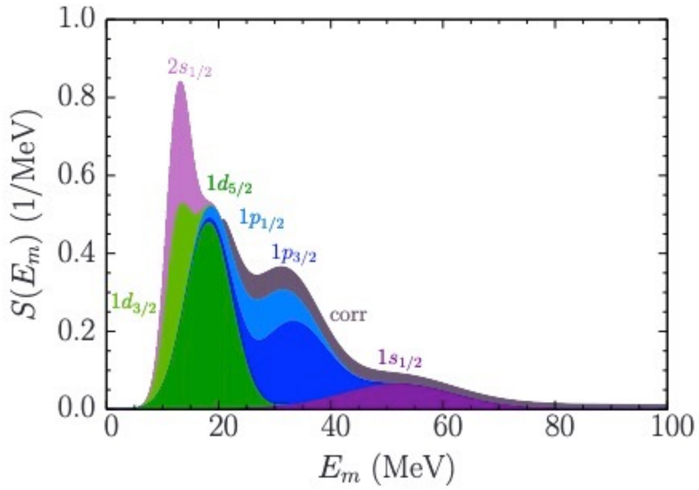
(a) Data



(b) MC

Ar (e,e'p) – Phys. Rev. D 105, 112002, (2022)

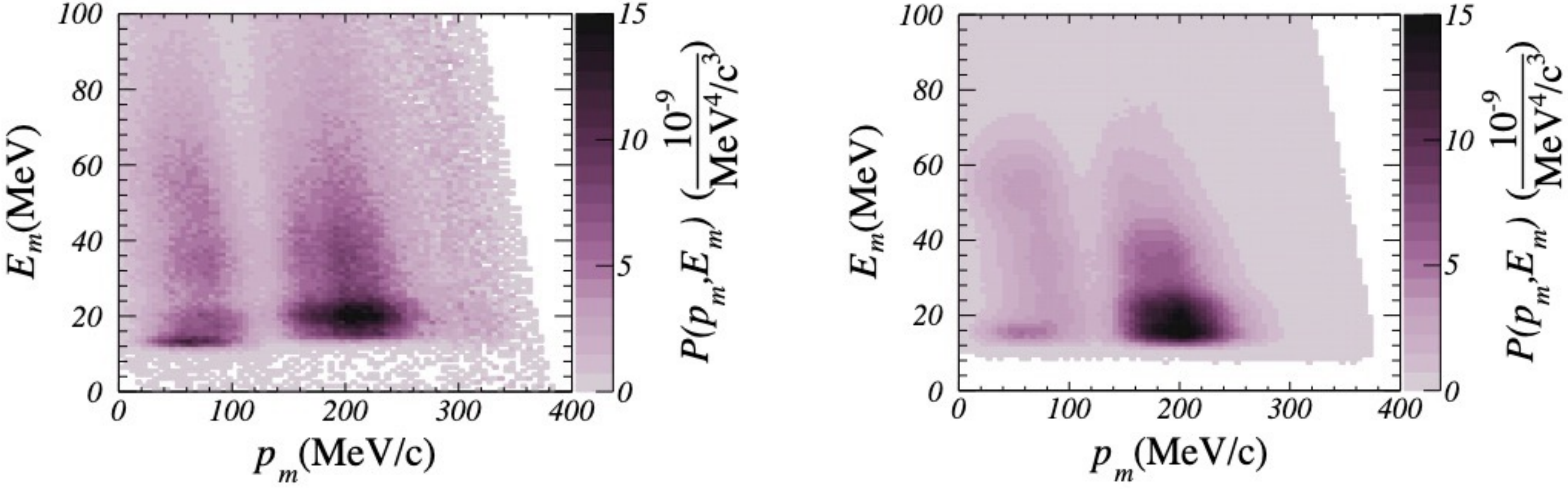




		all priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	2.51 ± 0.05	2.05 ± 0.23	2.52 ± 0.05
corr.	0	3.77 ± 0.28	3.85 ± 0.25	excluded
$\sum_\alpha S_\alpha$		17.02 ± 0.48	16.61 ± 0.57	14.12 ± 0.42
d.o.f		206	231	232
χ^2/d.o.f.		1.9	1.4	2.0

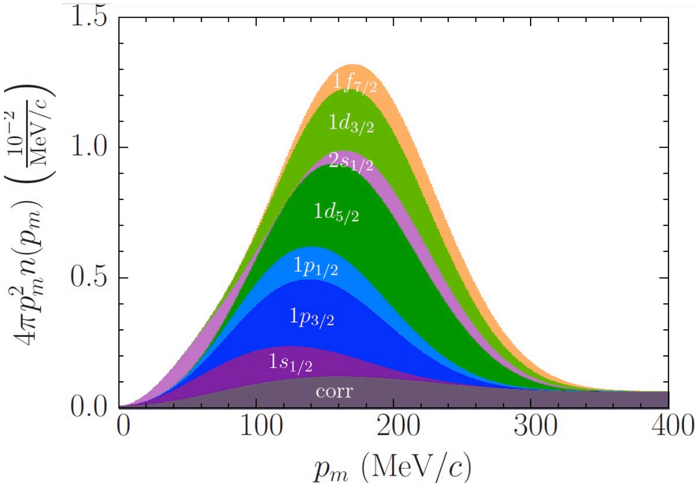
	E_α (MeV)		σ_α (MeV)	
α	w/ priors	w/o priors	w/ priors	w/o priors
$1d_{3/2}$	12.53 ± 0.02	10.90 ± 0.12	1.9 ± 0.4	1.6 ± 0.4
$2s_{1/2}$	12.92 ± 0.02	12.57 ± 0.38	3.8 ± 0.8	3.0 ± 1.8
$1d_{5/2}$	18.23 ± 0.02	17.77 ± 0.80	9.2 ± 0.9	9.6 ± 1.3
$1p_{1/2}$	28.8 ± 0.7	28.7 ± 0.7	12.1 ± 1.0	12.0 ± 3.6
$1p_{3/2}$	33.0 ± 0.3	33.0 ± 0.3	9.3 ± 0.5	9.3 ± 0.5
$1s_{1/2}$	53.4 ± 1.1	53.4 ± 1.0	28.3 ± 2.2	28.1 ± 2.3
corr.	24.1 ± 2.7	24.1 ± 1.7	—	—

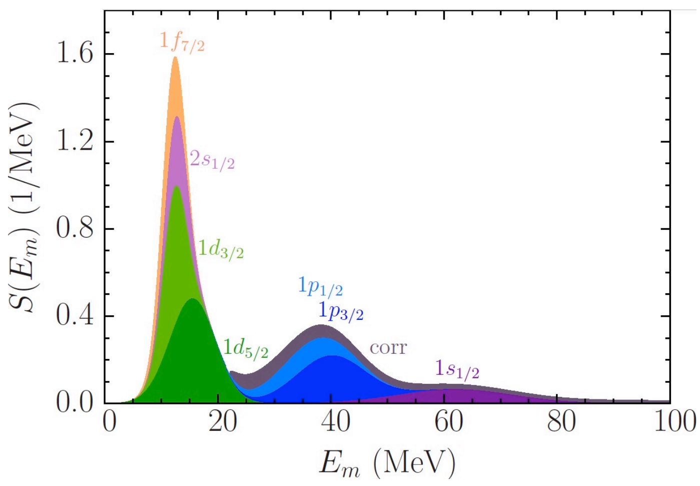
Ti (e,e'p) – arxiv: 2209.14108 - submitted to PRD



(a) Data (b) MC

Ti (e,e'p) – arxiv: 2209.14108 - submitted to PRD





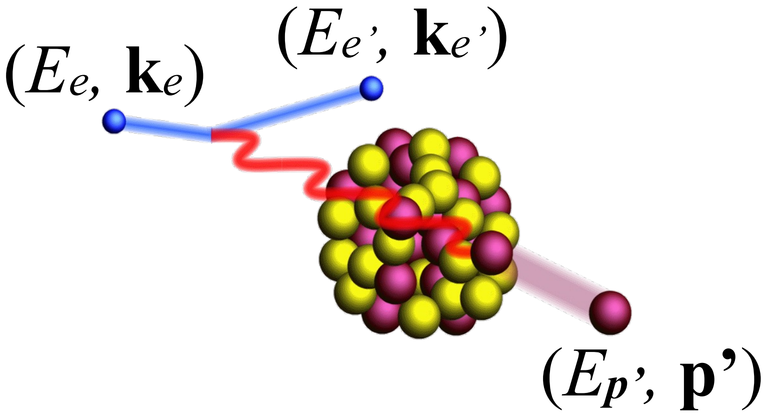
		all priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1f_{7/2}$	2	1.53 ± 0.25	1.55 ± 0.28	1.24 ± 0.22
$1d_{3/2}$	4	2.79 ± 0.37	3.15 ± 0.54	3.21 ± 0.37
$2s_{1/2}$	2	2.00 ± 0.11	1.78 ± 0.46	2.03 ± 0.11
$1d_{5/2}$	6	2.25 ± 0.16	2.34 ± 0.19	3.57 ± 0.29
$1p_{1/2}$	2	2.00 ± 0.20	1.80 ± 0.27	2.09 ± 0.19
$1p_{3/2}$	4	2.90 ± 0.20	2.92 ± 0.20	4.07 ± 0.15
$1s_{1/2}$	2	2.14 ± 0.10	2.56 ± 0.30	2.14 ± 0.11
corr.	0	4.71 ± 0.31	4.21 ± 0.46	excluded
$\sum_\alpha S_\alpha$		20.32 ± 0.65	20.30 ± 1.03	18.33 ± 0.59
d.o.f		121	153	125
χ^2/d.o.f.		0.95	0.71	1.23

	E_α (MeV)		σ_α (MeV)	
α	w/ priors	w/o priors	w/ priors	w/o priors
$1f_{7/2}$	11.32 ± 0.10	11.31 ± 0.10	8.00 ± 5.57	8.00 ± 6.50
$1d_{3/2}$	12.30 ± 0.24	12.33 ± 0.24	7.00 ± 0.61	7.00 ± 3.84
$2s_{1/2}$	12.77 ± 0.25	12.76 ± 0.25	7.00 ± 3.76	7.00 ± 3.84
$1d_{5/2}$	15.86 ± 0.20	15.91 ± 0.22	2.17 ± 0.27	2.23 ± 0.29
$1p_{1/2}$	33.33 ± 0.60	33.15 ± 0.65	3.17 ± 0.45	3.03 ± 0.48
$1p_{3/2}$	39.69 ± 0.62	39.43 ± 0.68	5.52 ± 0.70	5.59 ± 0.70
$1s_{1/2}$	53.84 ± 1.86	52.00 ± 3.13	11.63 ± 1.90	13.63 ± 2.59
corr.	25.20 ± 0.02	25.00 ± 0.29	—	—

Summary

- We completed the data analysis for the full data set collected by the E12-14-012 experiment at Jefferson Lab in 2017.
- Data has been published for both inclusive and exclusive analysis – 5 publications from 2017, 4 PhD thesis.
- We found reasonable parametrization for both the Ar and Ti spectral functions and reached the goal of the experiment.
- Separation of individual contributions requires improved analysis. Numerous theoretical developments are necessary. But we have data now.
- Interpretation of the Ti proton spectral function in terms of neutron spectral function on Ar is in progress, new theory development will be needed.

Missing momentum $\mathbf{p}_m$ and missing energy E_m



$$E_e + M_A = E_{e'} + E_{p'} + E^*_{A-1}$$

known

determined

$$\mathbf{k}_e + 0 = \mathbf{k}_{e'} + \mathbf{p}' + \mathbf{p}_{A-1}$$

In the absence of final state interactions

$-\mathbf{p}_{A-1} = \mathbf{p}_m$ initial proton momentum; $p_m \equiv |\mathbf{p}_m|$

$E^*_{A-1} = \sqrt{(M_A - M + E_m)^2 + \mathbf{p}_m^2}$, with excitation energy $E_m - E_{\rm thr}$