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

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for the E12-14-012 experiment

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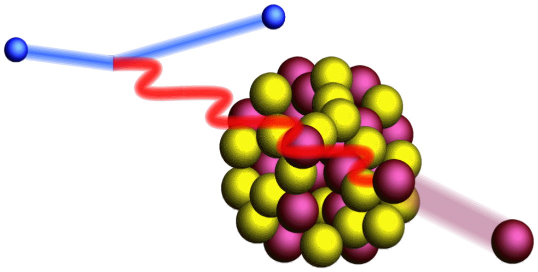
E12-14-012: (*e,e'*) and (*e,e'p*) on Ar and Ti

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]



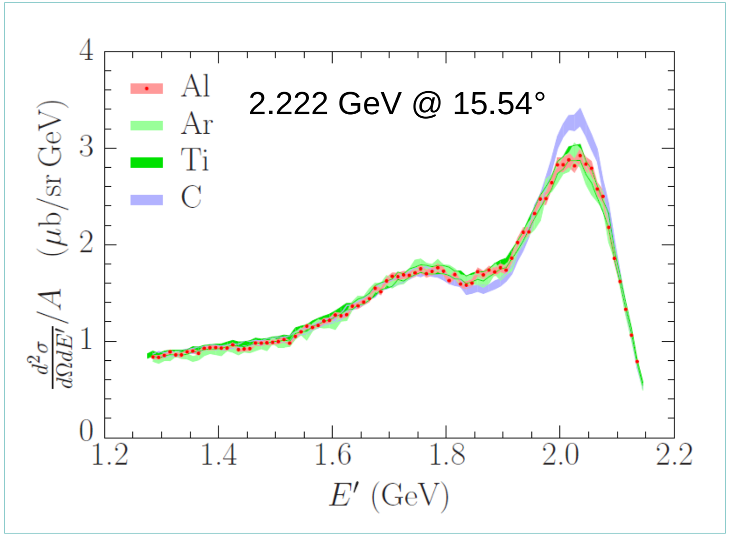
$E_e = 2.222$ GeV

	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

First, exploratory analysis of the full dataset

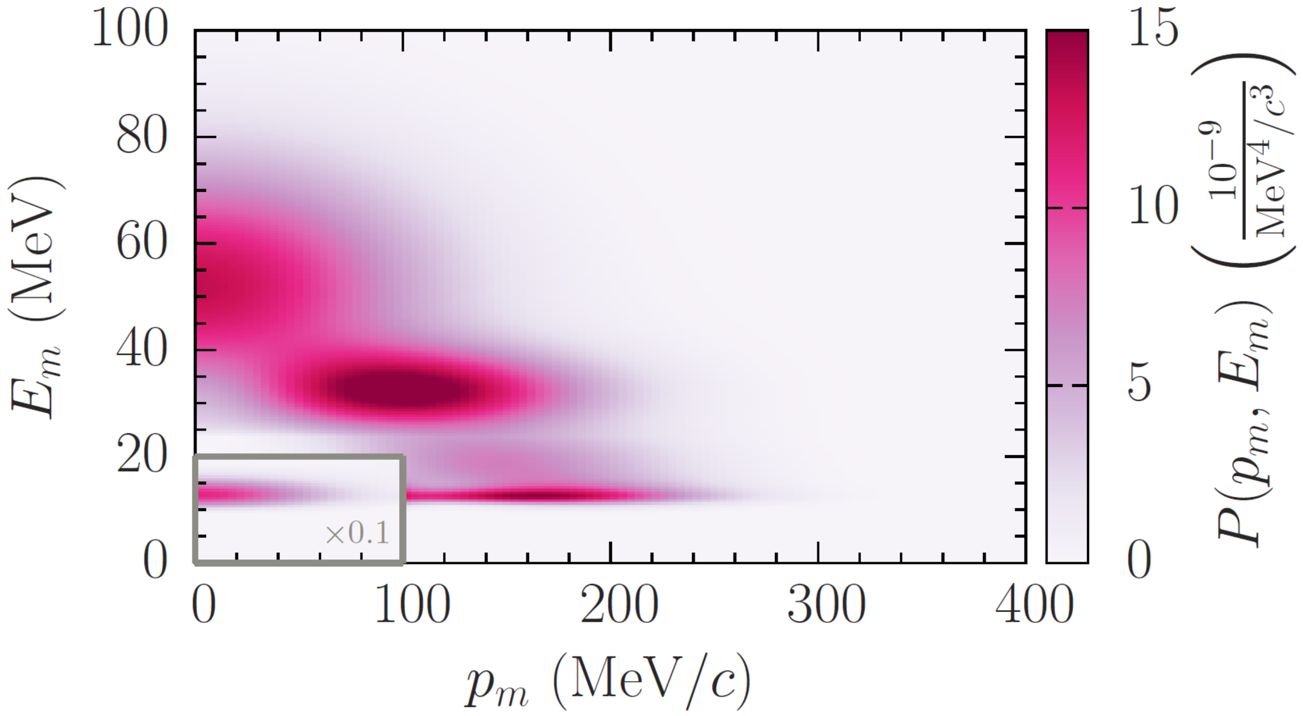
Previous results

- 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,
  A-, *y*- ,*ψ*-scaling of all (*e*,*e'*) data
  [Murphy *et al.*, PRC 100, 054606 (2019)]



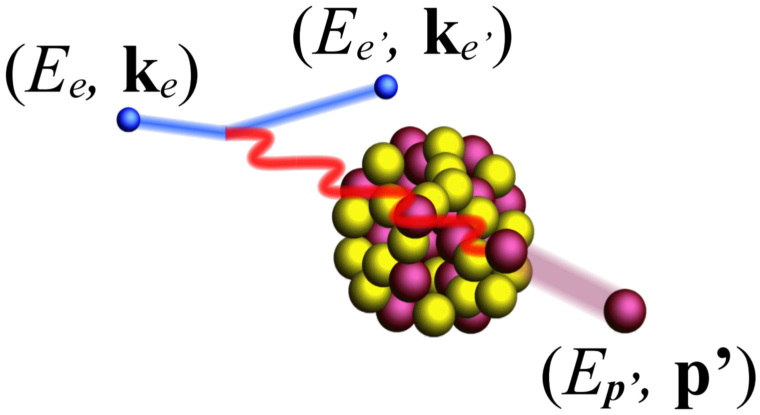
- Exclusive Ar & Ti cross sections for a single kinematics, p_m ~ 50–60 MeV, E_m ~ 50–70 MeV [Gu *et al.*, PRC 103, 034604 (2021)]

This analysis: extraction of the spectral function



Universal property of the nucleus, independent of the interaction.

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



Without final-state interactions,

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

known

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

$E_m - E_{\mathrm{thr}}$ is the excitation energy of ^{39}Cl

$p_m \equiv |\mathbf{p}_m|$ is the initial proton momentum

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

elementary cross section

nuclear transparency

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

spectral function

Analysis procedure

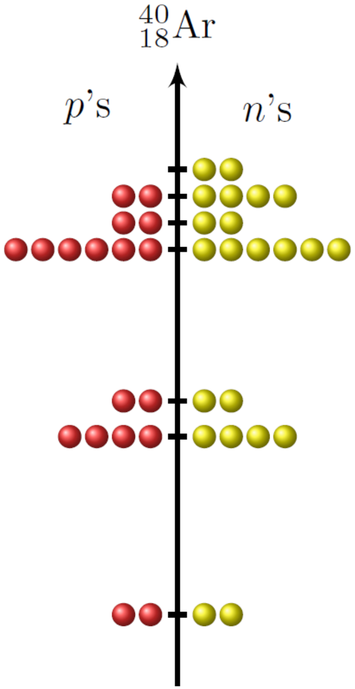
1) Extract of the (*e,e'p*) cross section

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.

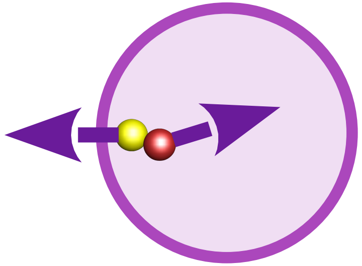
4) Using the priors from Step 3), find the parameters of the spectral function (*i.e.*, spectroscopic factors, peak positions, distribution widths) from the fits to the reduced cross sections as a function of E_m.

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

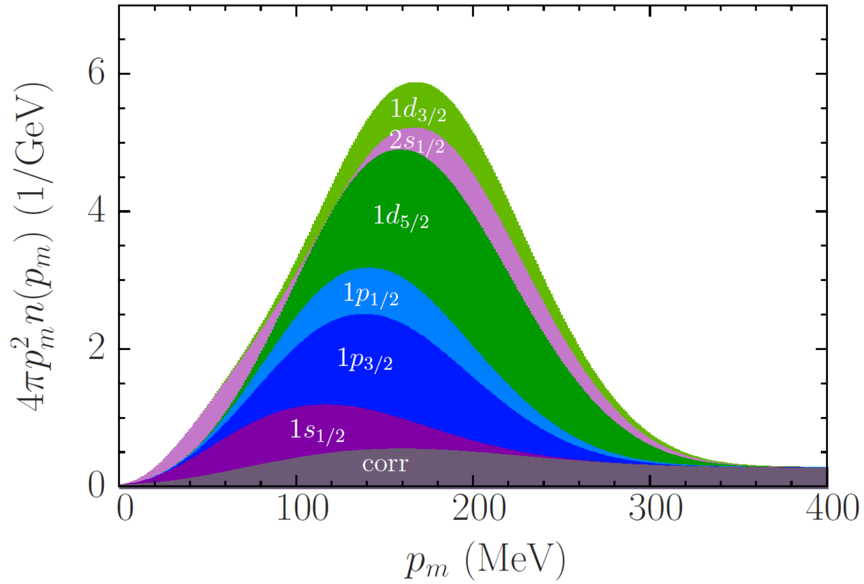
spectroscopic factor

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

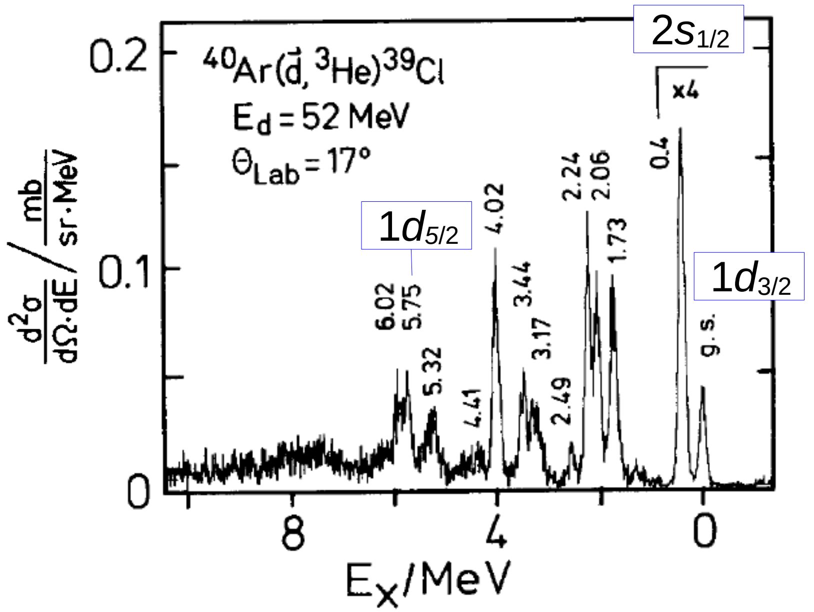


Mean-field part of the spectral function

α	S_α	E_α (MeV)
$1d_{3/2}$	1.6	12.53
$2s_{1/2}$	1.6	12.93
$1d_{5/2}$	4.8	18.23
$1p_{1/2}$	1.6	28.0
$1p_{3/2}$	3.2	33.0
$1s_{1/2}$	1.6	52.0

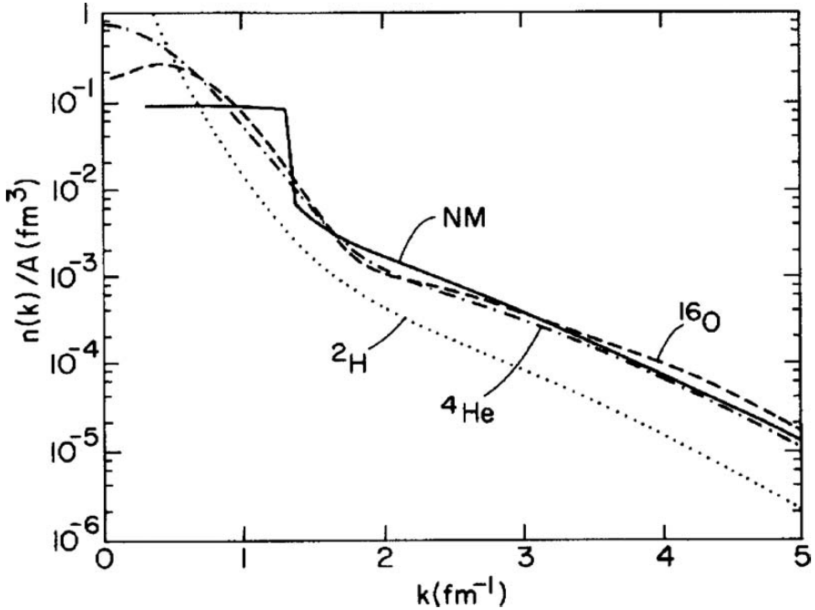
- $1d_{3/2}$: from the mass difference between ^{40}Ar and ^{39}Cl + p + e
- $2s_{1/2}$ and $1d_{5/2}$: from the dominant contribs. in the past ^{40}Ar(d, ^{3}He)^{39}Cl measurements
- Lower levels were not probed with deuteron
- Assumed Gaussian distribution

Mairle *et al.*, NPA **565**, 543 (1993)



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

p_m fit results

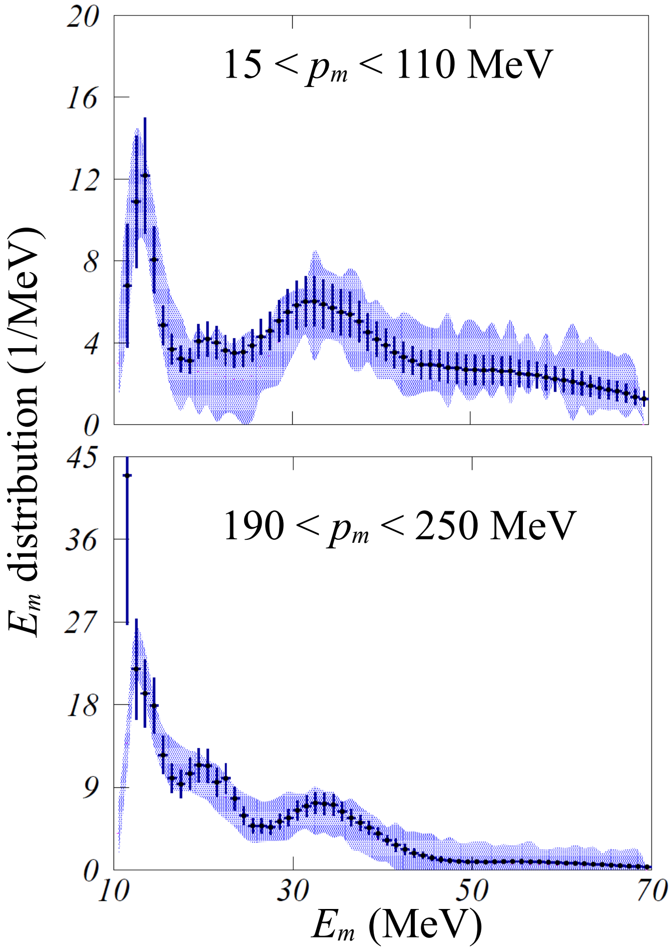
		w/ corr.	w/o corr.
α	N_α	S_α	
$1d_{3/2}$	2	0.78 ± 0.05	0.78 ± 0.09
$2s_{1/2}$	2	2.07 ± 0.07	2.10 ± 0.10
$1d_{5/2}$	6	2.27 ± 0.04	2.27 ± 0.08
$1p_{1/2}$	2	2.72 ± 1.23	2.72 ± 0.34
$1p_{3/2}$	4	3.36 ± 0.04	3.53 ± 0.06
$1s_{1/2}$	2	2.54 ± 0.04	2.65 ± 0.02
corr.	0	0.48 ± 0.01	excluded
$\sum_\alpha S_\alpha$		14.48 ± 1.24	14.05 ± 0.38
d.o.f.		1,132	1,133
χ^2/d.o.f.		1.9	3.2

In the p_m fit, only deeply bound states are sensitive to the correlated spectral function.

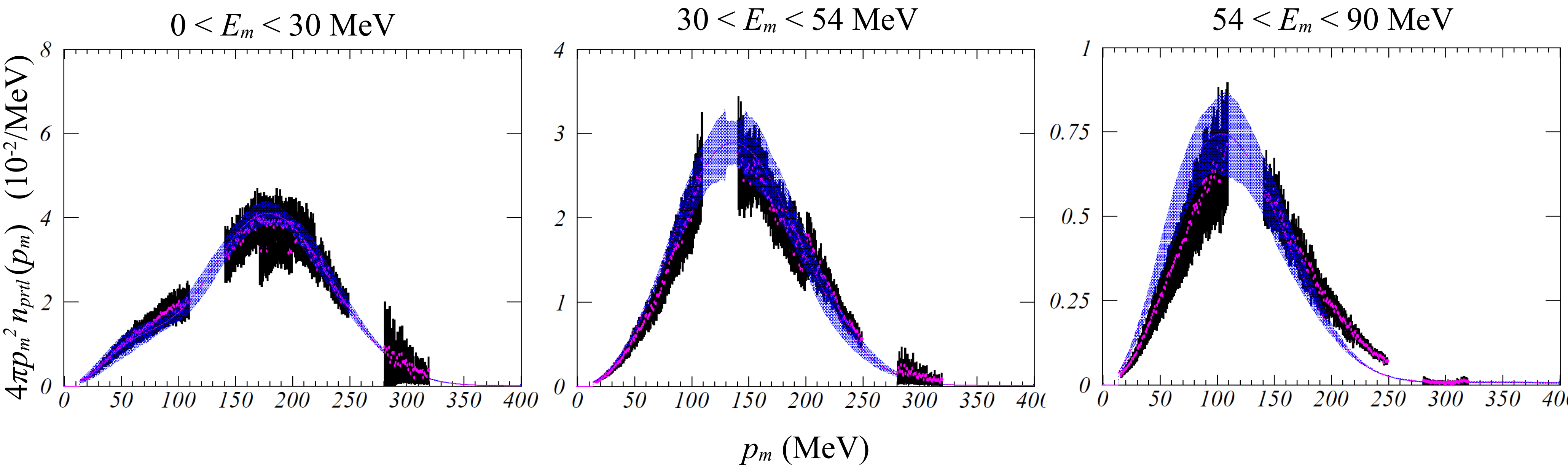
E_m fit results

		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	—	—



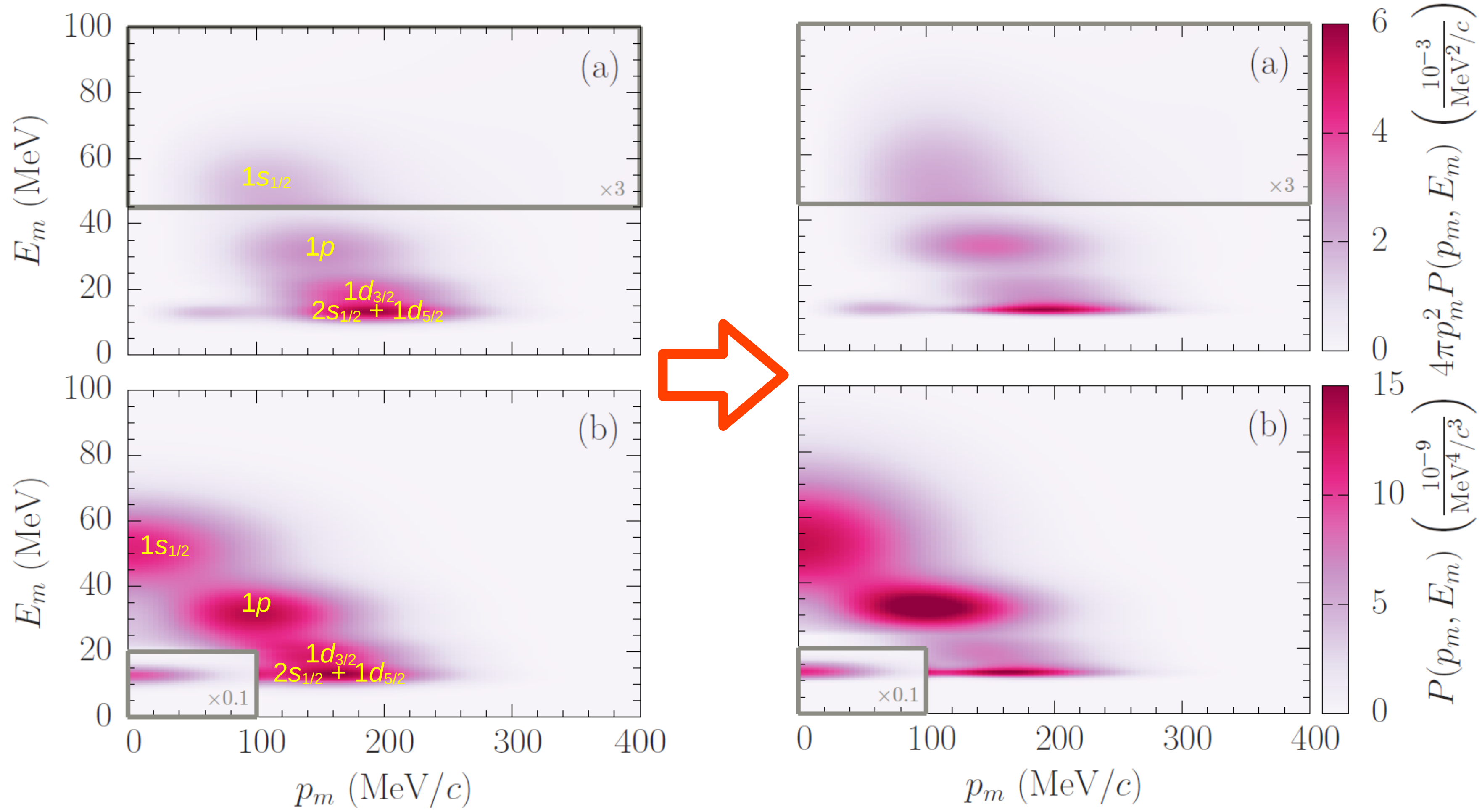
E_m fit results

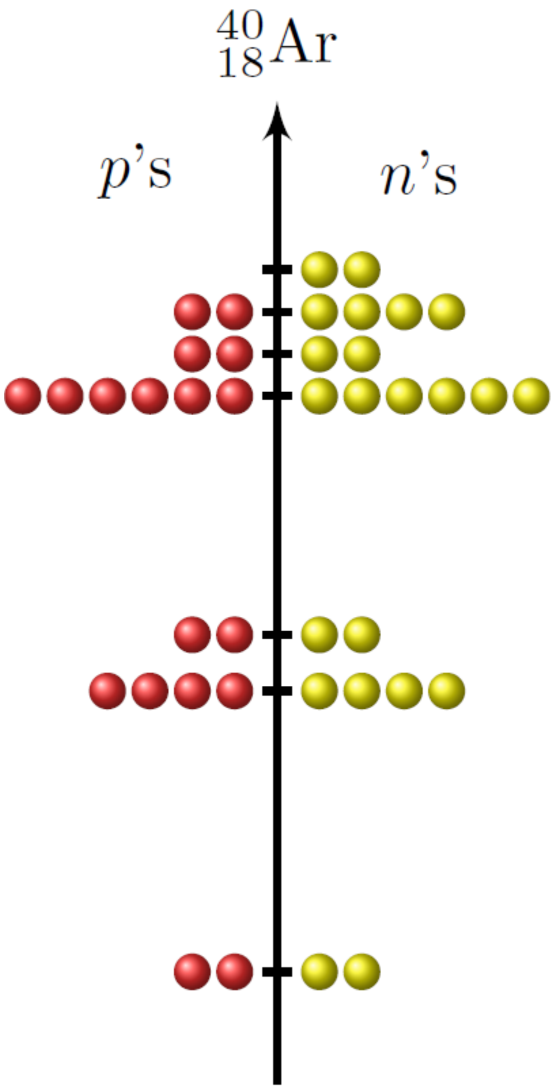


Data from different kinematics are consistent within uncertainties.

Test spectral function

Extracted spectral function



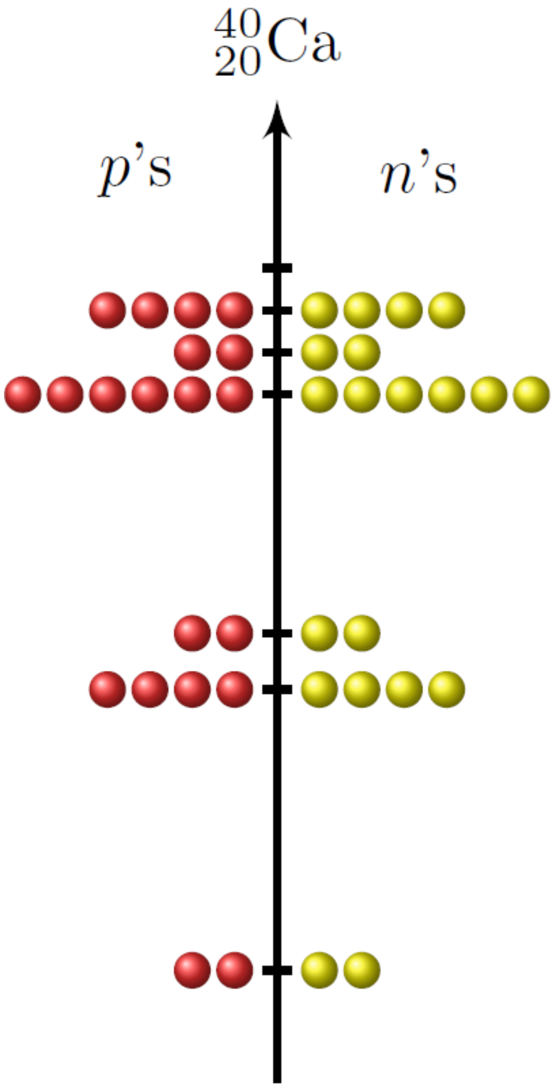


proton energy levels

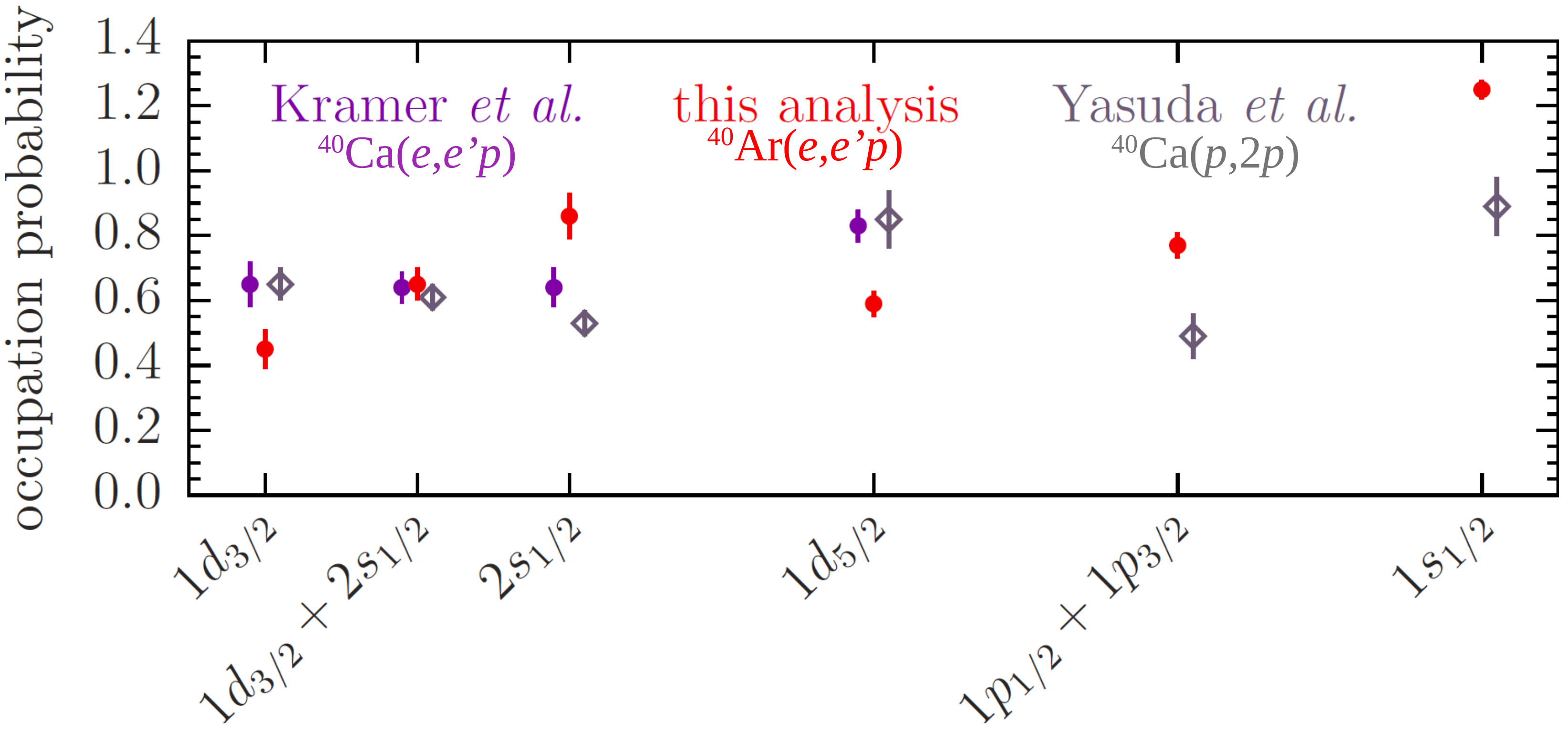
Ar		Ca
12.53	1d3/2	8.5
12.92	2s1/2	11.0
18.23	1d5/2	15.7
28.8	1p1/2	29.8
33.0	1p3/2	34.7
53.3	1s1/2	53.6

This analysis

Volkov *et al.*
SJNP 52, 848 (1990)



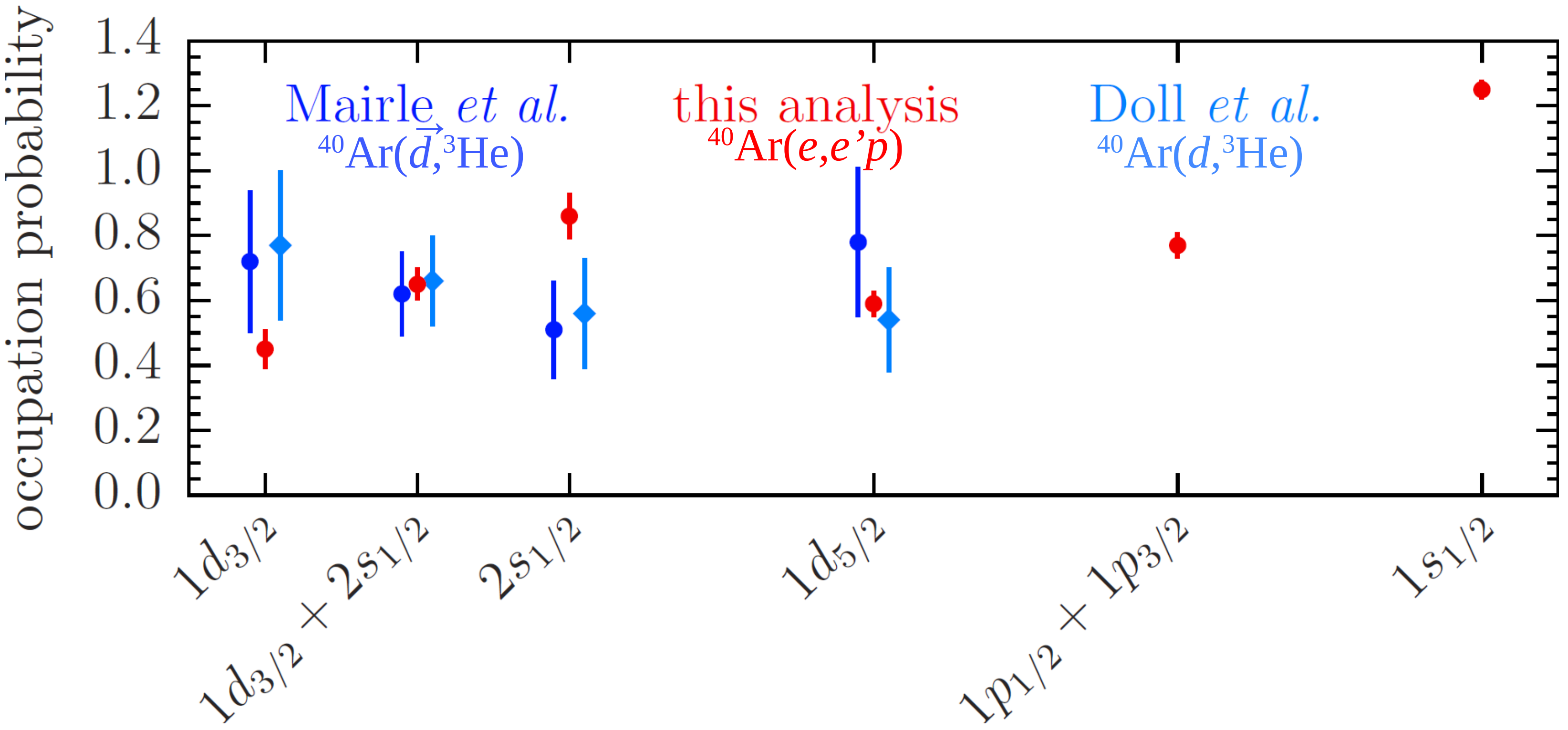
Occupation probability



Kramer *et al.* [Ph.D. thesis (1990)]: ~340–440-MeV electron beam at NIKHEF-K

Yasuda *et al.* [Ph.D. thesis (2012)]: 392-MeV polarized proton beam at RCNP

Occupation probability



52-MeV polarized [Mairle *et al.*, NPA **565**, 543 (1993); E_x < 9 MeV] and unpolarized [Doll *et al.*, NPA **230**, 329 (1974); **129**, 469 (1969); E_x < 7 MeV] deuteron beam at Karlsruhe

Kramer *et al.* [NPA **679**, 267 (2001)]: reanalysis of (d,^{3}He) experiments, $S_\alpha \rightarrow S_\alpha/1.5$

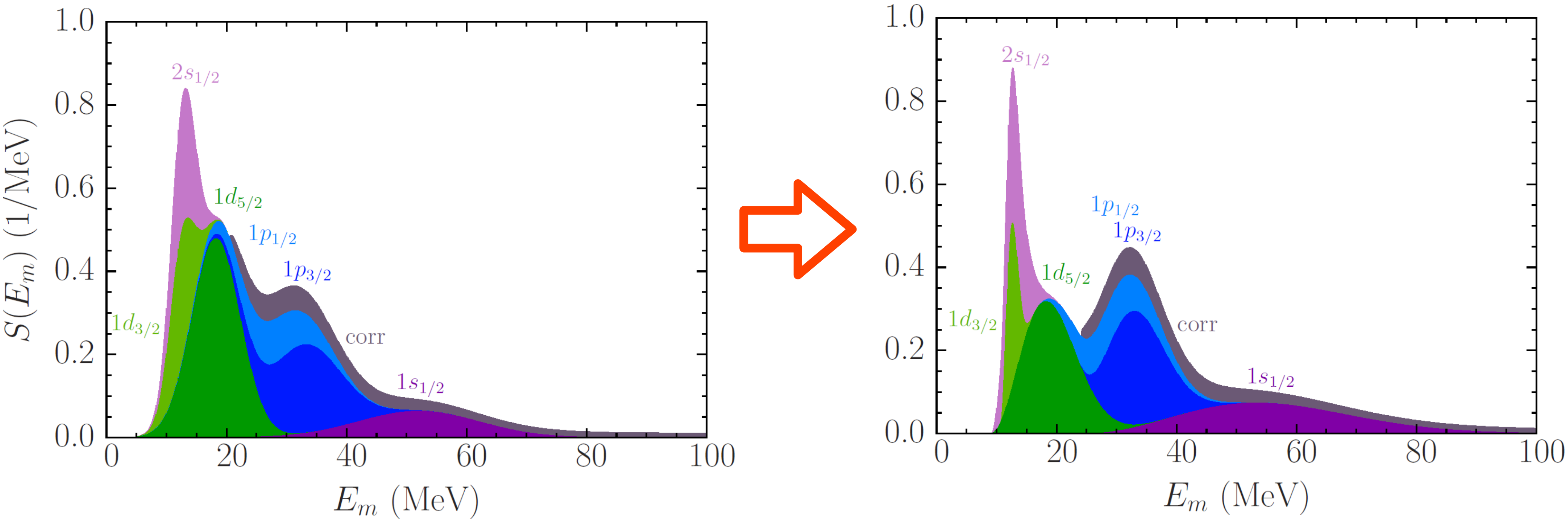
Directions for future improvements

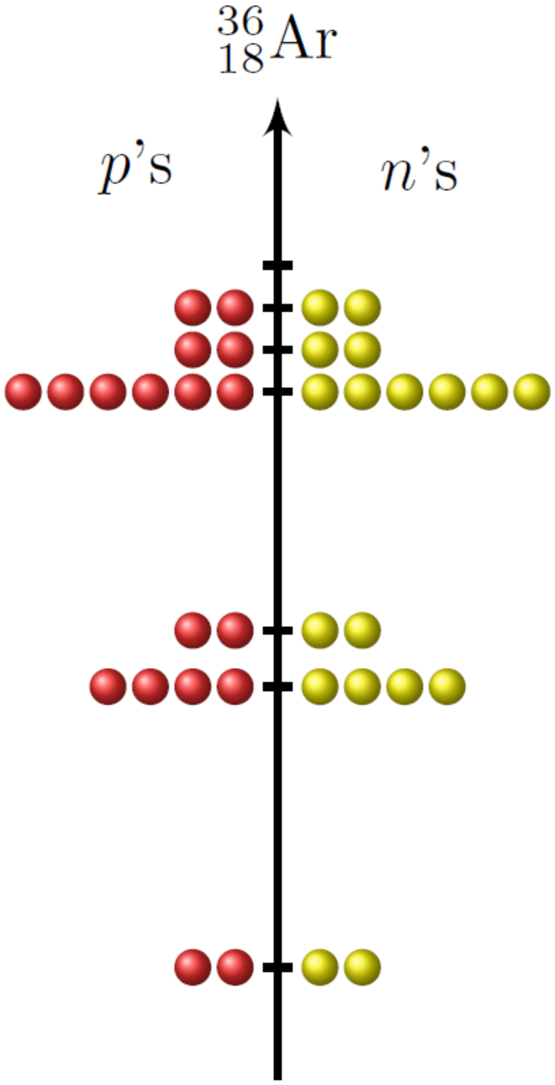
- 2D analysis
- Final-state interactions
- Wave functions
- Correlated part of the spectral function

Summary

- The first, exploratory analysis of the full dataset.
- Reasonable parametrization of the spectral function of ^{40}Ar is found.
- Comparison with past results shows strengths and limitations.
- Separation of individual contributions requires improved analysis. Numerous theoretical developments are necessary.

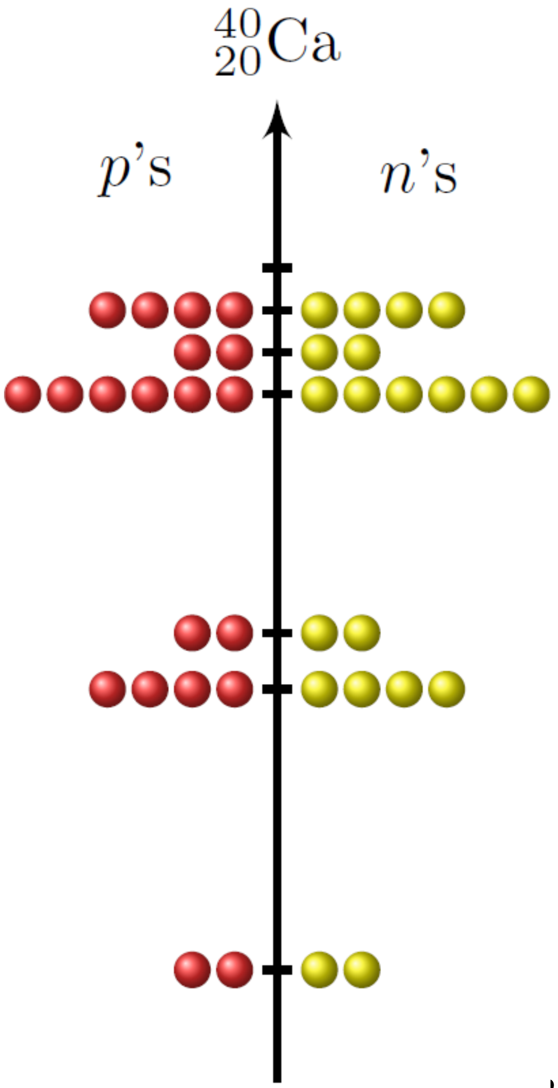
Backup


1.0
0.8
0.6
0.4
0.2
0.0
$S(E_m)$ (1/MeV)
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1d_{3/2}$
corr
$1s_{1/2}$
0
20
40
60
80
100
E_m (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
$2s_{1/2}$
$1p_{1/2}$
$1p_{3/2}$
$1d_{5/2}$
$1d_{3/2}$
corr
$1s_{1/2}$
0
20
40
60
80
100
E_m (MeV)



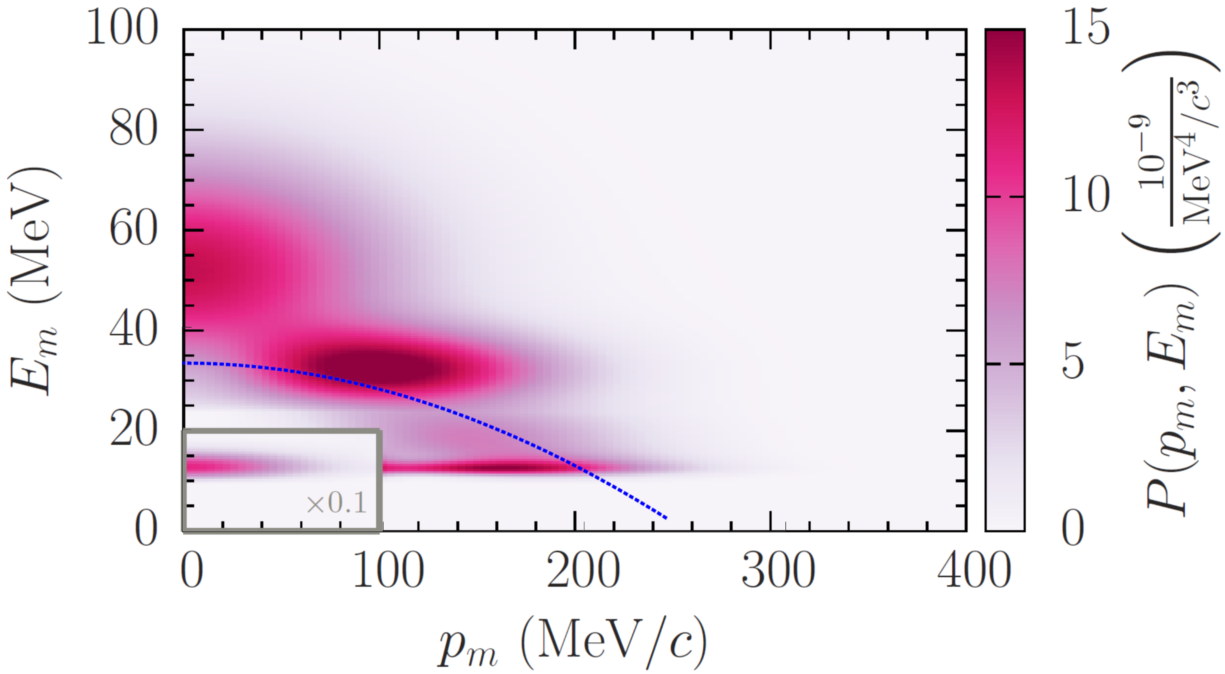
proton energy levels

Ar		Ca
8.51	1d3/2	8.33
9.73	2s1/2	10.85
	1d5/2	
	1p1/2	
	1p3/2	
	1s1/2	



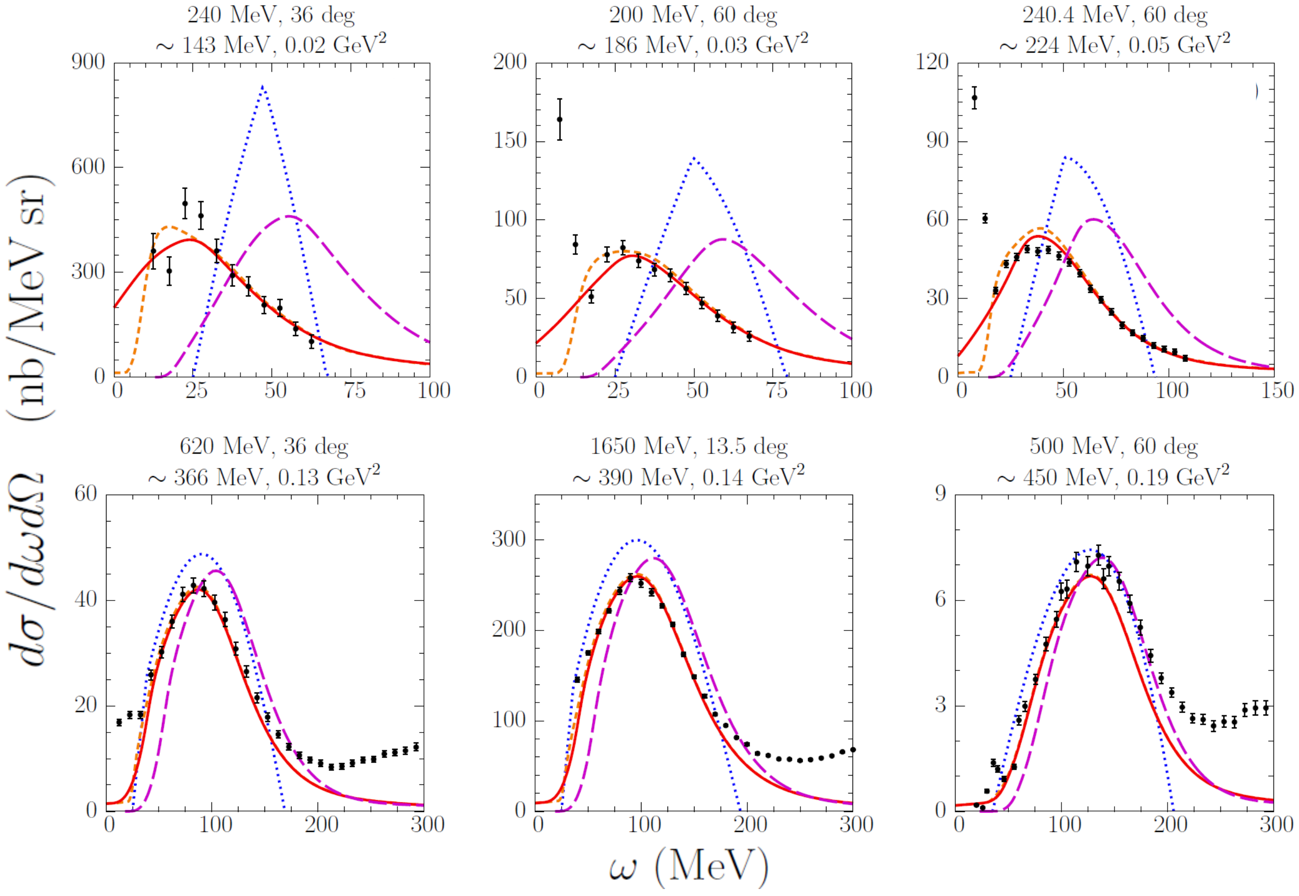
Realistic description of the nucleus

Fermi gas vs. spectral function



see e.g. L. Gu et al., PRC 103, 034604 (2021)

Realistic description of the nucleus



A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

Occupation probability

	This analysis	^{40}Ca($e,e'p$) Kramer *et al.*	^{40}Ca($\vec{p},2p$) Yasuda *et al.*
1d3/2 + 2s1/2	0.65 ± 0.05	0.64 ± 0.05	0.61 ± 0.04
1d3/2	0.45 ± 0.06	0.65 ± 0.07	0.65 ± 0.05
2s1/2	0.86 ± 0.07	0.64 ± 0.06	0.53 ± 0.04
1d5/2	0.59 ± 0.04	0.83 ± 0.05	0.85 ± 0.09
1p1/2 + 1p3/2	0.77 ± 0.04		0.49 ± 0.07
1s1/2	1.25 ± 0.03		0.89 ± 0.09

Kramer *et al.* [Ph.D. thesis (1990)]: ~340–440-MeV electron beam at NIKHEF-K

Yasuda *et al.* [Ph.D. thesis (2012)]: 392-MeV polarized proton beam at RCNP

Occupation probability

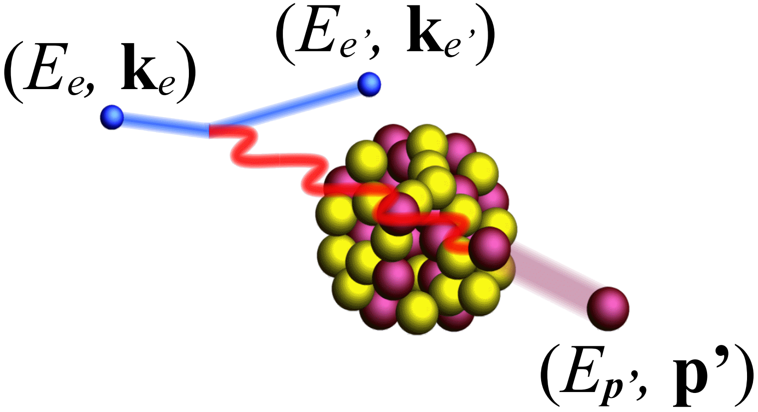
	This analysis	^{40}Ar($\vec{d}$,^{3}He) Mairle *et al.*	^{40}Ar(*d*,^{3}He) Doll *et al.*
1d3/2 + 2s1/2	0.65 ± 0.05	0.62 ± 0.13	0.66 ± 0.14
1d3/2	0.45 ± 0.06	0.72 ± 0.22	0.77 ± 0.23
2s1/2	0.86 ± 0.07	0.51 ± 0.15	0.56 ± 0.17
1d5/2	0.59 ± 0.04	0.78 ± 0.23	*0.54 ± 0.16*

Mairle *et al.* [NPA **565**, 543 (1993)]: 52-MeV polarized deuteron beam at Karlsruhe

Doll *et al.* [NPA **230**, 329 (1974); **129**, 469 (1969)]: 52-MeV deuteron beam at Karlsruhe (E_x < 7 MeV vs. 9 MeV in Mairle *et al.*, the 1d5/2 shell not fully probed)

Kramer *et al.* [NPA **679**, 267 (2001)]: reanalysis of (*d*,^{3}He) experiments, $S_\alpha \rightarrow S_\alpha/1.5$

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



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

known determined

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

In the absence of final state interactions

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

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