Towards accurate neutrino cross sections: the argon and titanium spectral functions from (*e,e'p*) data

Artur M. Ankowski
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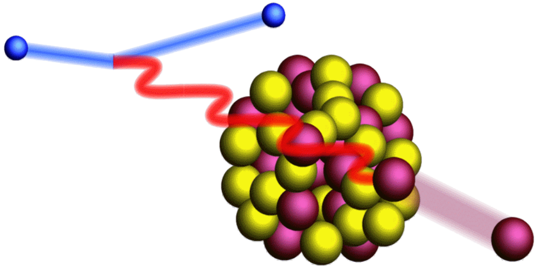
based on L. Jiang *et al.*,
PRD 105, 112002 (2022); PRD 107, 012005 (2023)

Neutrino scattering at Low and Intermediate Energies
Mainz Institute for Theoretical Physics, June 26–30, 2023

E12-14-012 in JLab: (*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

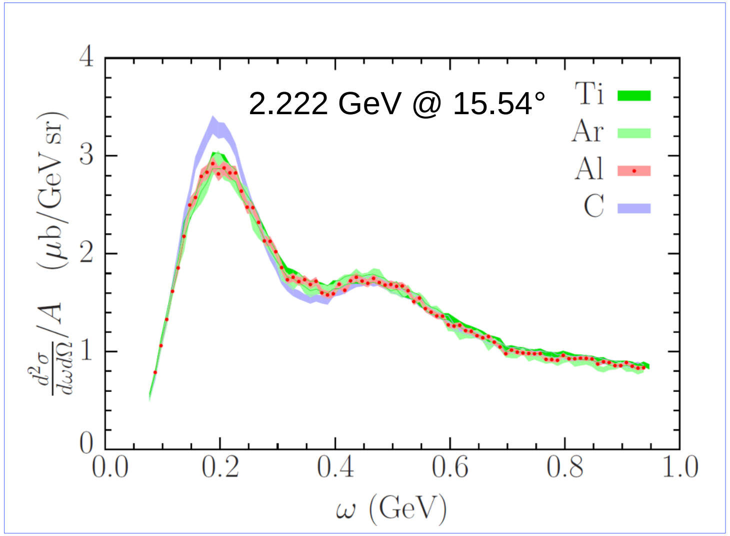
First, exploratory analyses of the full datasets

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)]

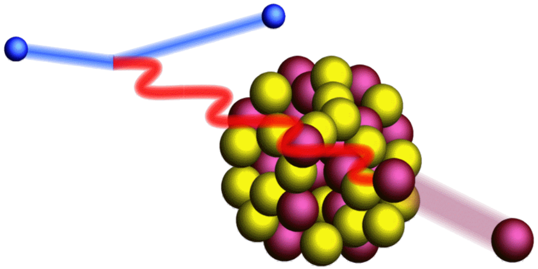
- Inclusive cross section for Al-7075,
  A-, *y*- ,*ψ*-scaling of all (*e,e'*) data
  [Murphy *et al.*, PRC 100, 054606 (2019)]



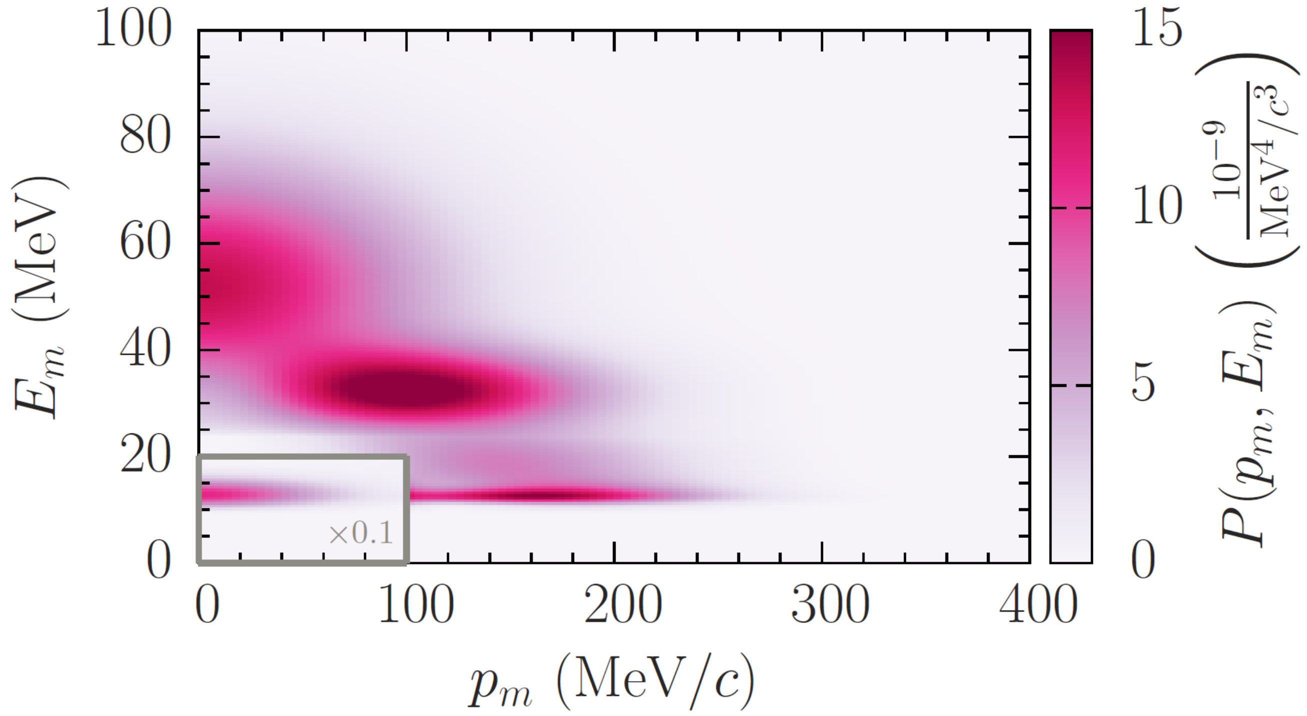
- Exclusive Ar & Ti cross sections for a single kinematics, p_m ~ 50–60 MeV, E_m ~ 50–70 MeV [Gu *et al.*, PRC 103, 034604 (2021)]

This analysis: extraction of the spectral function

The proton spectral function $P(p_m, E_m)$ describes the probability distribution of removing a proton of momentum p_m from the target nucleus, leaving the residual system with excitation energy $E_m - E_{thr}$, with E_{thr} being the proton emission threshold.



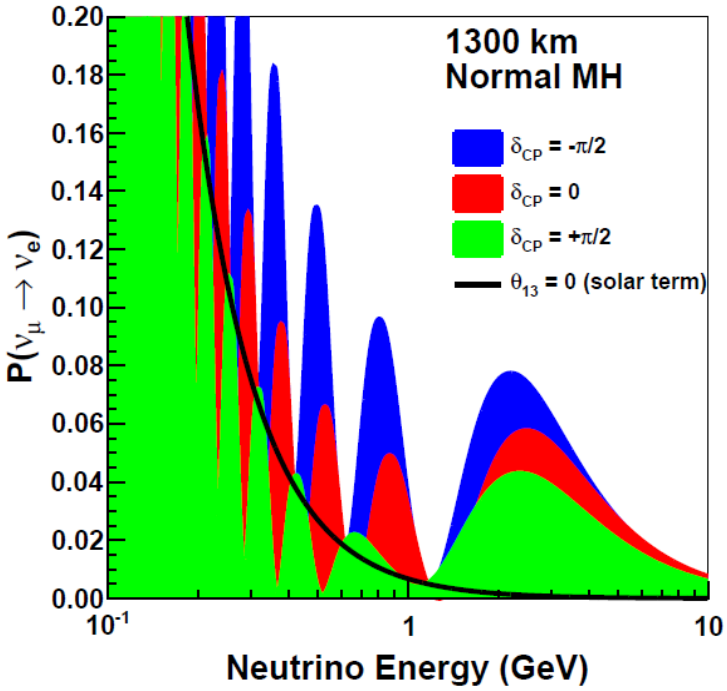
This analysis: extraction of the spectral function



Universal property of the nucleus, independent of the interaction.

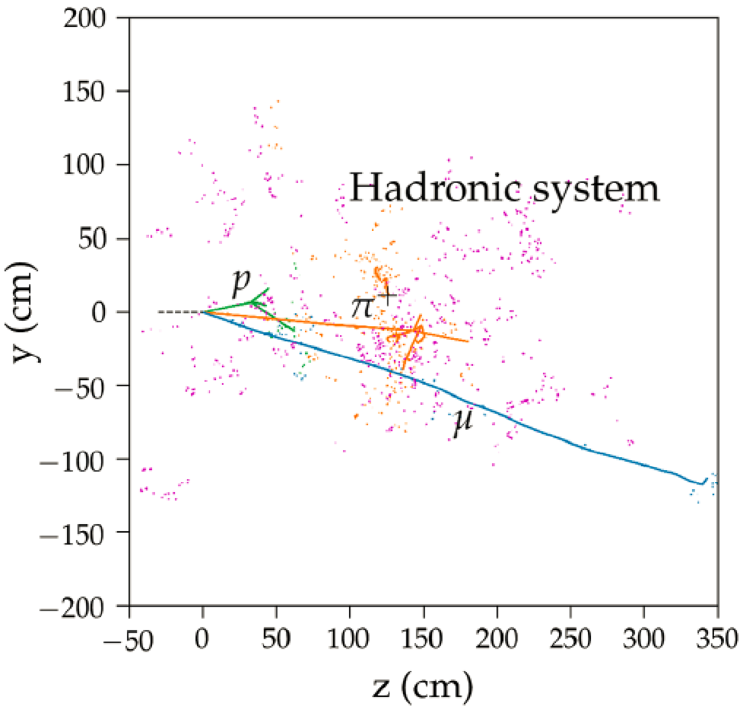
MC Generators in long-baseline neutrino physics

- Main goal: extract the ν & $\bar{\nu}$ oscillation probabilities.
- Polychromatic beams, neutrino energy reconstructed from visible energy deposited by interaction products.
- Calorimetric reconstruction of neutrino energy.
- Sizable contributions of hadrons. Neutrons' energy estimate heavily dependent on Monte Carlo.
- Accuracy of simulations translates into the accuracy of the extracted oscillation parameters.
- We are no longer after $\mathcal{O}$ (1) effects, **without reliable cross sections precise measurements cannot succeed.**



DUNE Collaboration, arXiv:1512.06148

GENIE+FLUKA simulation of a 4-GeV ν_μAr event



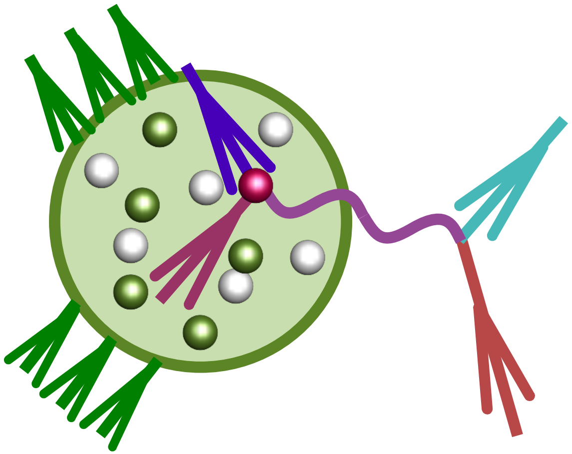
A. Friedland & S.W. Li, PRD 99, 036009 (2019)

Multiply differential cross sections required for energy reconstruction.

Impulse approximation

To calculate the neutrino-argon cross sections we need to know

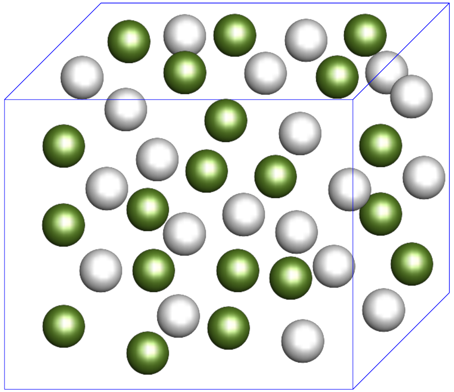
- elementary cross sections (QE, resonant pion production, DIS ...)
- proton and neutron spectral functions (shell structures, correlations between nucleons)
- final-state interactions (nuclear transparency, optical potentials)
- hadronization



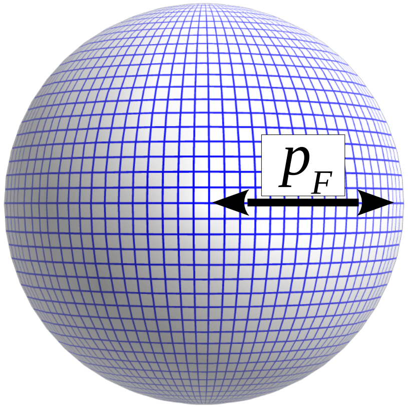
Fermi gas

Nucleus treated as a fragment of non-interacting infinite nuclear matter of constant density.

Eigenstates have definite momenta and energies $E_p = \sqrt{M^2 + \mathbf{p}^2} - \epsilon$.

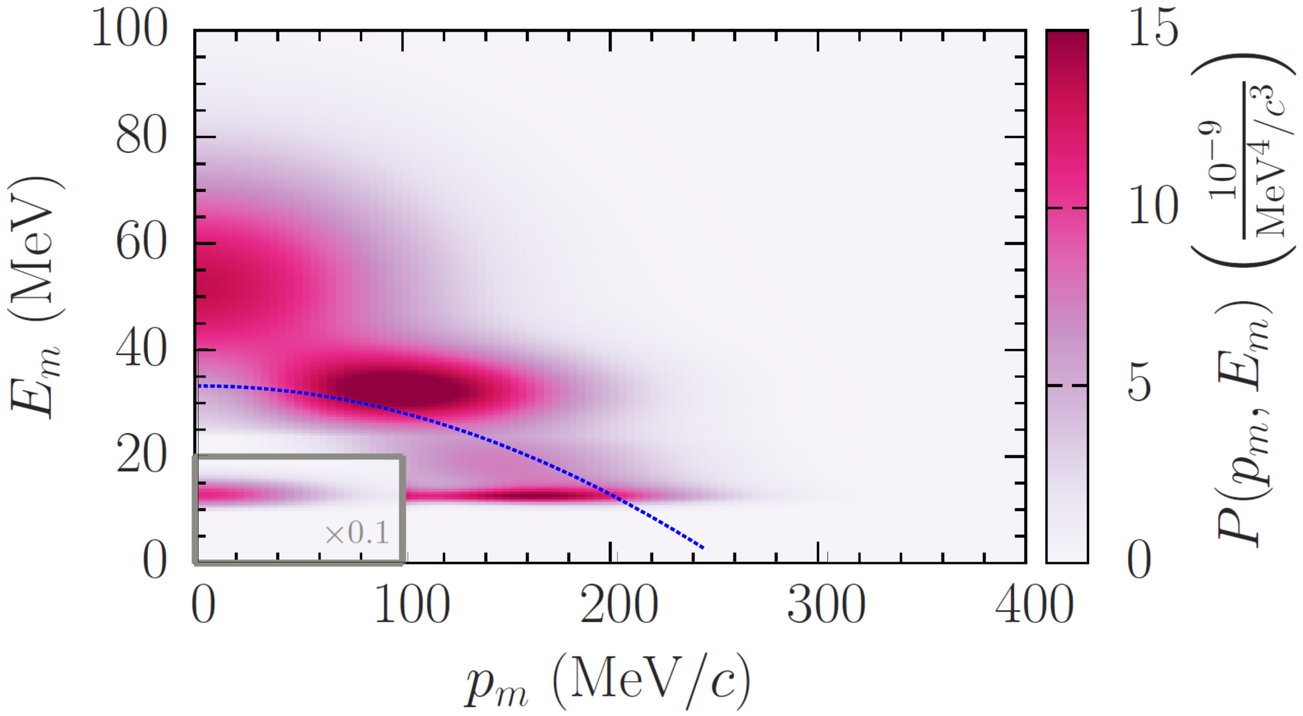


Coordinate space

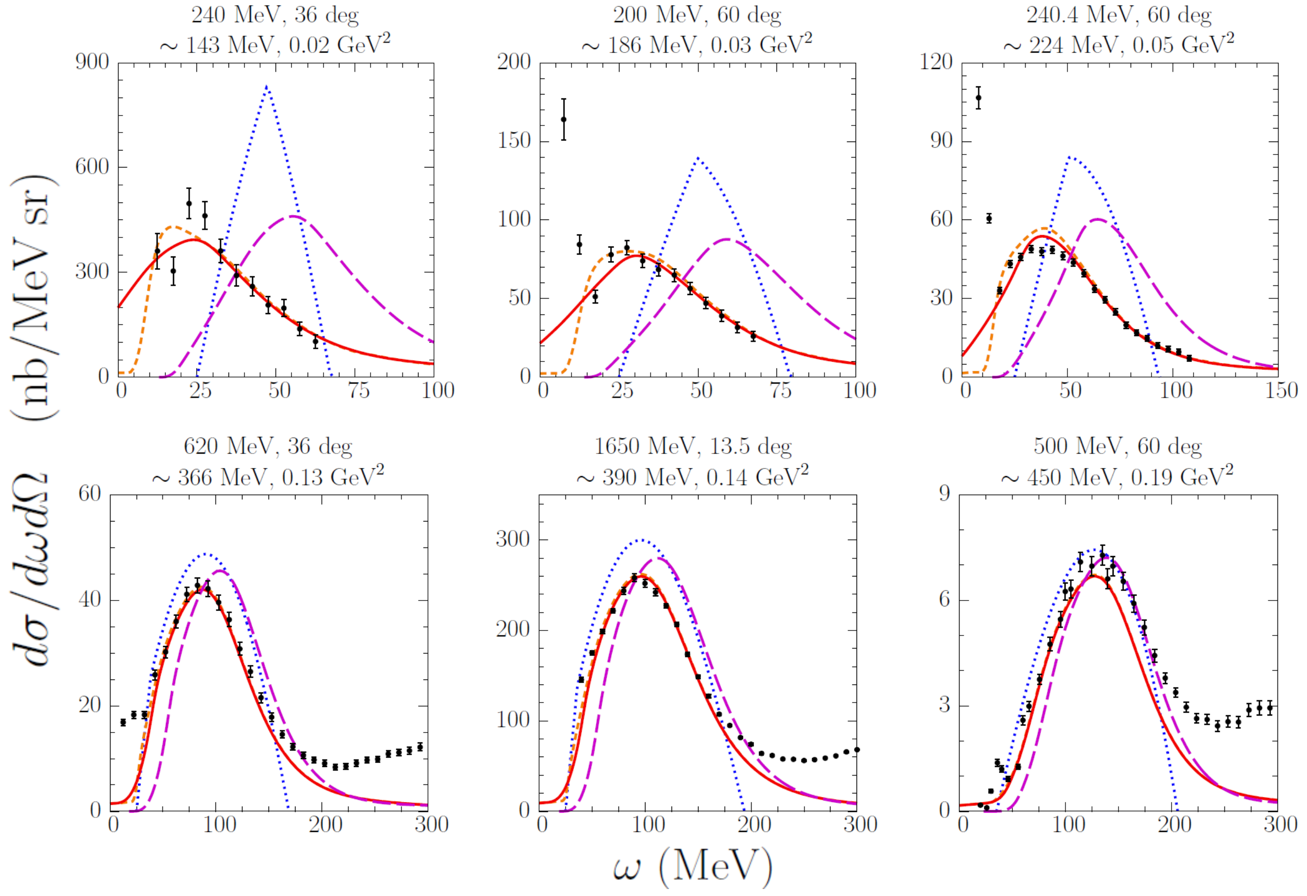


Momentum space

Fermi gas vs. spectral function



Realistic description of the nucleus: C(*e*,*e'*)



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

2.L

Nuclear Physics **31** (1962) 139—151; © *North-Holland Publishing Co., Amsterdam*

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QUASI-FREE ELECTRON-PROTON SCATTERING (I)

GERHARD JACOB † and TH. A. J. MARIS ††

Instituto de Física and Faculdade de Filosofia, Universidade do Rio Grande do Sul, Pôrto Alegre, Brasil

Received 6 July 1961

"… quasi-free **(e,e′p) scattering should offer a clear advantage over the (p,2p) processes**. … In a quasi-free (e,e′p) scattering event only the outgoing proton has an appreciable chance of being absorbed in the nucleus. Therefore surface interactions are much less accentuated than in the (p,2p) scattering and **the contributions of the inner shells relatively to those of the upper shell will be much larger**, especially for medium or heavy nuclei."

"The electron-proton angular correlation distributions would, for light and medium nuclei, nearly directly give **the momentum distributions of the separate shells**."

2.L

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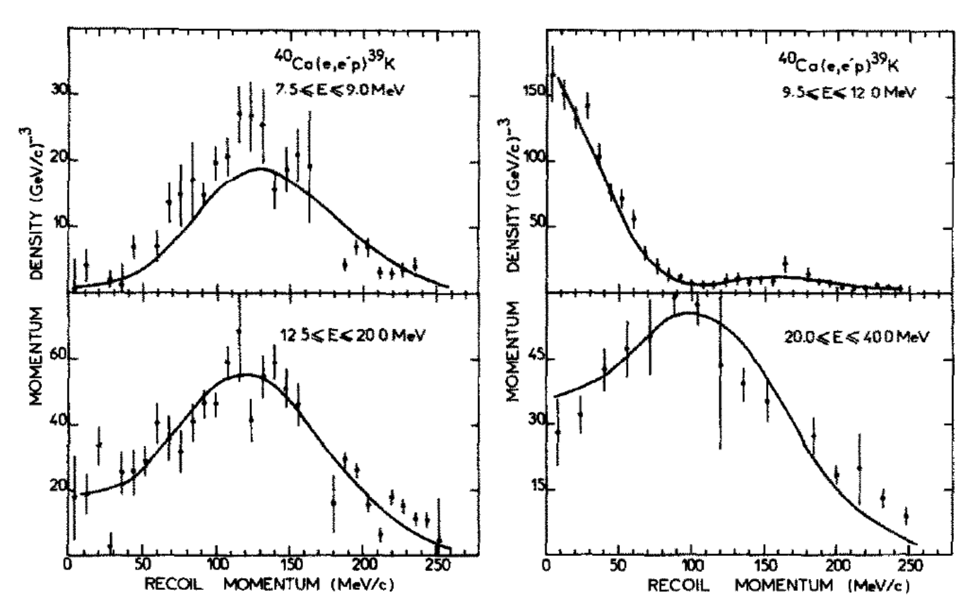
"One should, however, not forget that the negligible absorption of a high energy electron in the nucleus is caused by the weakness of the electromagnetic interaction. This same fact results in **small absolute cross sections for the quasi-free events, which make the experiments difficult, though not out of question**."

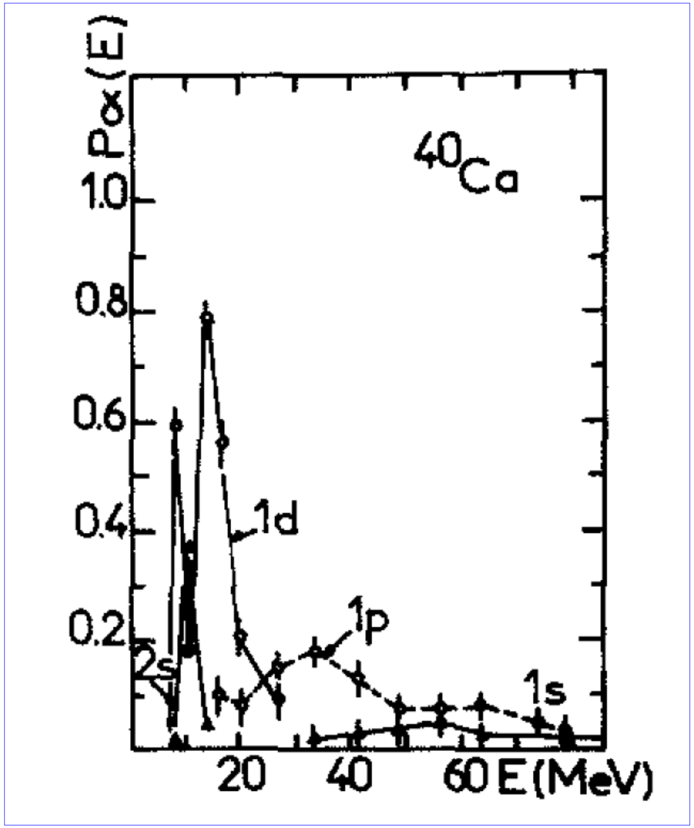
"Observed high momentum components might give indications of the **deviations from the single particle model**."

"Thanks are due to Professors R. Hofstadter and J. A. McIntyre whose comments on the experimental feasibility of the relevant measurements made us start this work."

^{40}Ca(e,$e'p$) in Saclay

- Beam energy ~500 MeV
- $0 \leq p_m \leq 250$ MeV, resolution 8 MeV
- $0 \leq E_m \leq 80$ MeV, resolution 1.2 MeV

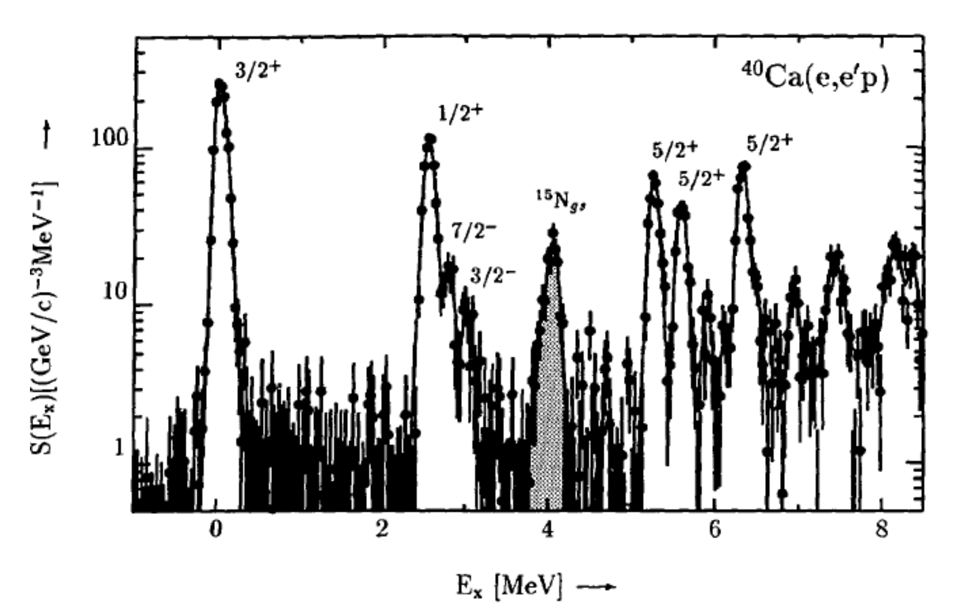


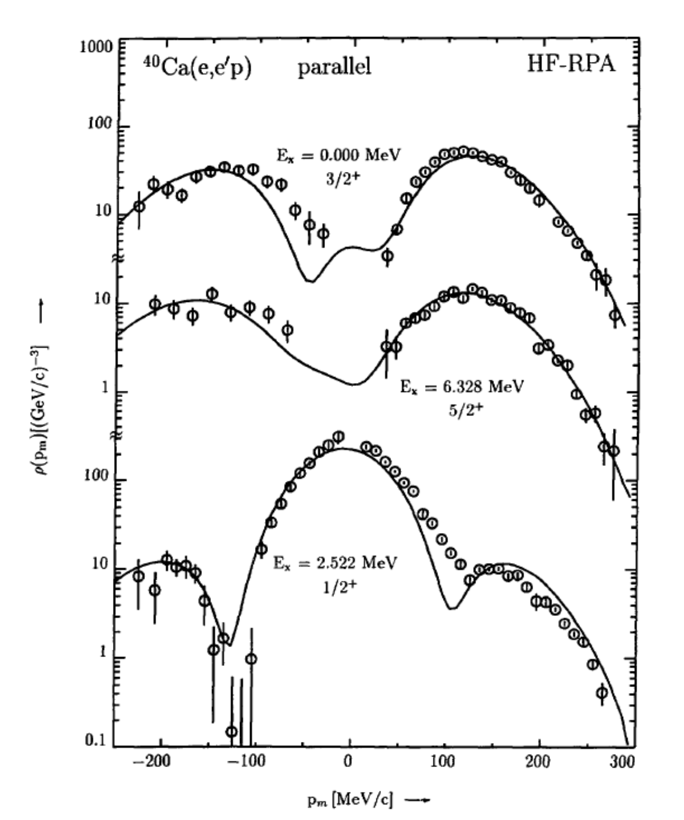


Mougey *et al.*, NPA PLB 262, 461 (1976)

^{40}Ca($e,e'p$) in NIKHEF-K

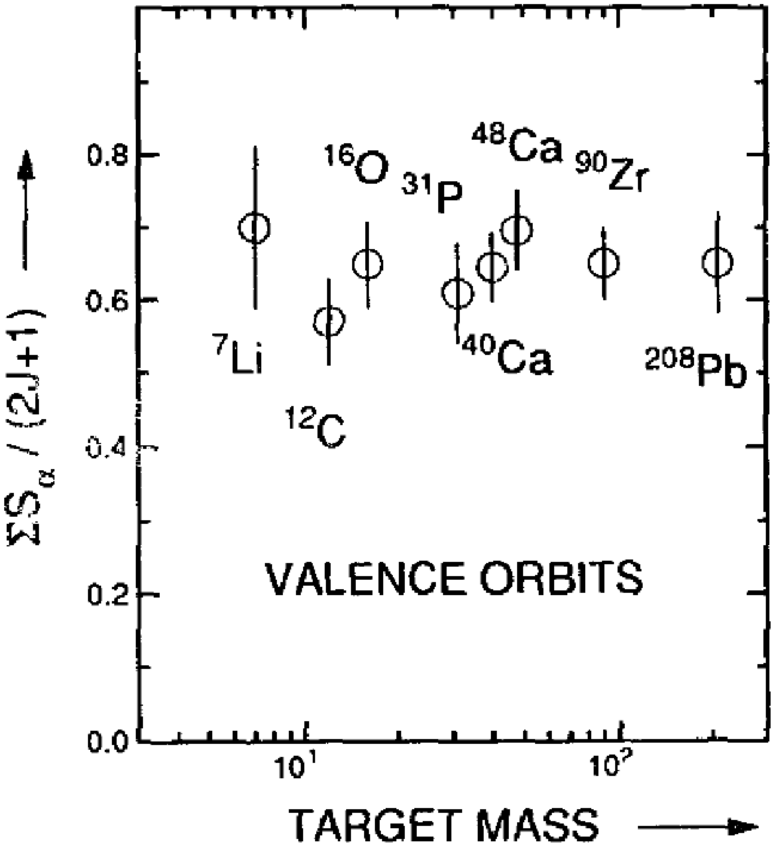
- Beam energies ~340–440 MeV
- $0 \leq p_m \leq 280$ MeV, resolution 2 MeV
- $0 \leq E_x \leq 22$ MeV, resolution 0.13 MeV



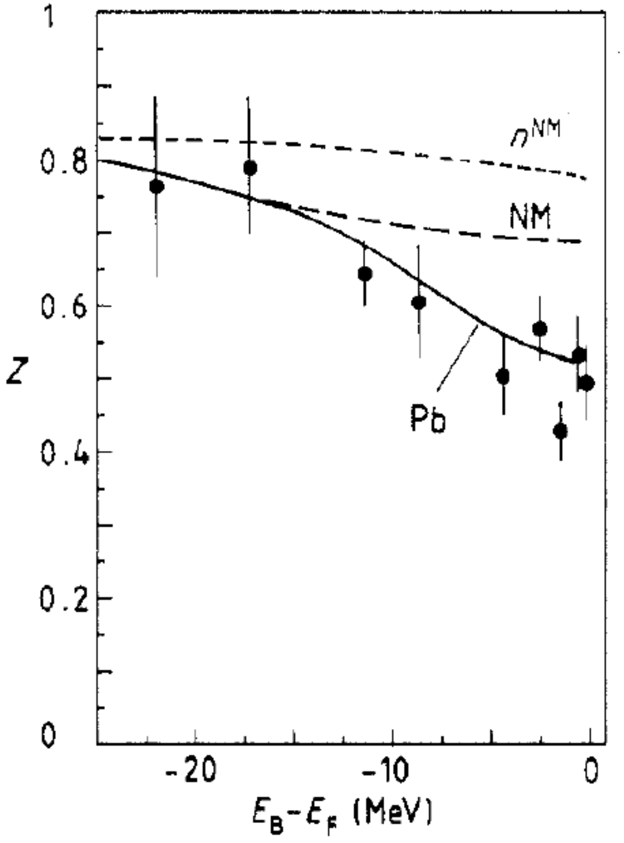


Kramer, Ph.D. thesis (1990)
Kramer *et al.*, NPA PLB 277, 199 (1989)

Independent-particle shell model



Lapikás, NPA 553, 297c (1993)



de Witt Huberts, NPA 553, 297c (1993)
Benhar *et al.*, PRC 41, R24 (1990)

Spectral function for complex nuclei

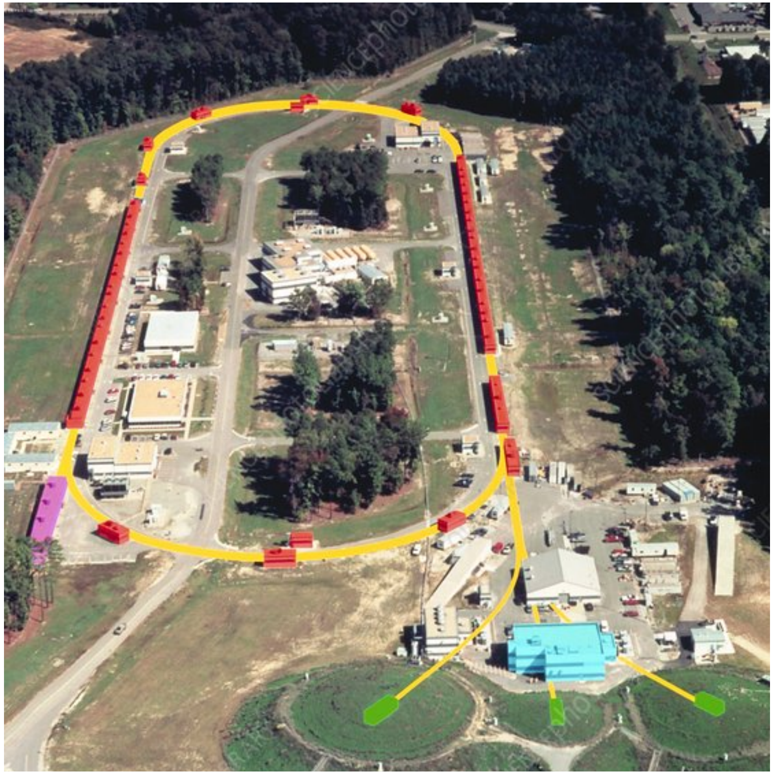
Mean-field part

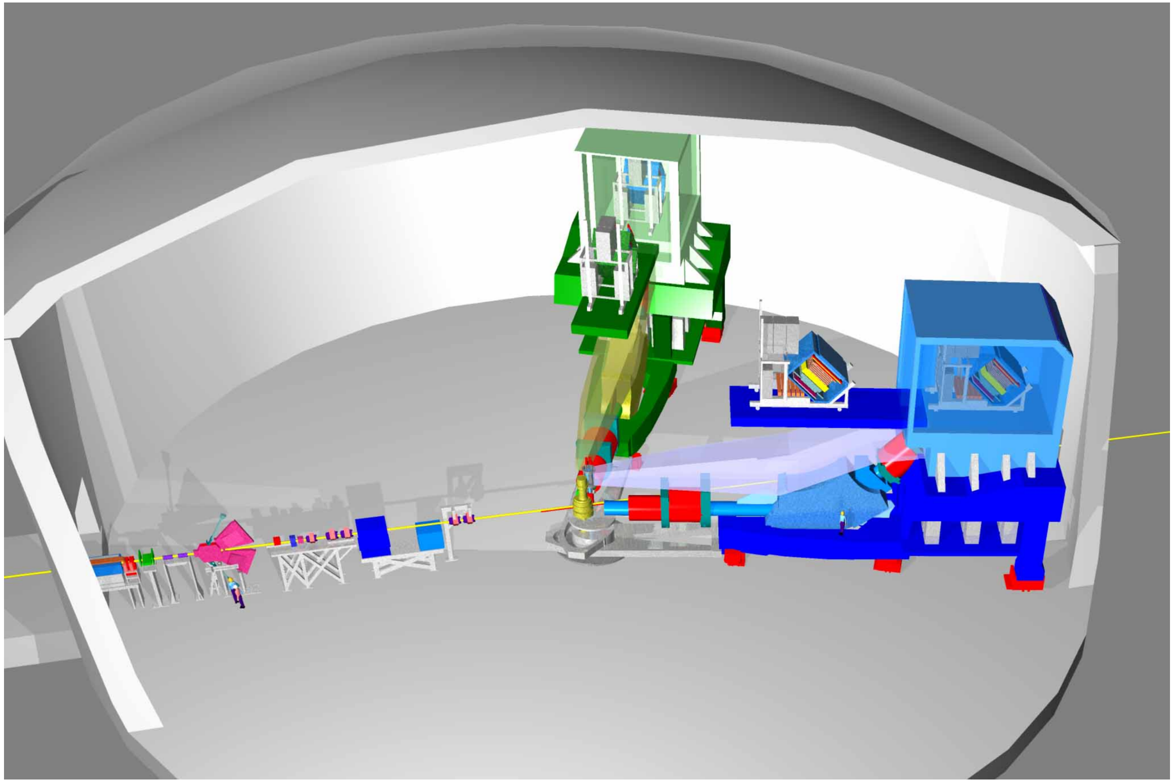
- describes the shell structure
- can be determined from experimental data
- 70–80% of nucleons

Correlated part

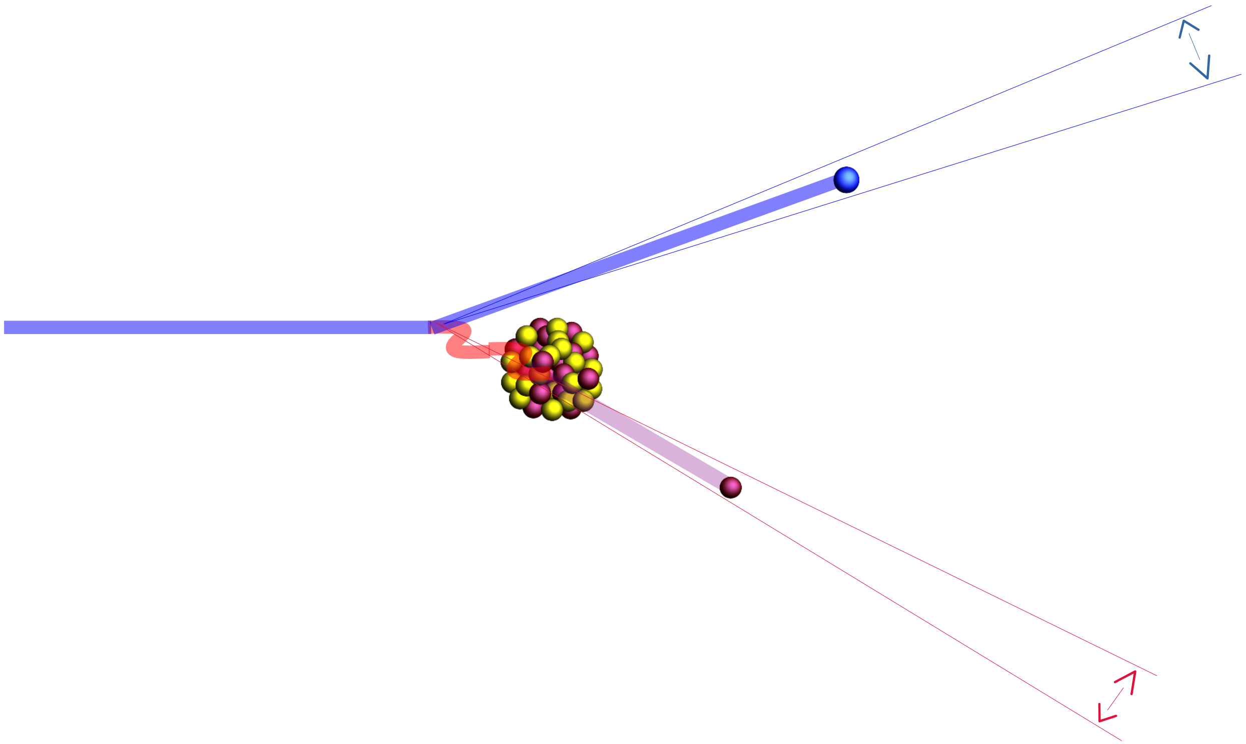
- describes correlated nucleons
- easier to determine from theoretical estimates

Jefferson Laboratory Hall A



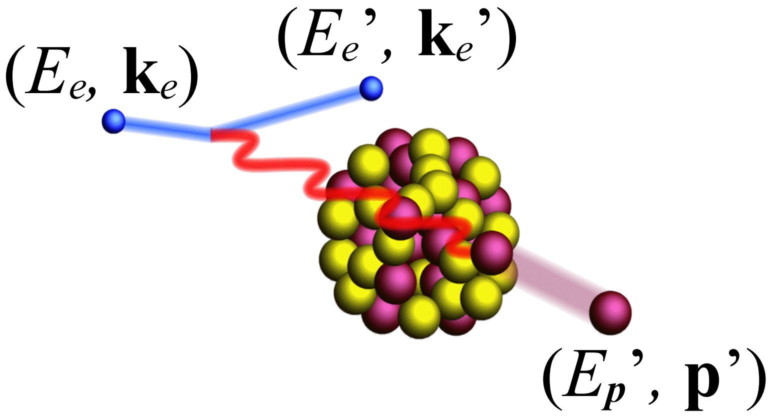


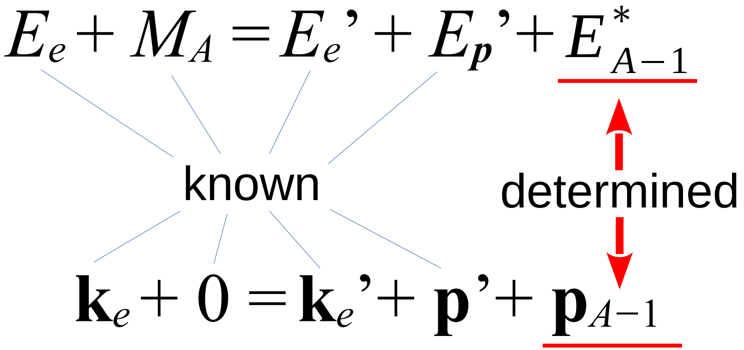
Coincidence scattering



Tracks required to be
±3 mrad (±0.17°) in-plane
±6 mrad (±0.34°) out of plane
…
to reduce the contribution of FSI

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





In general,

$$E^*_{A-1} = \sqrt{(M_A - M + E_m)^2 + p^2_{A-1}}$$

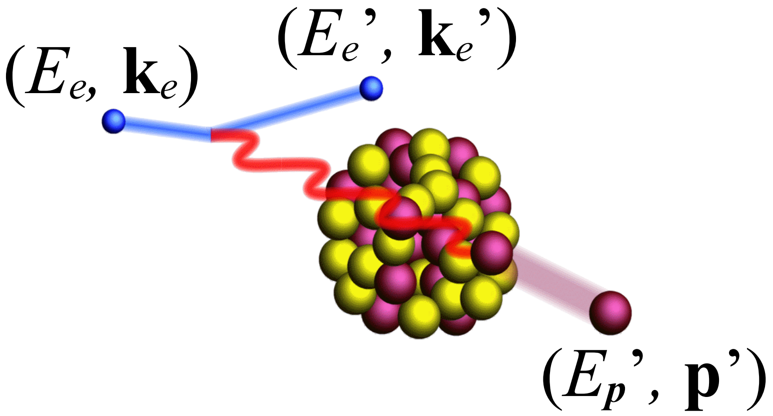
$E_m - E_{thr}$ is the excitation energy of ^{39}Cl

Without final state interactions

$$-\mathbf{p}_{A-1} = \mathbf{p}_m$$

is the initial proton momentum

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



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

known   missing

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

For negligible recoil energy,

$$E^*_{A-1} = M_A - M + E_m$$

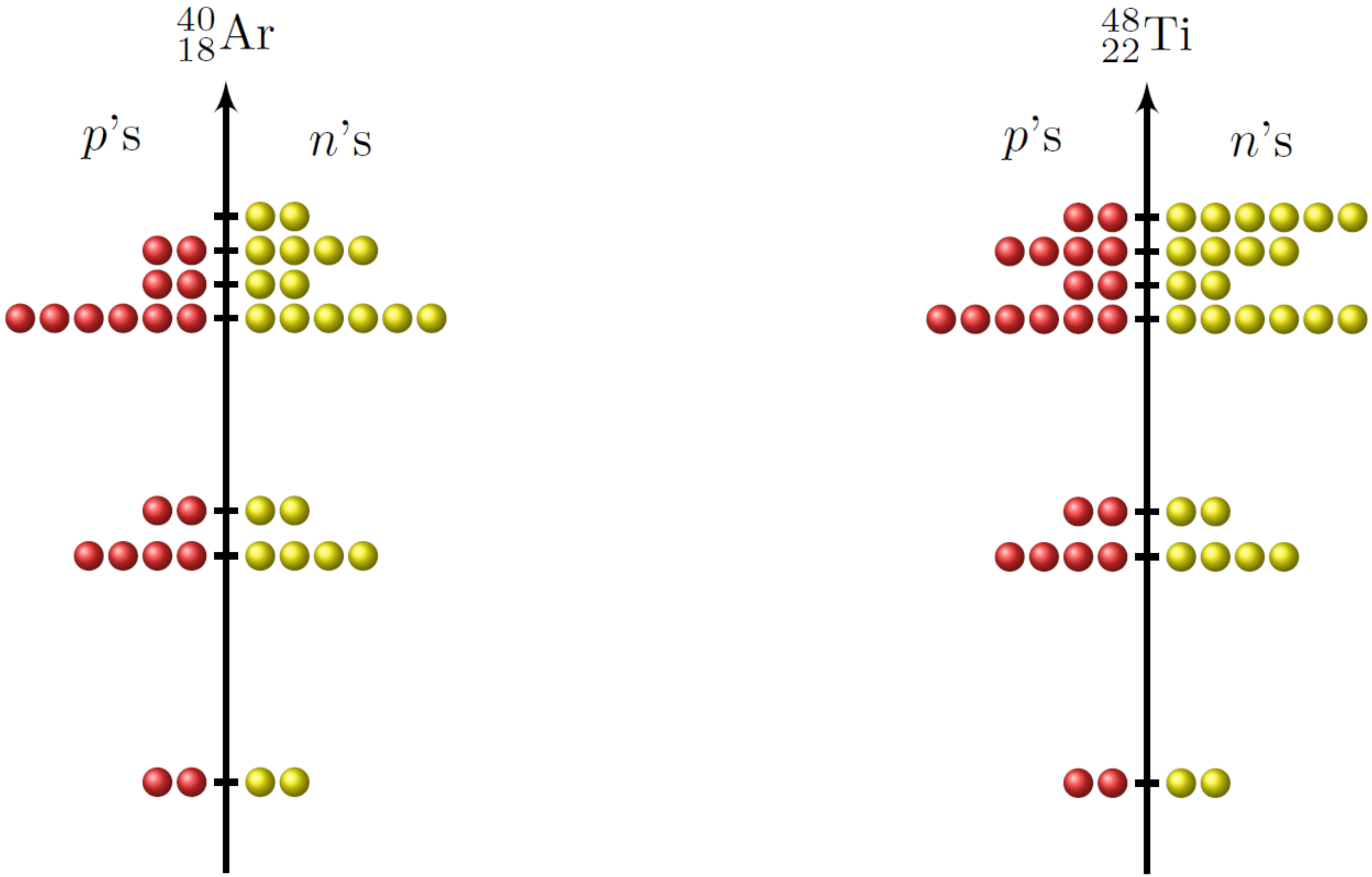
$E_m - E_{\mathrm{thr}}$ is the excitation energy of ^{39}Cl

Without final state interactions

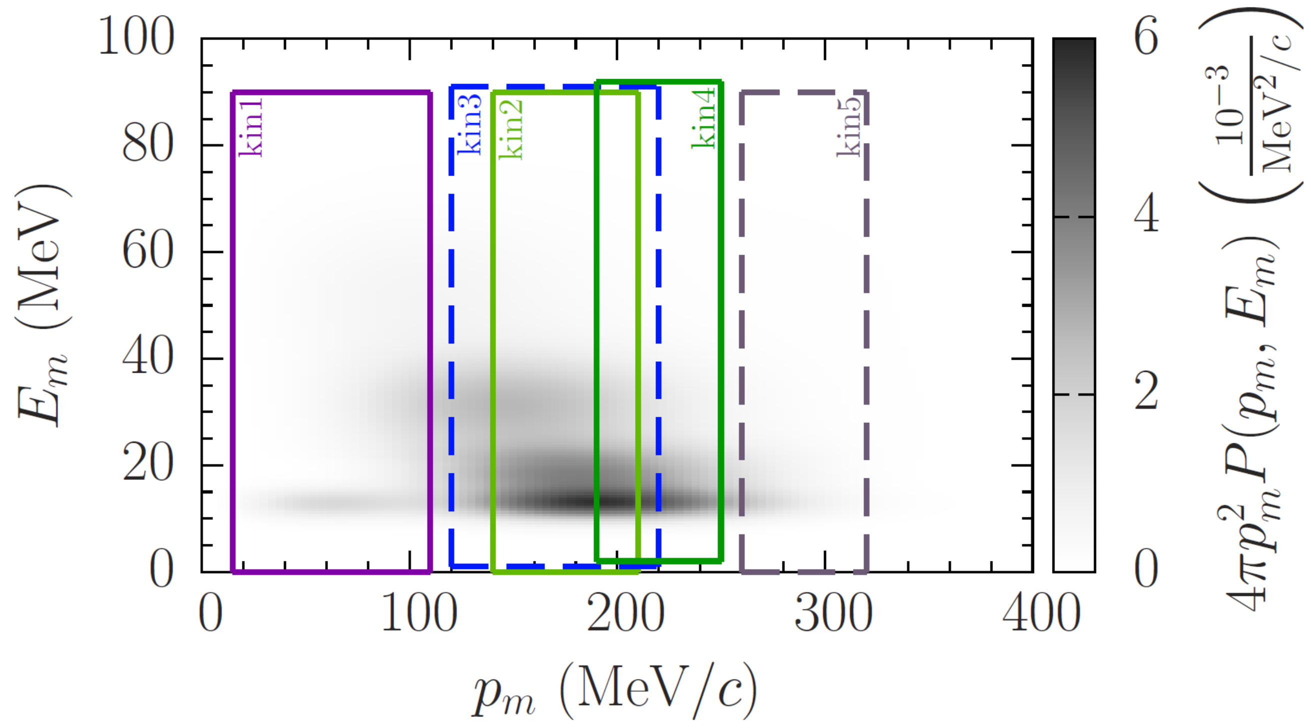
$$-\mathbf{p}_{A-1} = \mathbf{p}_m$$

is the initial proton momentum

Why titanium?



^{40}Ar(*e*,*e'p*) in E12-14-012



(e,$e'p$) cross section

elementary cross section

nuclear transparency

$$\frac{d^4\sigma_{\mathrm{IA}}}{d\Omega_{k'}dE_{k'}d\Omega_{p'}dE_{p'}} \propto \sigma_{ep}\, S(\mathbf{p}, E)\, T_A(E_{p'})$$

spectral function

T. de Forest Jr., NPA 392, 232 (1983)

Mean-field part of the spectral function

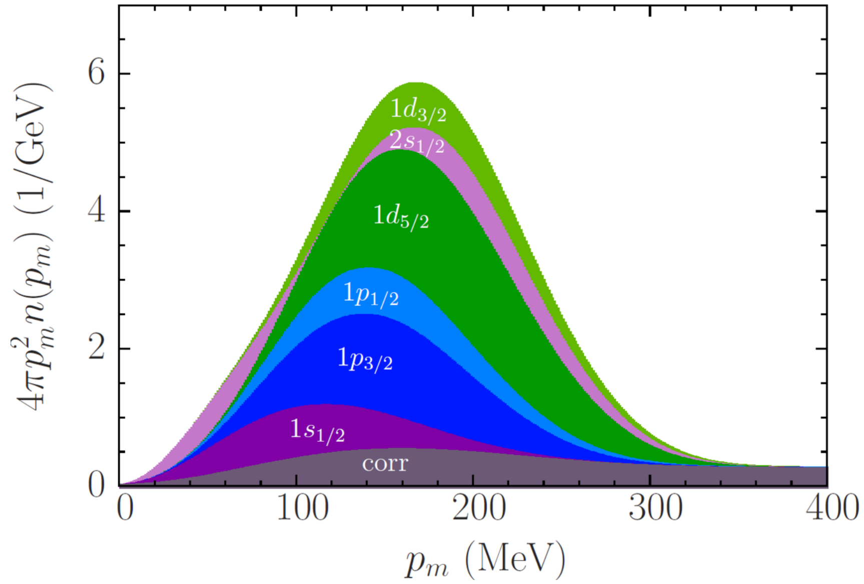
spectroscopic factor

energy distribution

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

wave function in momentum space

Relativistic MF calculations by C. Giusti

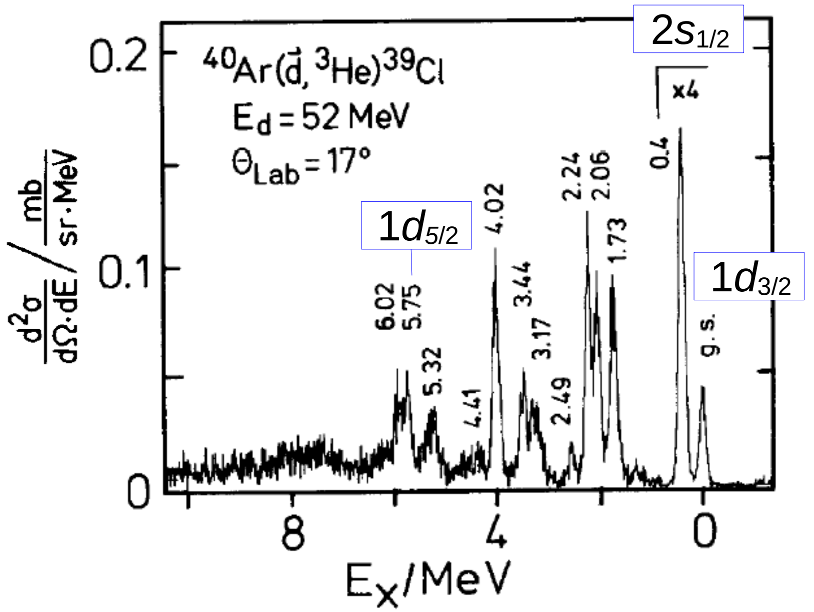


Mean-field part of the spectral function

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

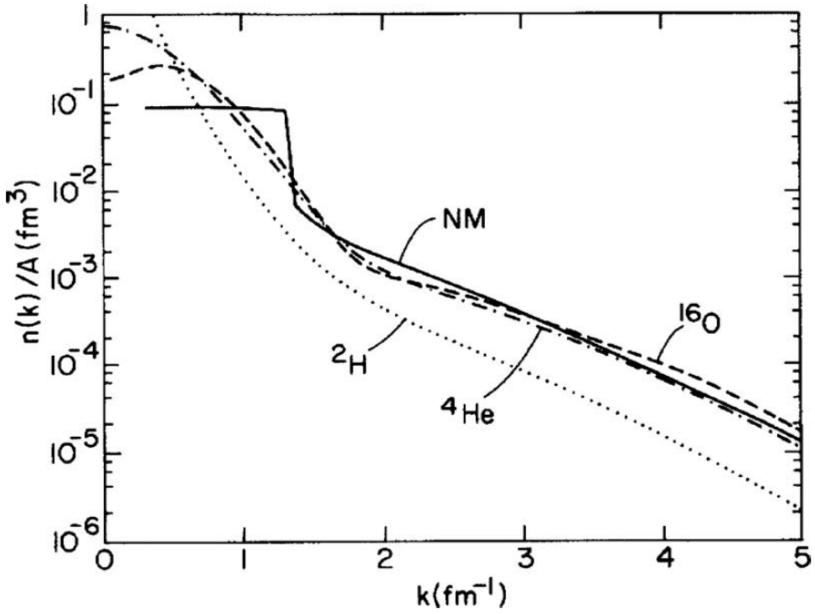
- $1d_{3/2}$: from the mass difference between ^{40}Ar and ^{39}Cl + p + e
- $2s_{1/2}$ and $1d_{5/2}$: from the dominant contribs. in the past ^{40}Ar(d, ^{3}He)^{39}Cl measurements
- Lower levels were not probed with deuteron
- Assumed Maxwell-Boltzmann distribution of missing energy

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



Correlated part of the spectral function

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



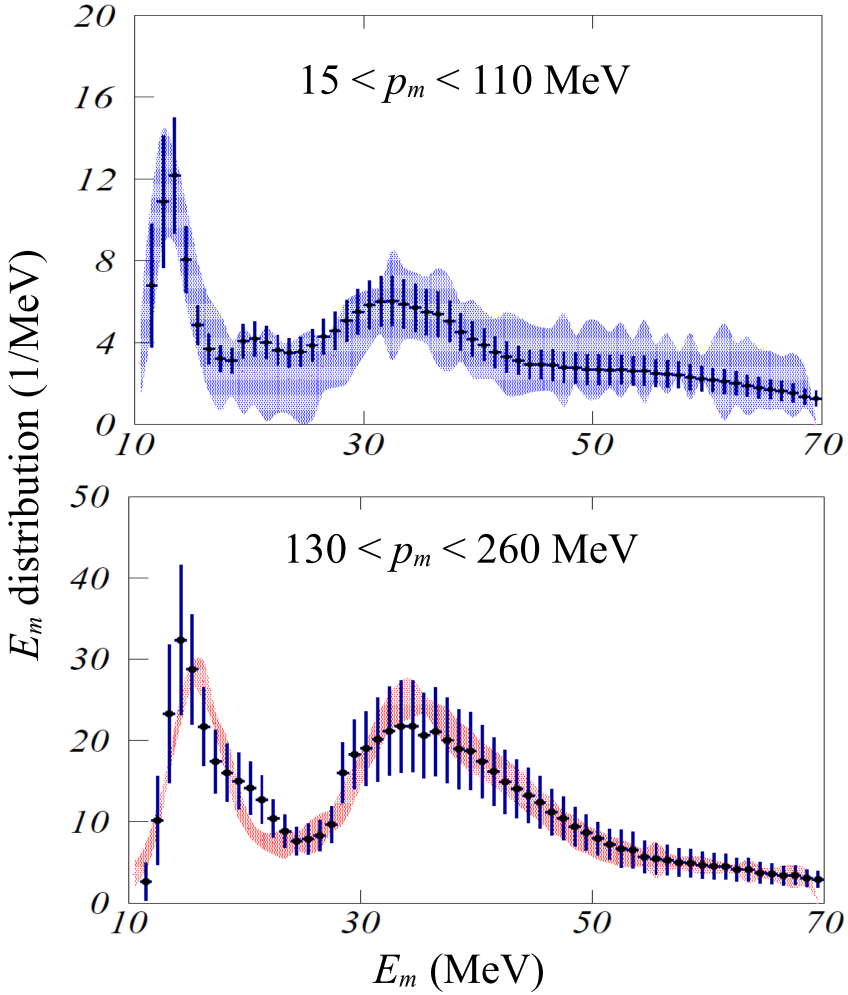
Ciofi degli Atti and Simula, PRC **53**, 1689 (1996)

- 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

Missing energy distributions for Ar and Ti

α	E_α (MeV) w/ priors	E_α (MeV) w/o priors	σ_α (MeV) w/ priors	σ_α (MeV) 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	—	—

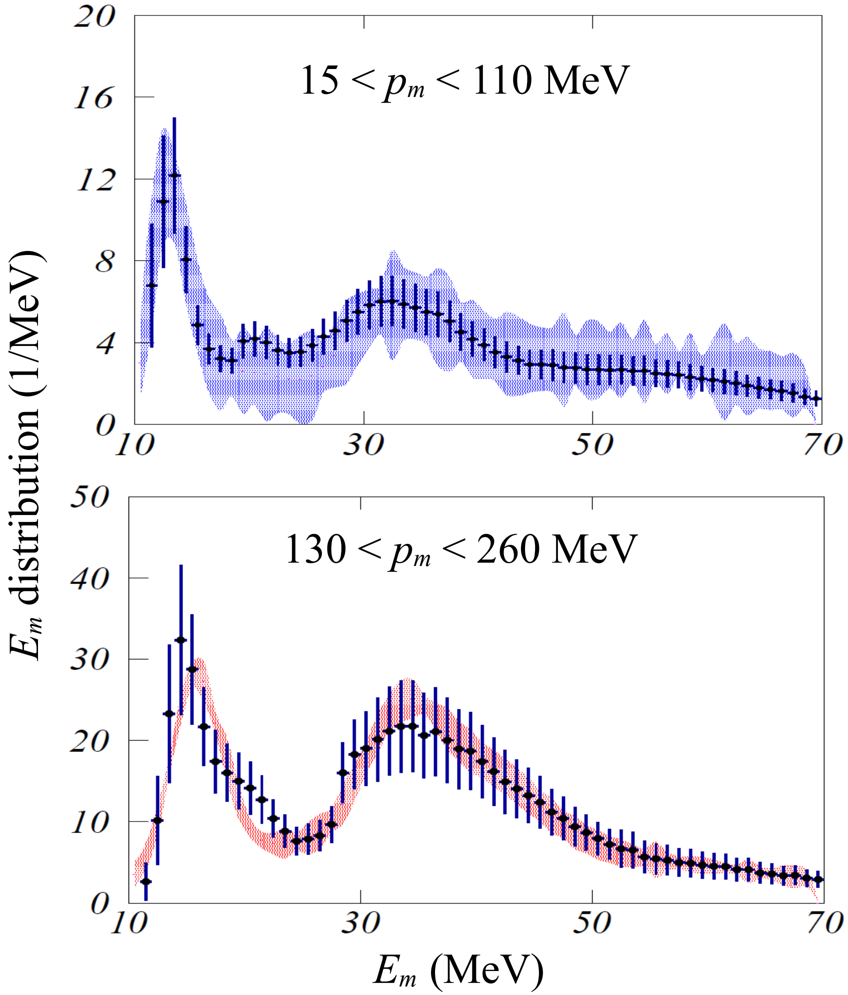
α	E_α (MeV) w/ priors	E_α (MeV) w/o priors	σ_α (MeV) w/ priors	σ_α (MeV) w/o priors
$1f_{7/2}$	11.32 ± 0.10	11.31 ± 0.10	8.00 ± 5.57	8.00 ± 6.50
$1d_{3/2}$	12.30 ± 0.24	12.33 ± 0.24	7.00 ± 0.61	7.00 ± 3.84
$2s_{1/2}$	12.77 ± 0.25	12.76 ± 0.25	7.00 ± 3.76	7.00 ± 3.84
$1d_{5/2}$	15.86 ± 0.20	15.91 ± 0.22	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	—	—



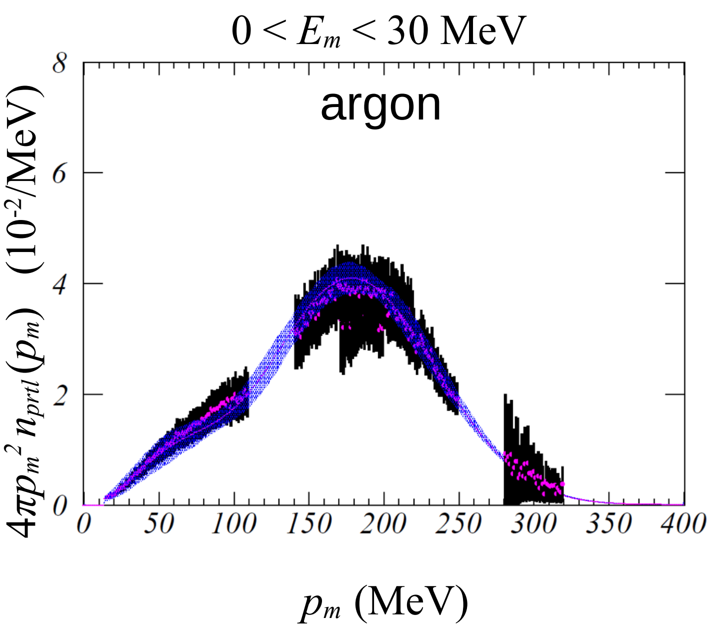
Spectroscopic factors for Ar and Ti

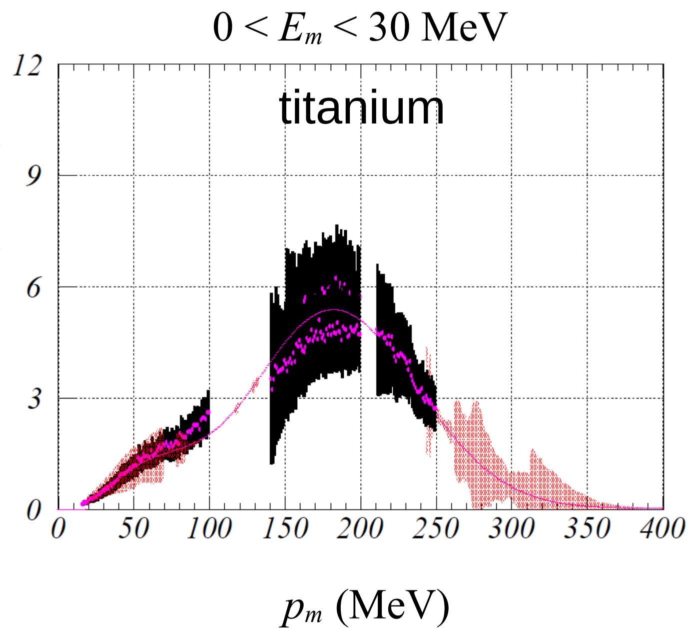
α	N_α	all priors	w/o p_m	w/o corr.
			S_α	
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	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

$1f_{7/2}$	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



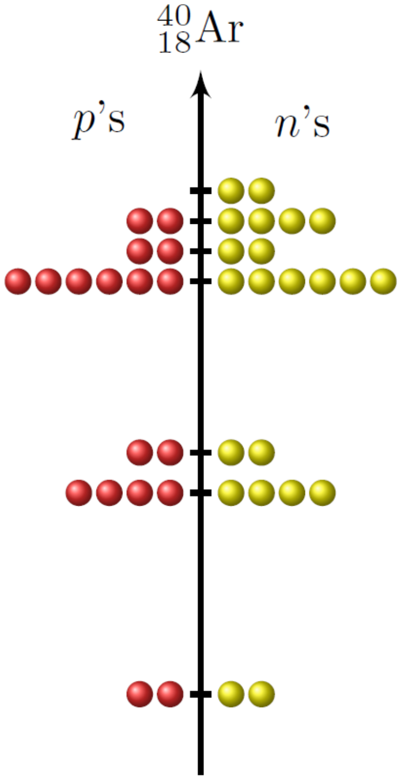
Partial momentum distributions





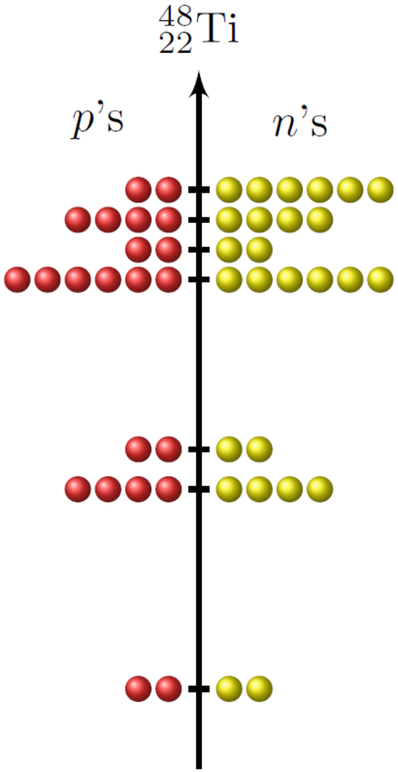
Data from different kinematics are consistent within uncertainties.

Energy levels

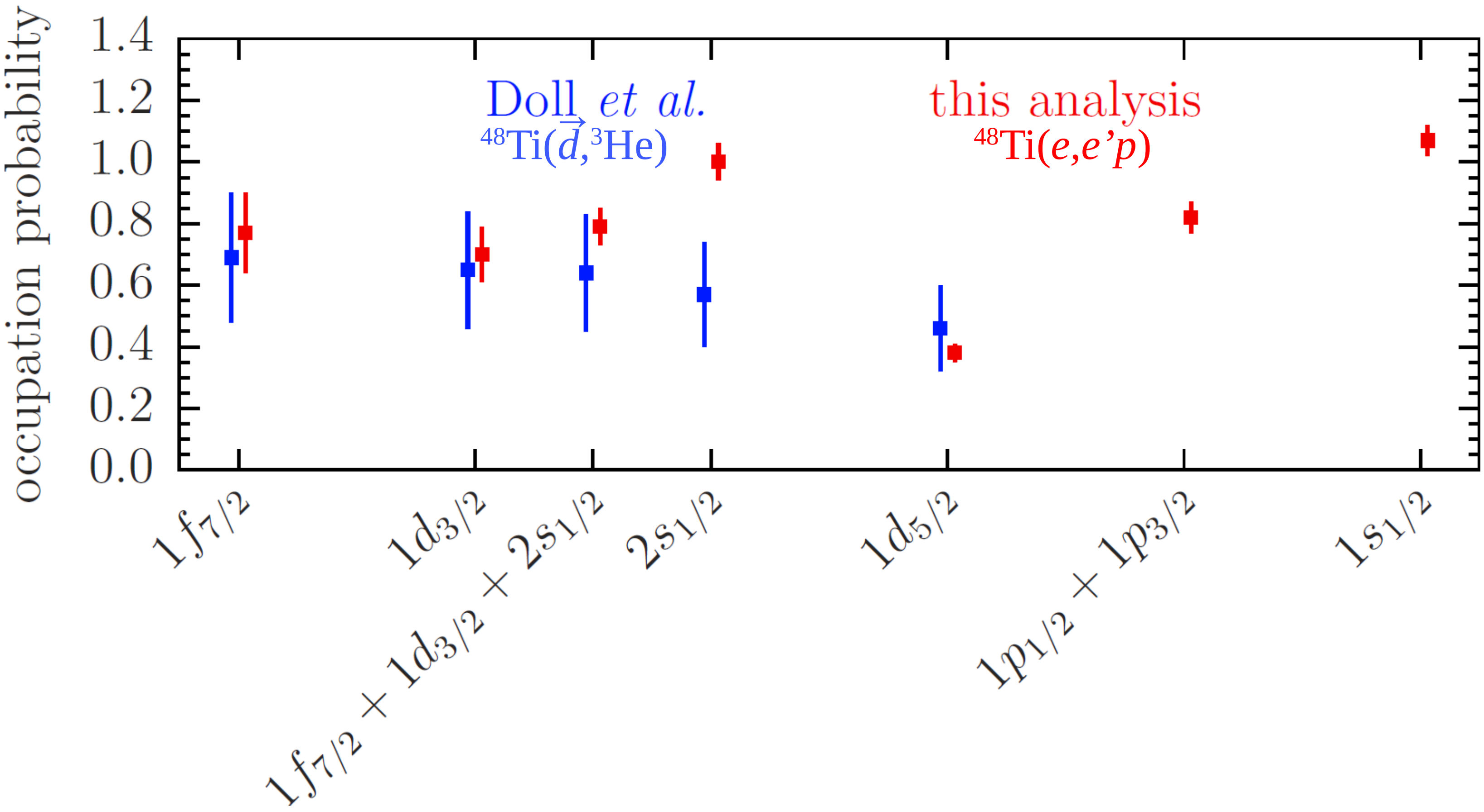


^{40}Ar		^{48}Ti
neutrons		protons
9.87	1f7/2	11.45
11.39	1d3/2	12.21
12.23	2s1/2	12.84
13.23	1d5/2	15.45

Agreement to 0.6–2.2 MeV

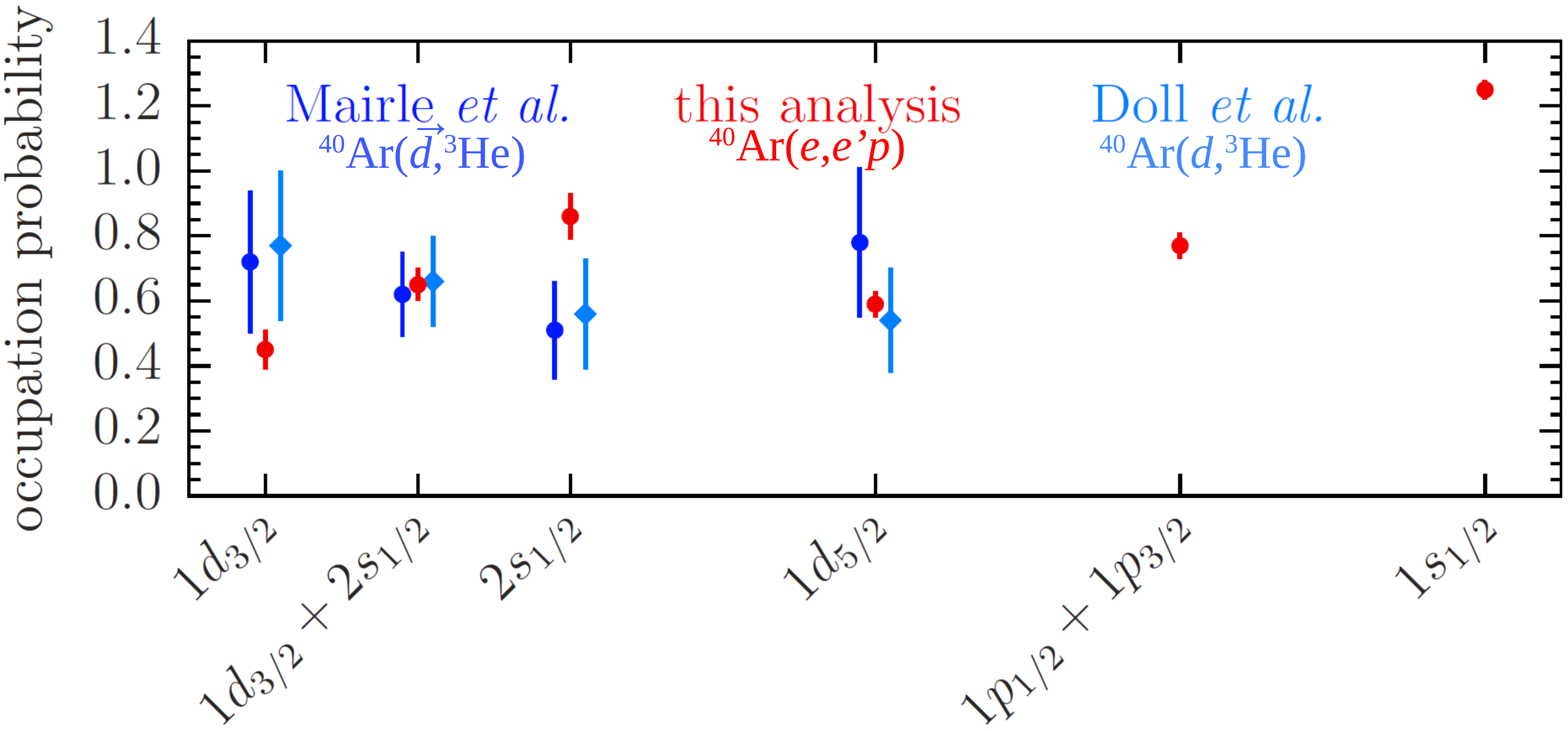


Occupation probability



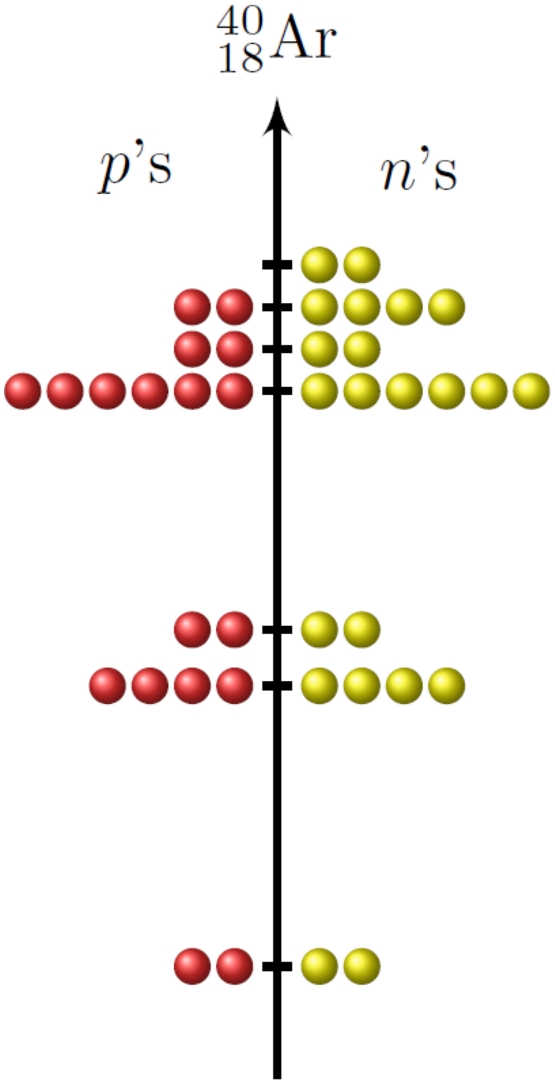
52-MeV polarized [Doll *et al.*, JPG **5**, 1421 (1979); $E_x < 7.54$ MeV] deuteron beam at Karlsruhe

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, $S_\alpha \rightarrow S_\alpha/1.5$

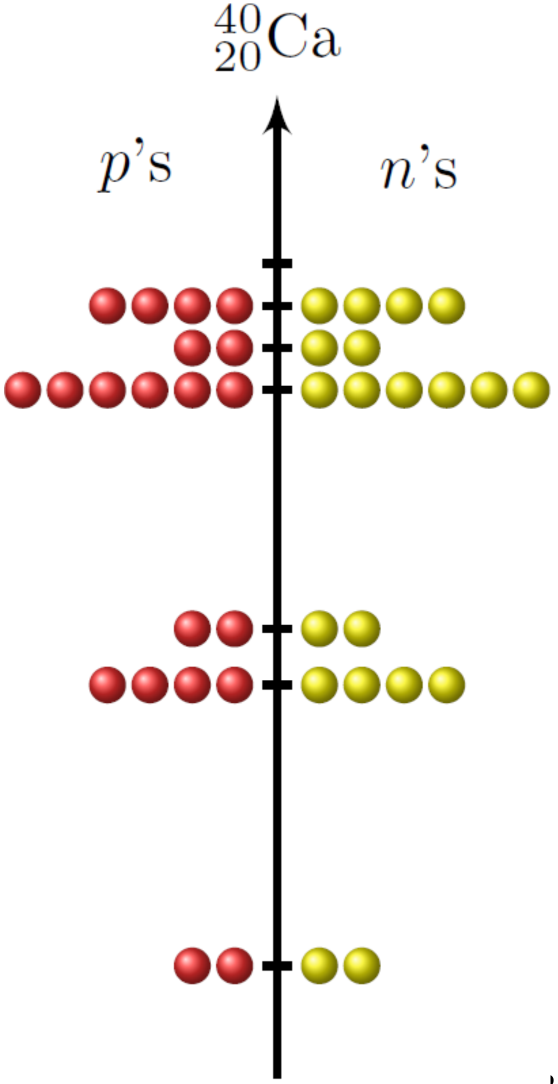


proton energy levels

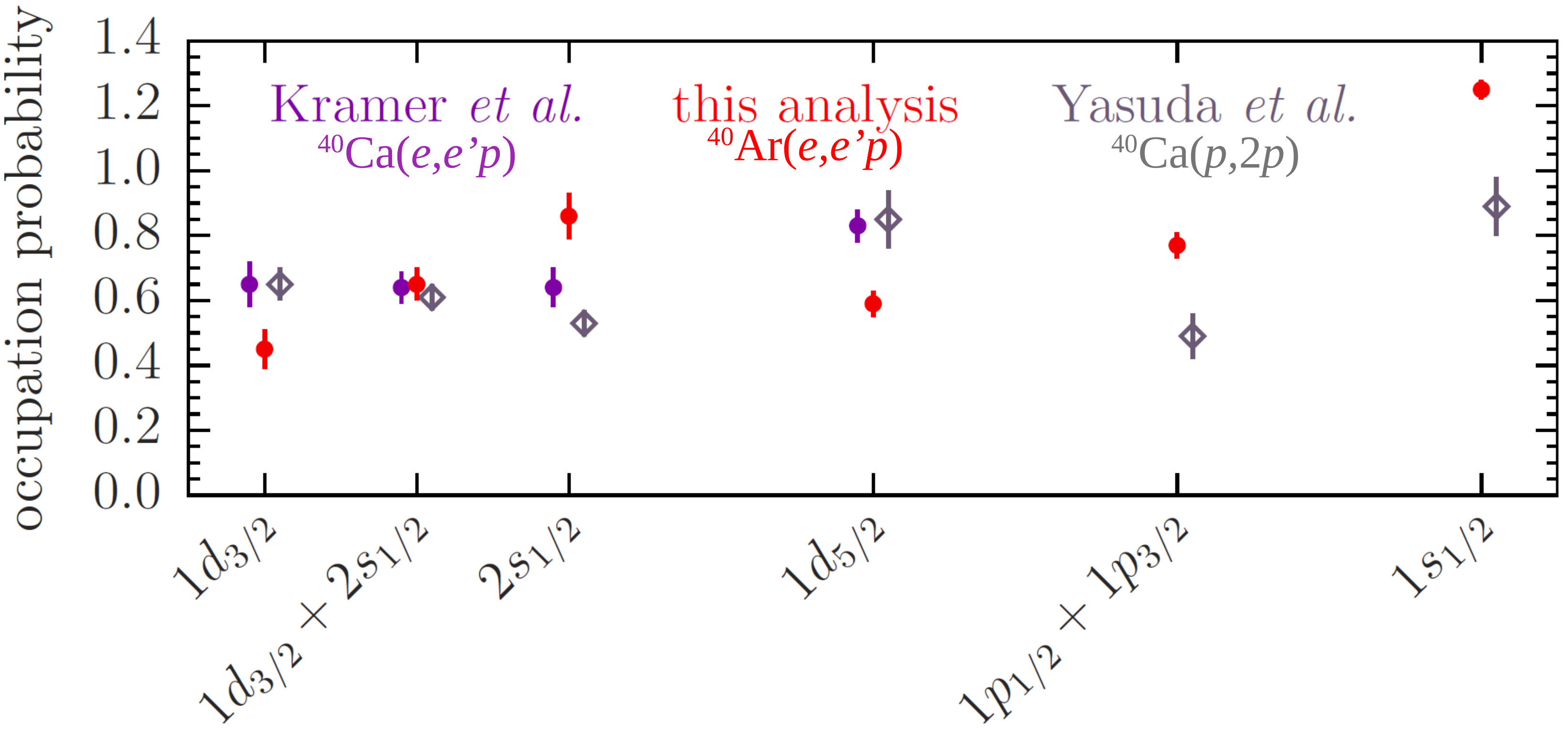
Ar		Ca
12.53(2)	1d3/2	8.5(1)
12.92(2)	2s1/2	11.0(1)
18.23(2)	1d5/2	15.7(1)
28.8(7)	1p1/2	29.8(7)
33.0(3)	1p3/2	34.7(3)
53.4(1.1)	1s1/2	53.6(7)

Jiang *et al.*,
PRD 105, 112002 (2022)

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

Directions for future improvements

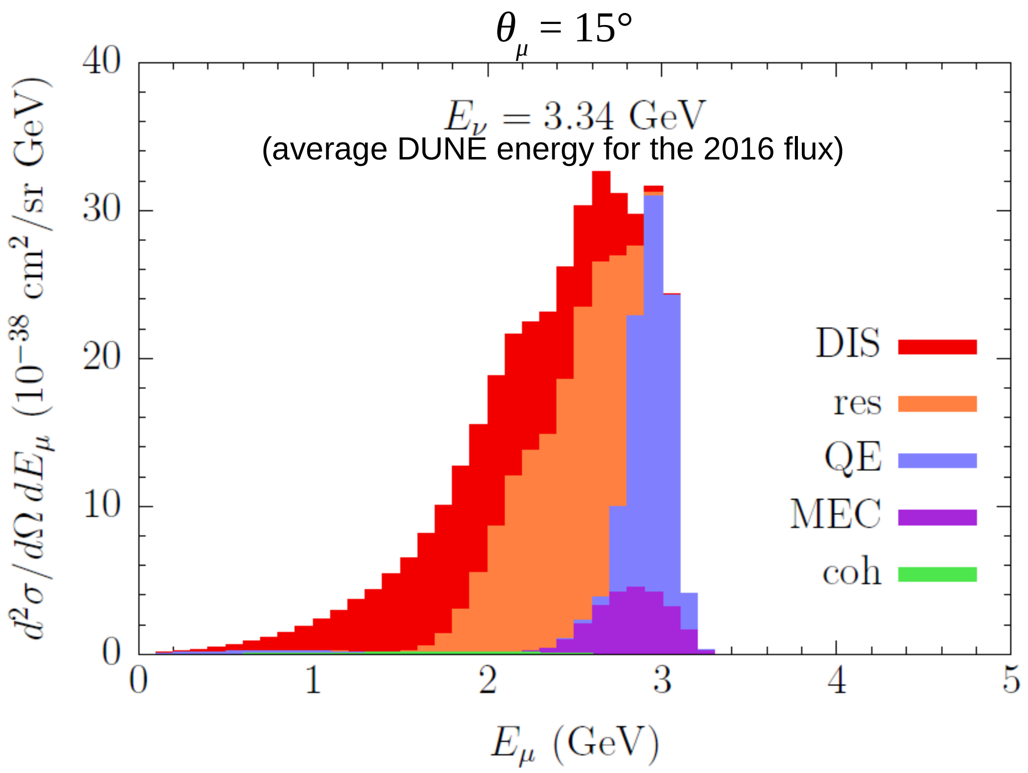
- 2D analysis
- Final-state interactions
- Wave functions
- Correlated part of the spectral function

Summary

- The success of the long-baseline neutrino program requires reliable cross sections.
- The spectral function approach is a viable option.
- The first, exploratory analysis of the full dataset of the JLab experiment E12-14-012 found reasonable parametrizations of the spectral functions of ^{40}Ar and ^{48}Ti.
- Comparison with past results shows strengths and limitations.
- Separation of individual contributions requires improved analysis. Numerous theoretical developments are necessary.

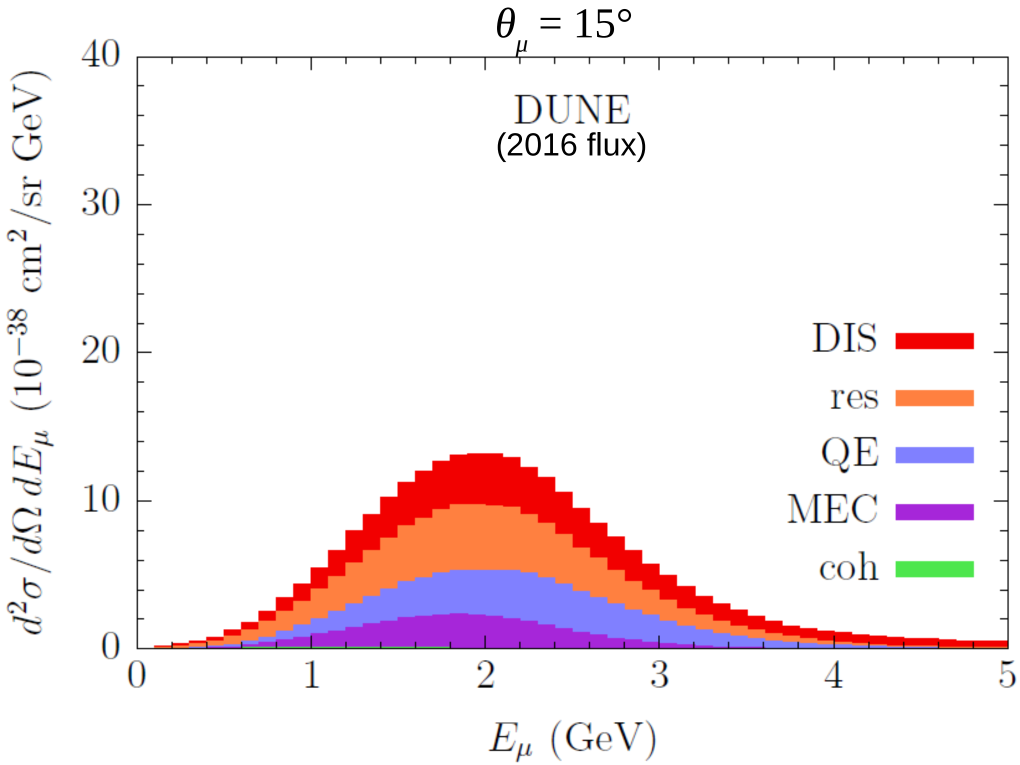
Thank you!

Neutrino double differential cross section



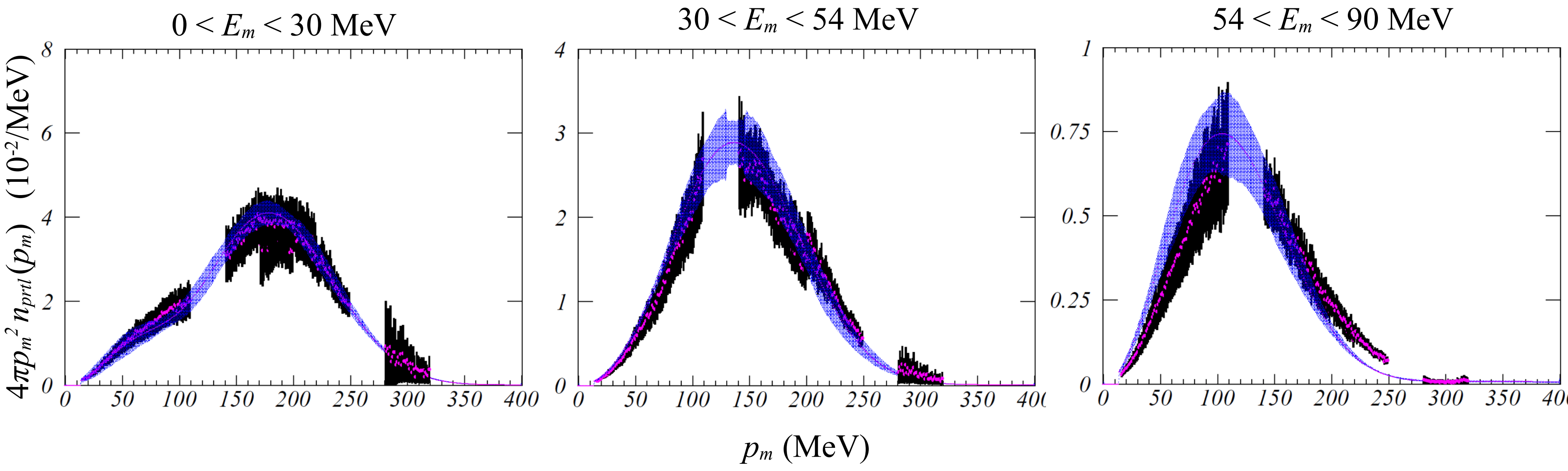
A.M.A. & A. Friedland, PRD 102, 053001 (2020)

Neutrino double differential cross section



A.M.A. & A. Friedland, PRD 102, 053001 (2020)

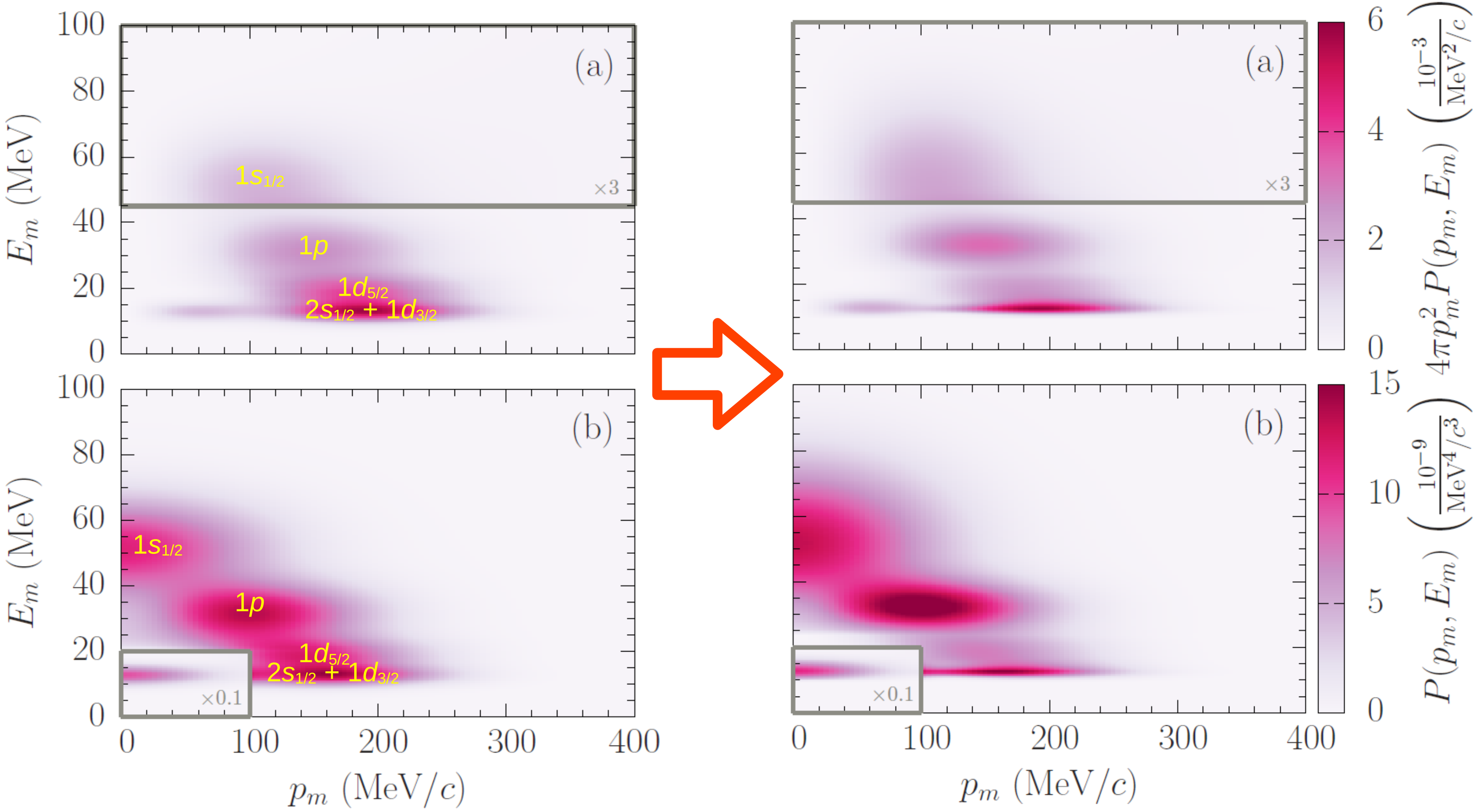
Partial momentum distributions



Data from different kinematics are consistent within uncertainties.

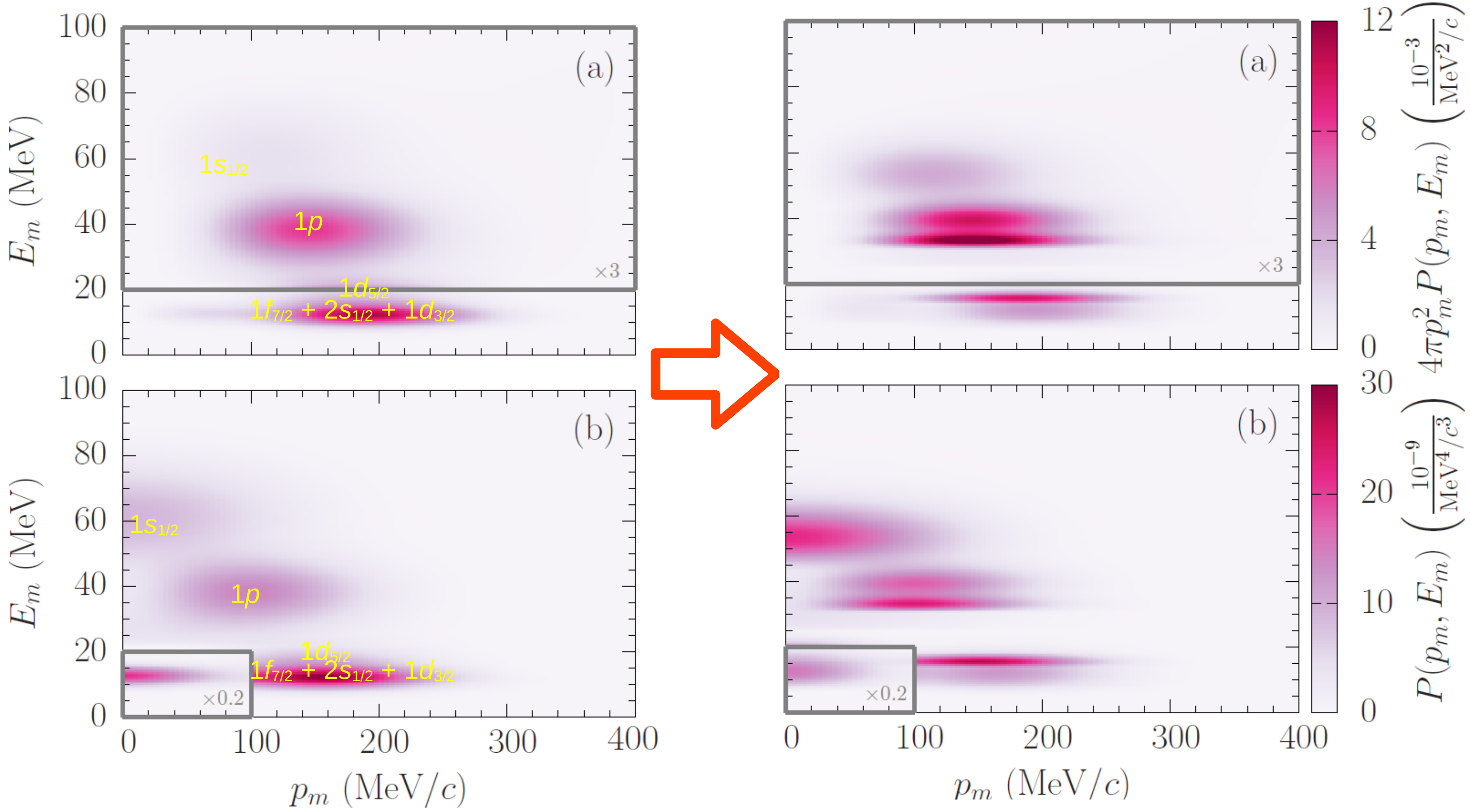
Test spectral function

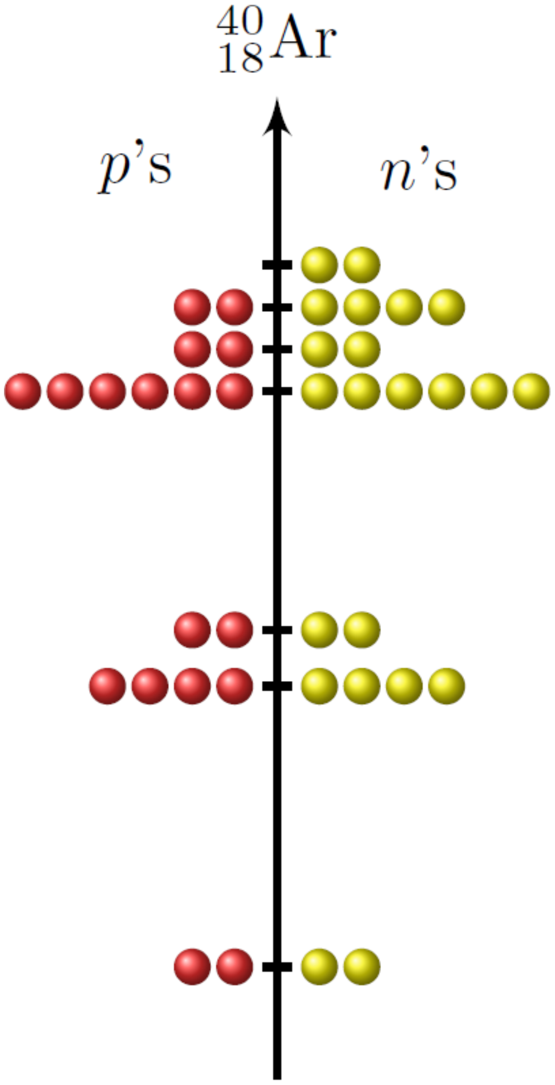
Extracted spectral function



Test spectral function

Extracted spectral function



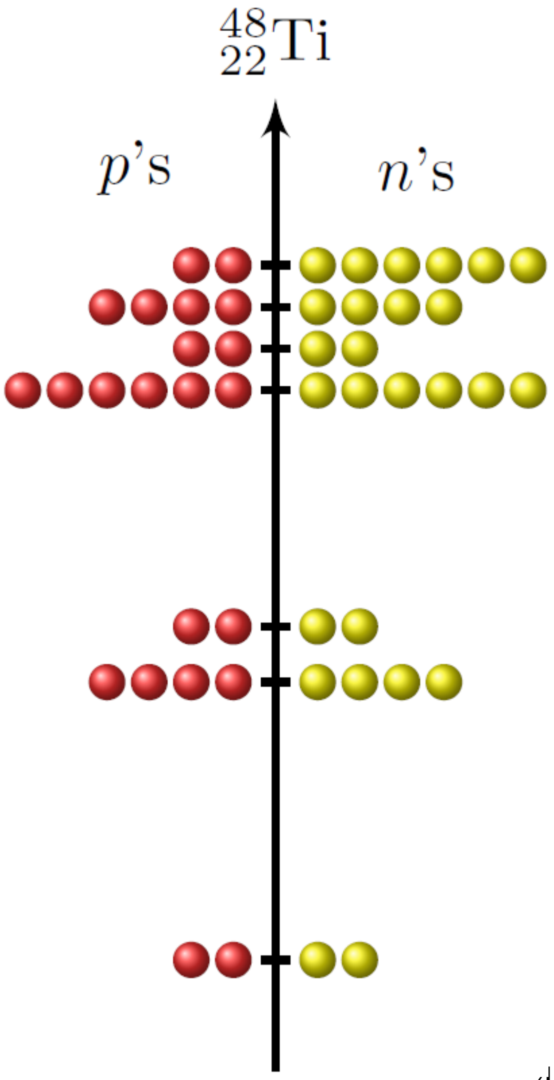


proton energy levels

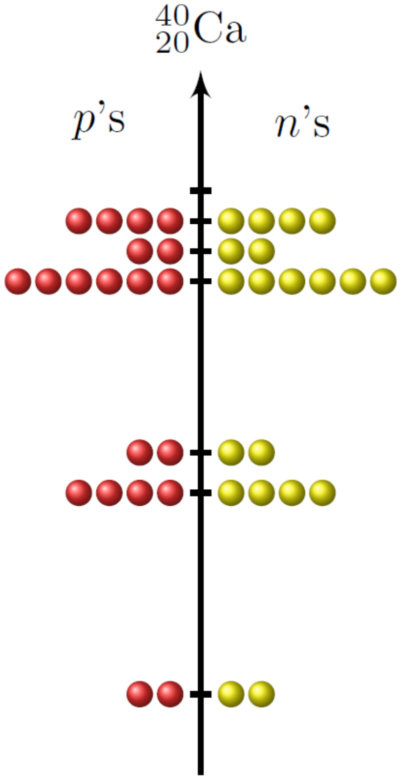
Ar		Ti
	1f7/2	11.32(10)
12.53(2)	1d3/2	12.30(24)
12.92(2)	2s1/2	12.77(25)
18.23(2)	1d5/2	15.86(20)
28.8(7)	1p1/2	33.3(6)
33.0(3)	1p3/2	39.7(6)
33.0(3)	1p3/2	39.7(6)
53.4(1.1)	1s1/2	53.8(1.9)

Jiang *et al.*,
PRD 105, 112002 (2022)

Jiang *et al.*
PRD 107, 012005 (2023)

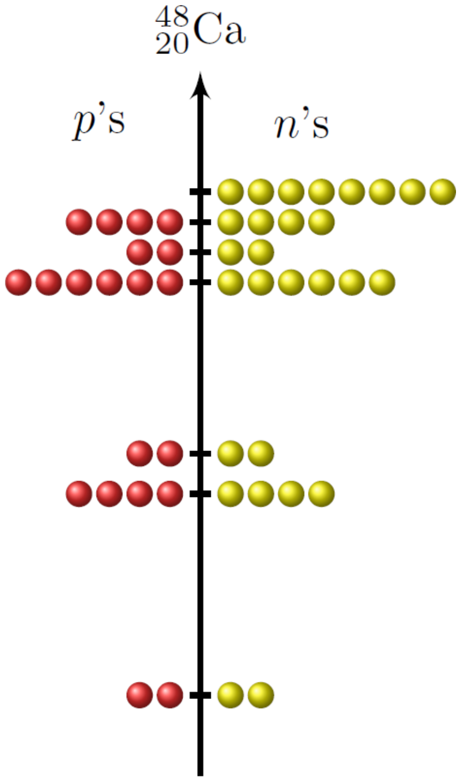


Calcium isotopes



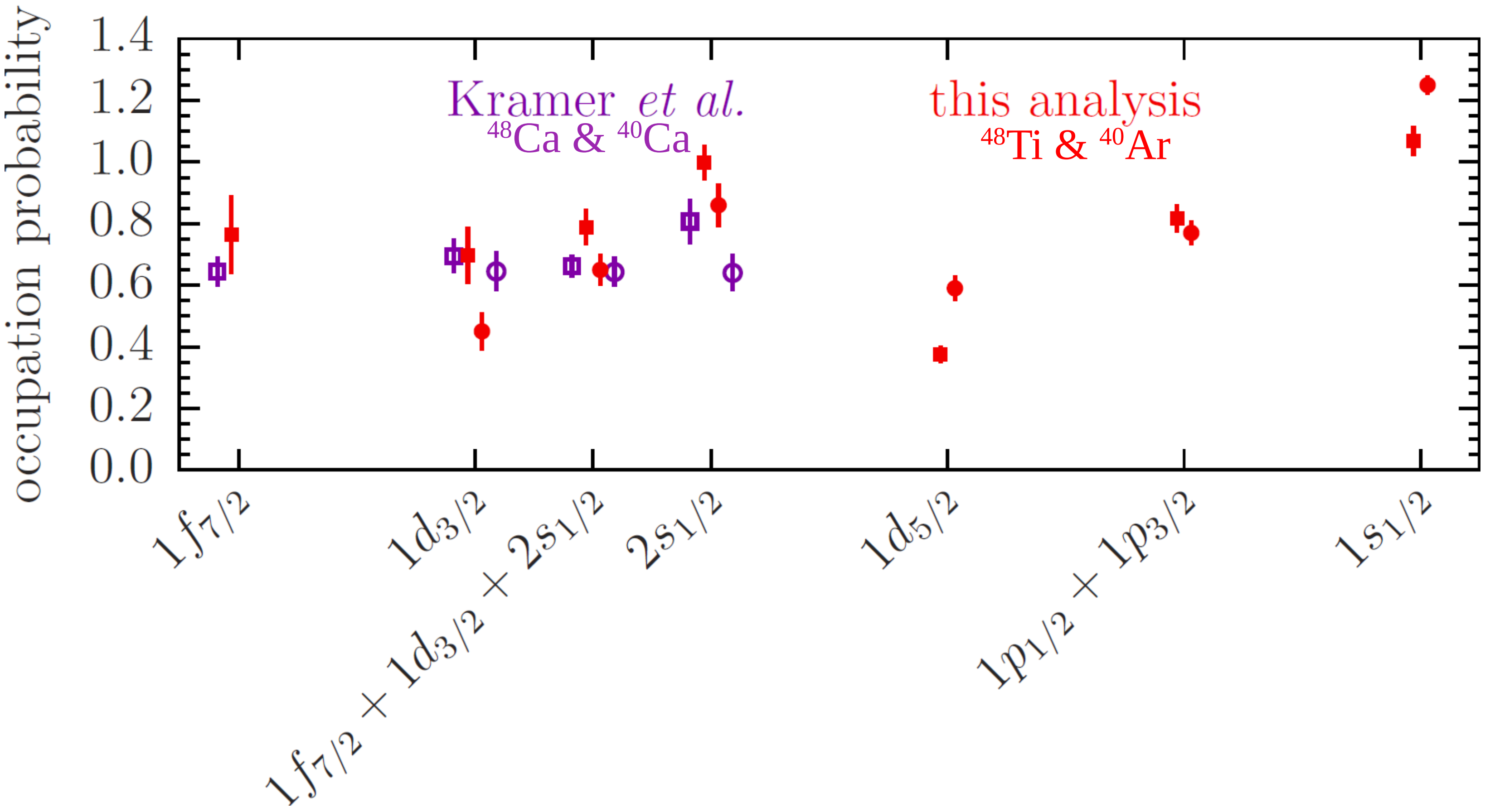
^{40}Ca		^{48}Ca
8.3(3)	1d3/2	16.8(3)
11.1(3)	2s1/2	17.1(3)
16.8(4)	1d5/2	23.9(7)

Kramer, Ph.D. thesis (1990)



6–8.5 MeV differences

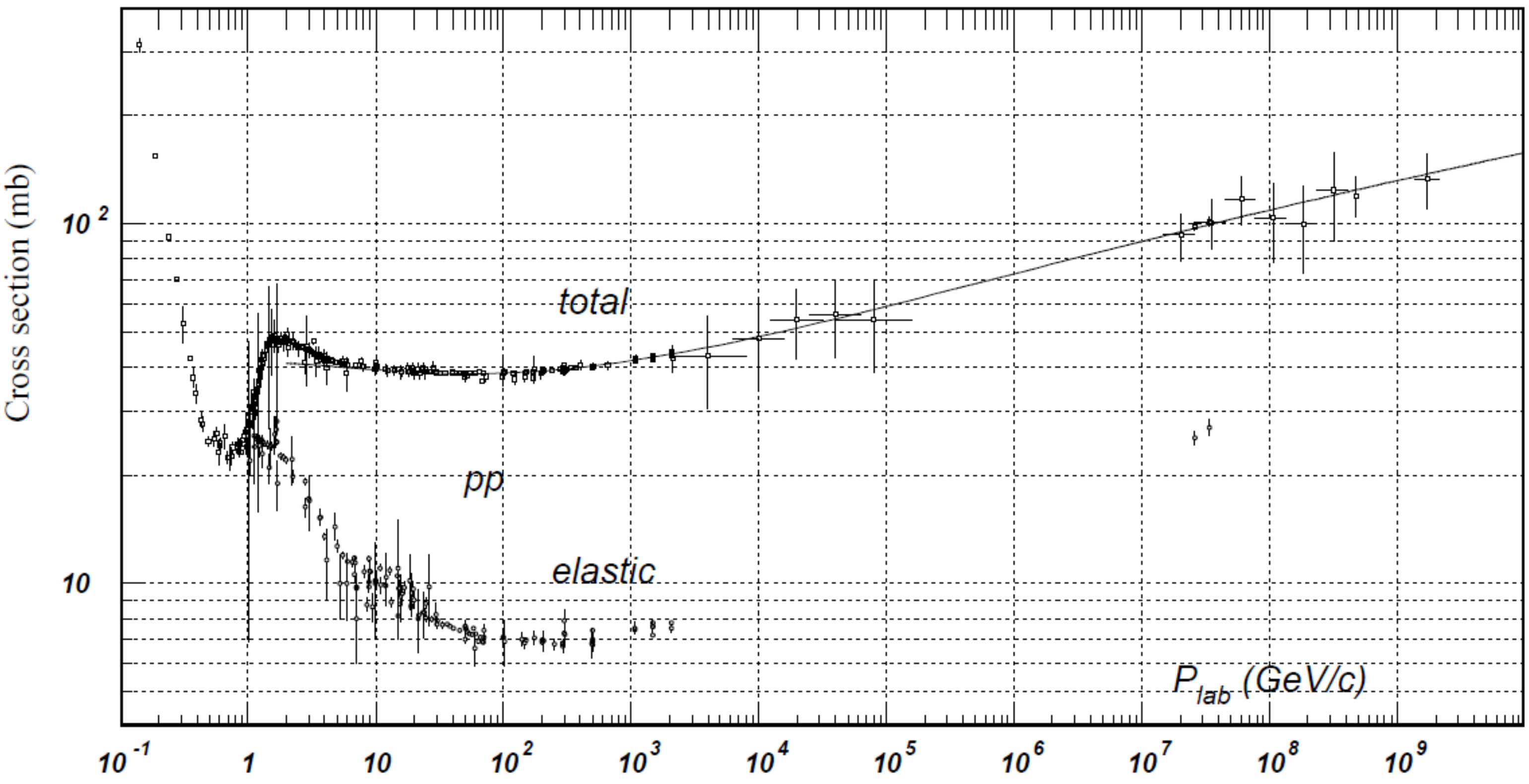
Occupation probability



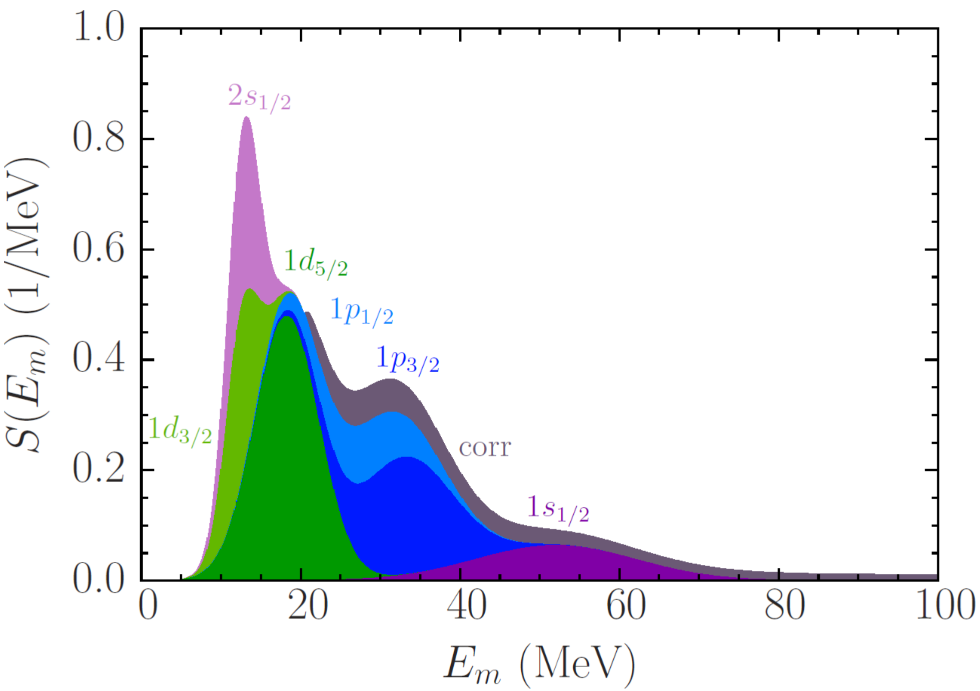
Kramer *et al.* [Ph.D. thesis (1990)]: ~340–440-MeV electron beam at NIKHEF-K

TABLE I. Kinematics settings used to collect the data analyzed here.

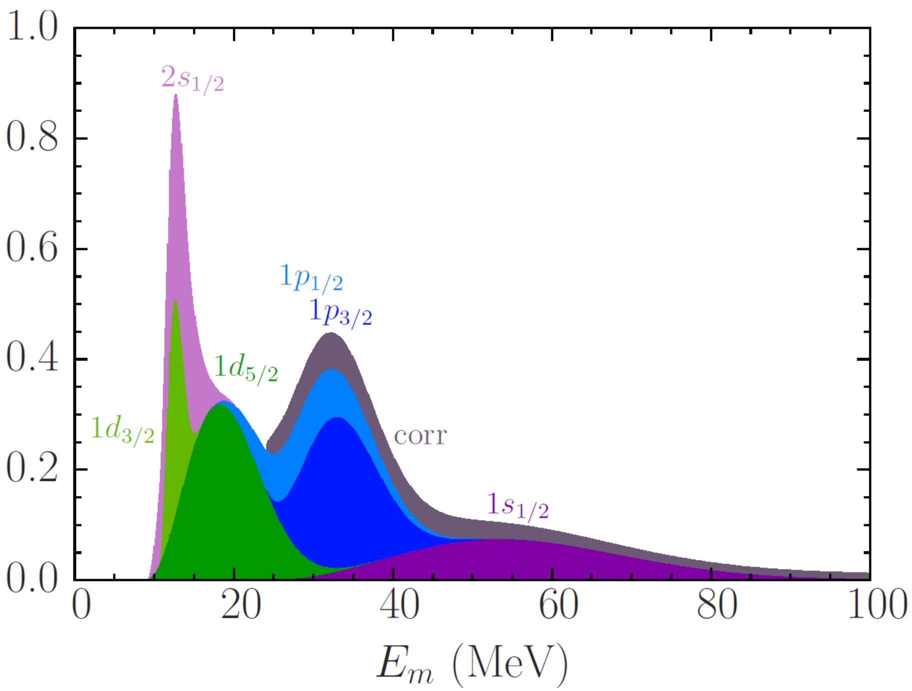
	E'_e (GeV)	θ_e (deg)	Q^2 (GeV^2/c^2)	$\lvert\mathbf{p}'\rvert$ (MeV/c)	$T_{p'}$ (MeV)	$\theta_{p'}$ (deg)	$\lvert\mathbf{q}\rvert$ (MeV/c)	p_m (MeV/c)	E_m (MeV)
kin1	1.777	21.5	0.549	915	372	−50.0	865	50	73
kin2	1.716	20.0	0.460	1030	455	−44.0	846	184	50
kin3	1.799	17.5	0.370	915	372	−47.0	741	174	50
kin4	1.799	15.5	0.291	915	372	−44.5	685	230	50
kin5	1.716	15.5	0.277	1030	455	−39.0	730	300	50



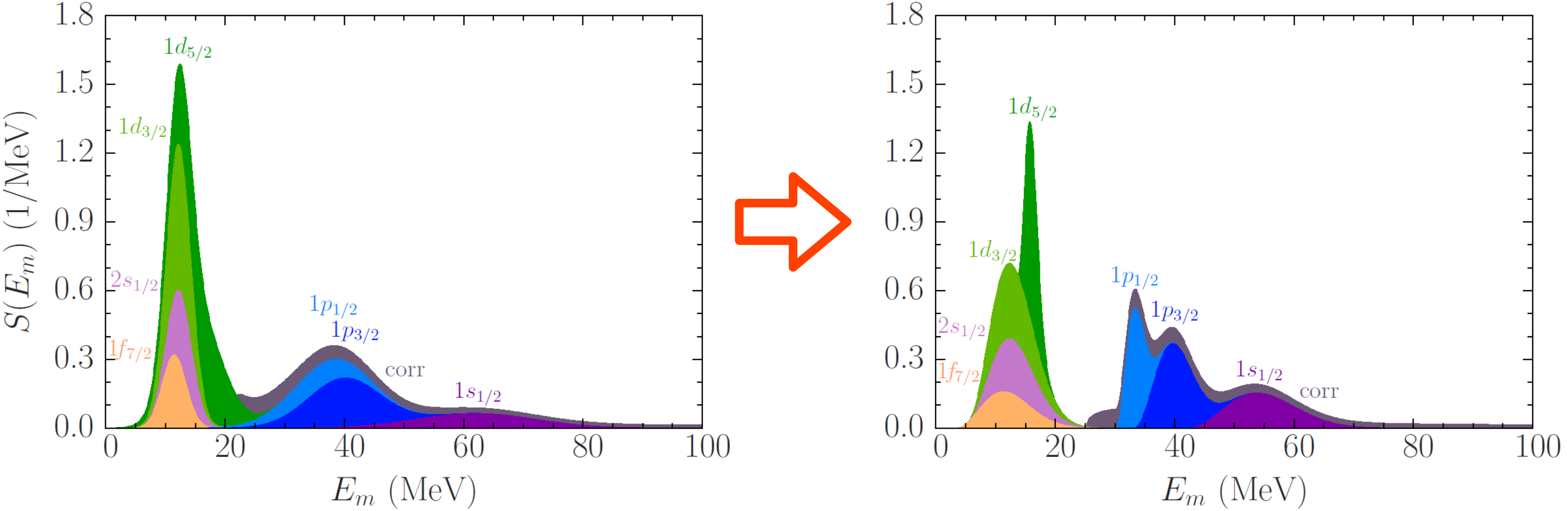
K.A. Olive *et al*. (PDG), Chin. Phys. C, 38, 090001 (2014)
https://pdg.lbl.gov/2014/hadronic-xsections/hadron.html

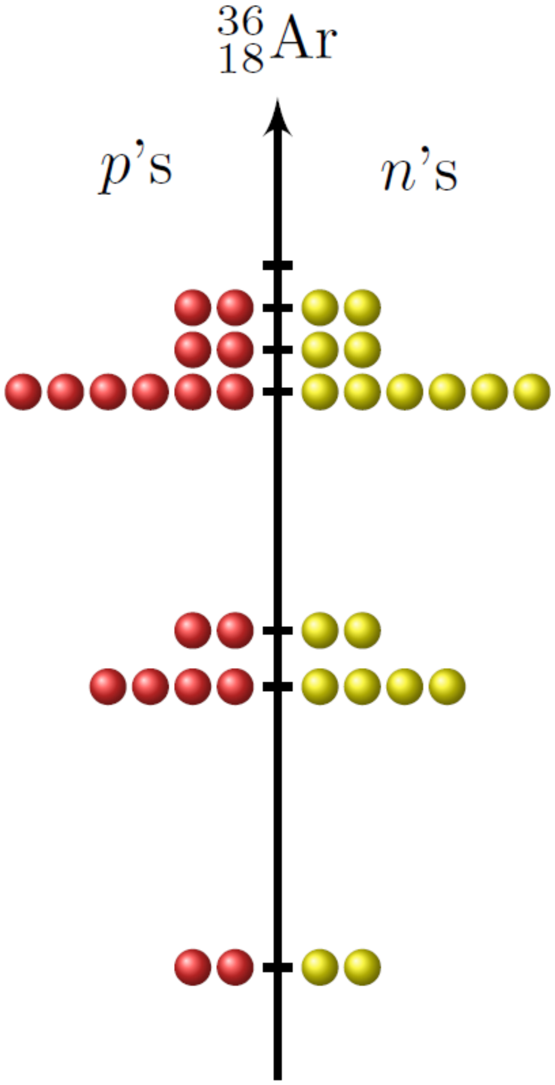


1.0
0.8
0.6
0.4
0.2
0.0
$S(E_m)$ (1/MeV)
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1d_{3/2}$
corr
$1s_{1/2}$
0
20
40
60
80
100
E_m (MeV)



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)


1.8
1.5
1.2
0.9
0.6
0.3
0.0
$S(E_m)$ (1/MeV)
$1d_{5/2}$
$1d_{3/2}$
$2s_{1/2}$
$1f_{7/2}$
$1p_{1/2}$
$1p_{3/2}$
corr
$1s_{1/2}$
0
20
40
60
80
100
E_m (MeV)
1.8
1.5
1.2
0.9
0.6
0.3
0.0
$1d_{5/2}$
$1d_{3/2}$
$2s_{1/2}$
$1f_{7/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
corr
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
14.23	1d5/2	14.66
	1p1/2	
	1p3/2	
	1s1/2