KEK 理論センター JPARC 分室、JAEA 先端基礎研究センター共催研究会

「ストレンジネス核物理の発展方向」

Aug. 3–7, 2015

^{19}F を標的とする sd 殻ハイパー核の生成断面積

(Productions of sd-shell hypernuclei)

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Introduction

$S = -1$ **sector (Λ hypernuclei, ΛN interaction)**

(π^+, K^+) reaction (for wide-mass region)

O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57, 564 (2006).

γ spectroscopy (for p-shell hypernuclei)

H. Tamura, Nucl. Phys. A827, 153c (2009).

Effective ΛN interaction (for s- and p-shell hypernuclei)

$$V^{\rm eff}_{\Lambda N} = V_0 + V_{\sigma\sigma}\,\boldsymbol{\sigma}_N\cdot\boldsymbol{\sigma}_\Lambda + V_{\rm SLS}\,\boldsymbol{\ell}_{\Lambda N}\cdot(\boldsymbol{s}_\Lambda + \boldsymbol{s}_N) + V_{\rm ALS}\,\boldsymbol{\ell}_{\Lambda N}\cdot(\boldsymbol{s}_\Lambda - \boldsymbol{s}_N) + V_{\rm Tensor}\,S_{12}$$

- **p-shell model** **D.J. Millener, Nucl. Phys. A 804, 84 (2008).**
- **Few-body** **E. Hiyama, Prog. Part. Nucl. Phys. 63, 339 (2009).**

Next stage of hypernuclear studies

- ***sd*-shell region $\longleftarrow$ This study**
- $S = -2$ **sector (Ξ hypernuclei)**
- **ΛN-ΣN coupling interaction, ΞN-$\Lambda\Lambda$ coupling interaction**

Λ hypernuclei in *sd*-shell region

- **The level structures of *sd*-shell nuclei are richer and more complex than those of *p*-shell nuclei.**

For example

- **Parity doublet** $E({}^{19}\mathrm{Ne}, 1/2^-) - E({}^{19}\mathrm{Ne}, 1/2^+_{\mathrm{g.s.}}) = 0.275\mathrm{MeV}$
- **Rotational band**

Effects of hyperon addition for these core nuclei?

- **Even the Λ single-particle energies are not well known experimentally.**

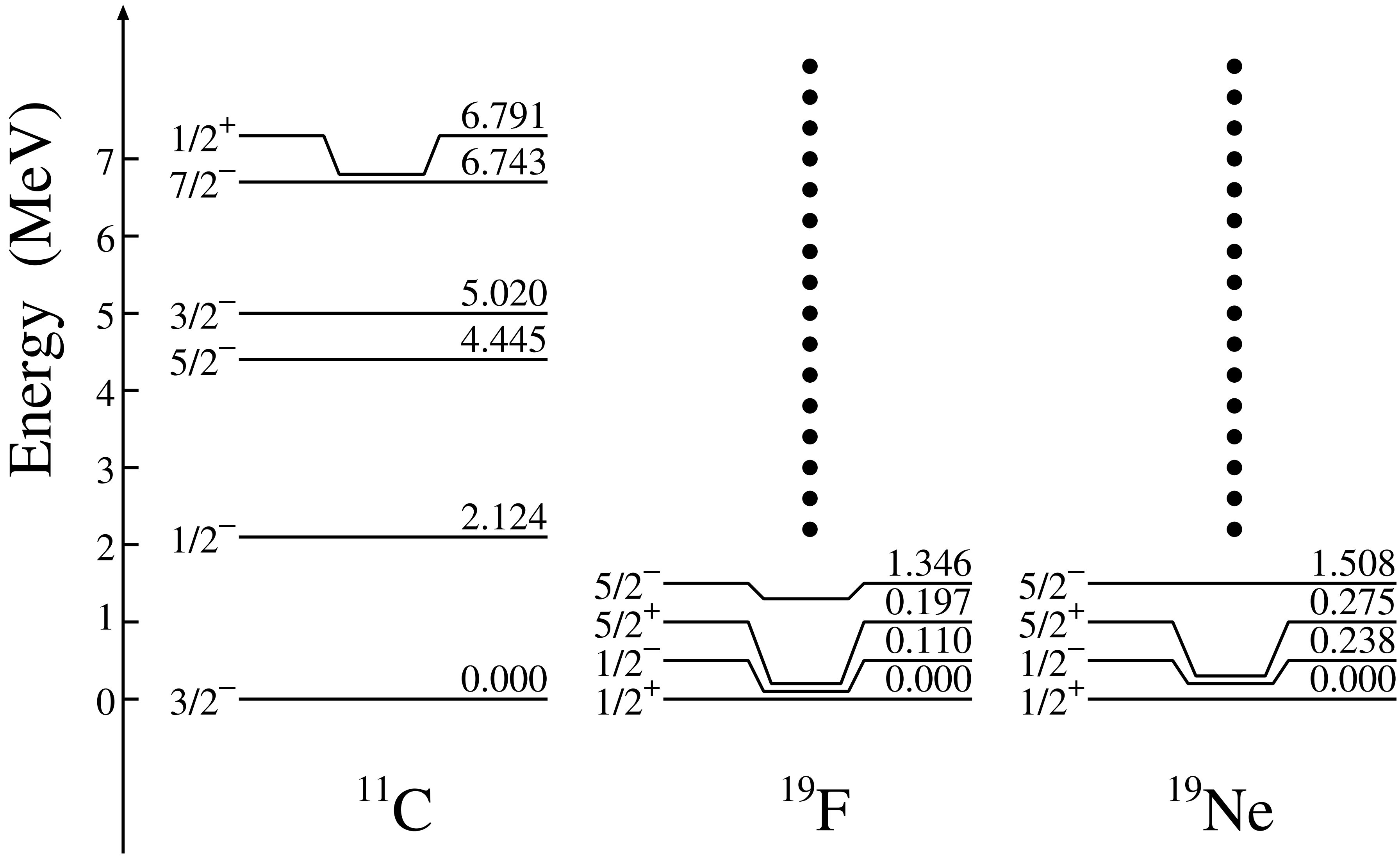
Production experiments

- (K^-, π^-) **reaction — J-PARC E13 (Production of ${}^{19}_{\Lambda}\mathrm{F}$, γ spectroscopy)**
- $(e, e'K^+)$ **reaction — JLab, MAMI**

This study

Energy levels, production cross-sections and electro-magnetic transitions of ${}^{19}_{\Lambda}\mathrm{F}$ (balence $2N$ in *sd*-shell)

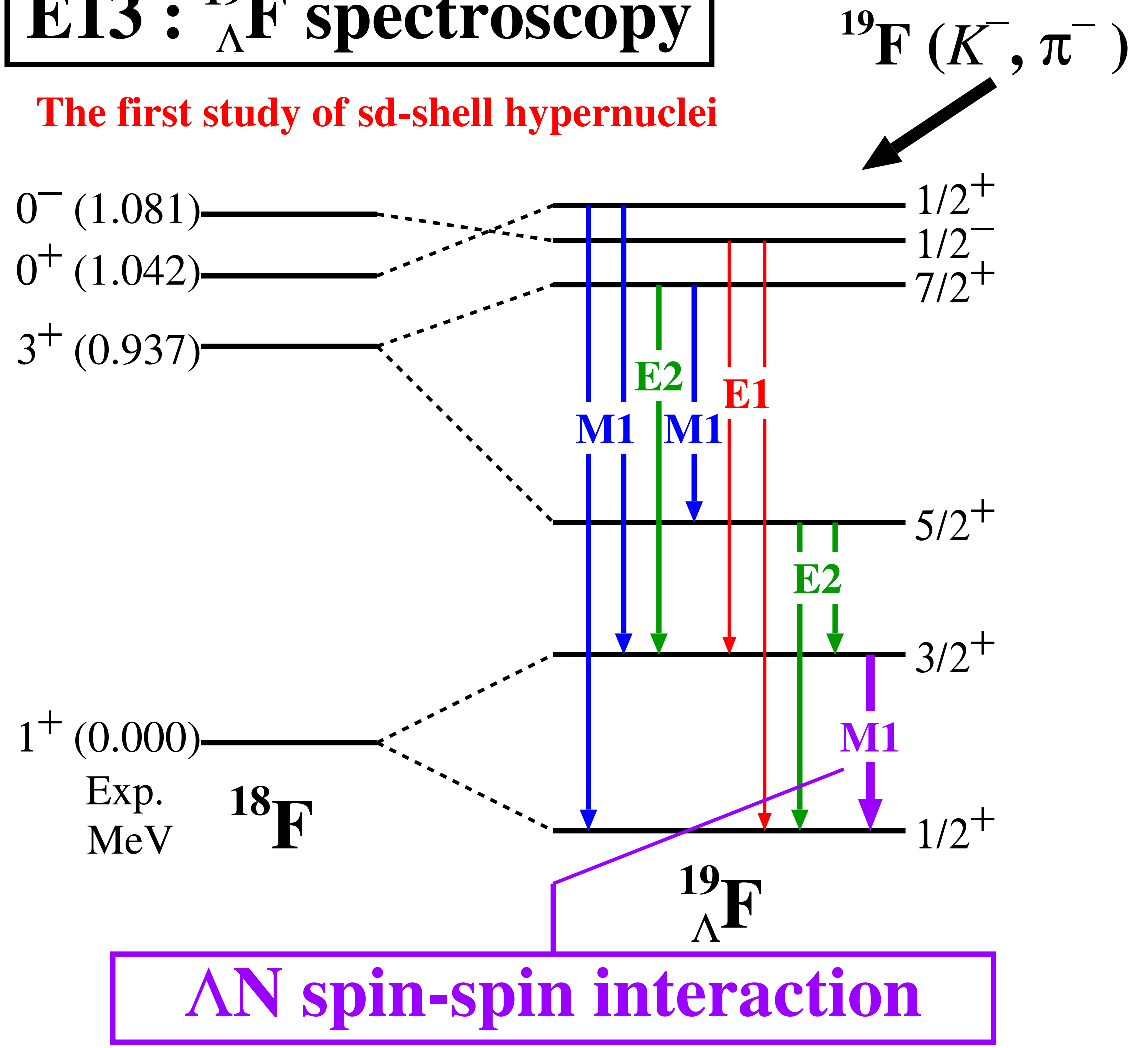
Energy levels of ^{11}C, ^{19}F, ^{19}Ne



J-PARC E13 Experiment

E13 : $^{19}_{\Lambda}$F spectroscopy

The first study of sd-shell hypernuclei



J-PARC E13

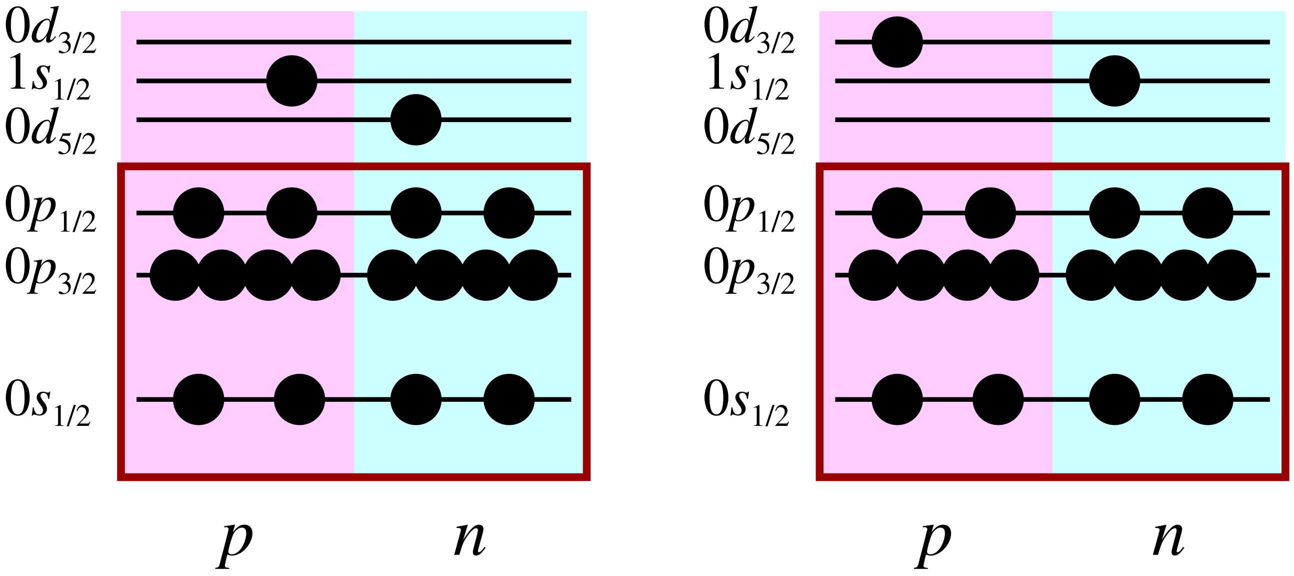
γ spectroscopy
($E1$, $M1$, $E2$ transitions)
for low-lying states of $^{19}_{\Lambda}$F

⇓

This study

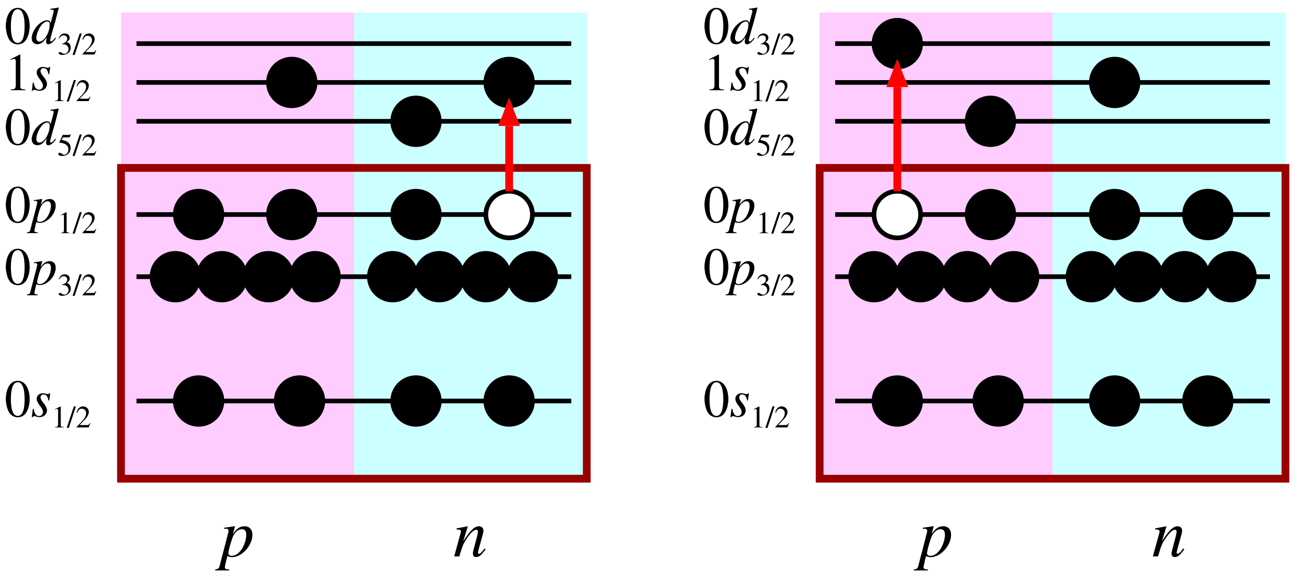
Calculation of the production cross-section of $^{19}_{\Lambda}$F by the (K^-, π^-) reaction at incident momentum of $1.8\,\mathrm{GeV}/c$

Shell model calculation (1)



$0\hbar\omega$ basis states

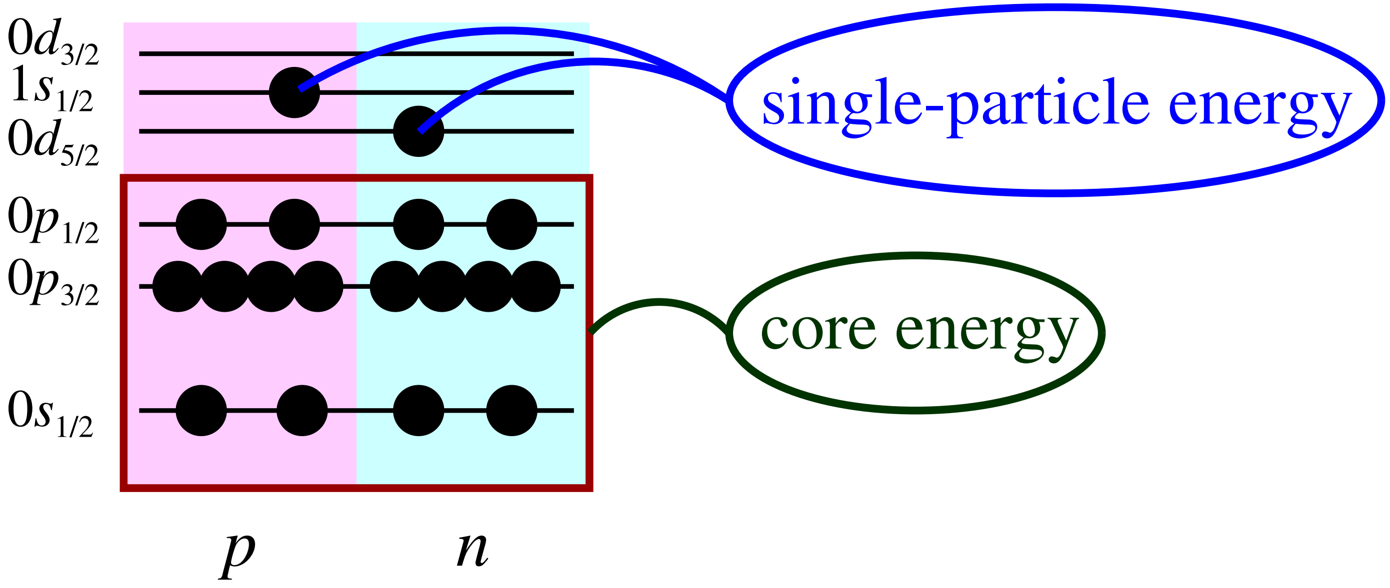
positive parity

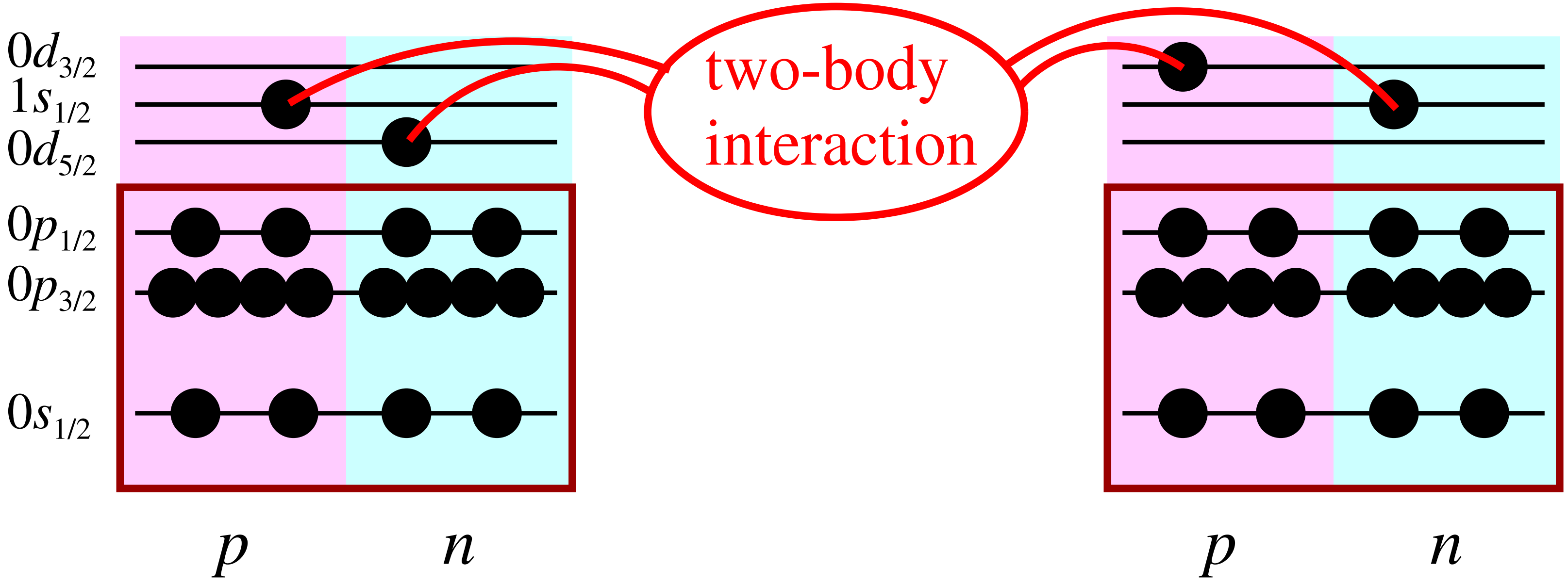


$1\hbar\omega$ basis states

negative parity

Shell model calculation (2)





Shell-model wave functions (1)

Model space (for $^{19}_{\Lambda}$F)

- **16 nucleons are inert in the ^{16}O core.**
- **2 valence nucleons move in the *sd*-shell orbits.**
- **$1p$-$1h$ $1\hbar\omega$-excited states are considered for J^- states.**
- **Λ hyperon is assumed to be in the $0s$, $0p$, *sd*-shell orbits.**

Core states (^{18}F)	**+ parity ($J^+_{\rm core}$)**	$(0s)^4\,(0p)^{12}$	$(sd)^2$	**($0p$-$0h$)**
	− parity ($J^-_{\rm core}$)	$(0s)^4\,(0p)^{11}$	$(sd)^3$	**($1p$-$1h$)**
Λ single-particle state	**+ parity (j^+_{Λ})**	$0s^{\Lambda}_{1/2}$,	$0d^{\Lambda}_{5/2}$, $0d^{\Lambda}_{3/2}$, $1s^{\Lambda}_{1/2}$	
	− parity (j^-_{Λ})	$0p^{\Lambda}_{3/2}$, $0p^{\Lambda}_{1/2}$		

4 types of basis states

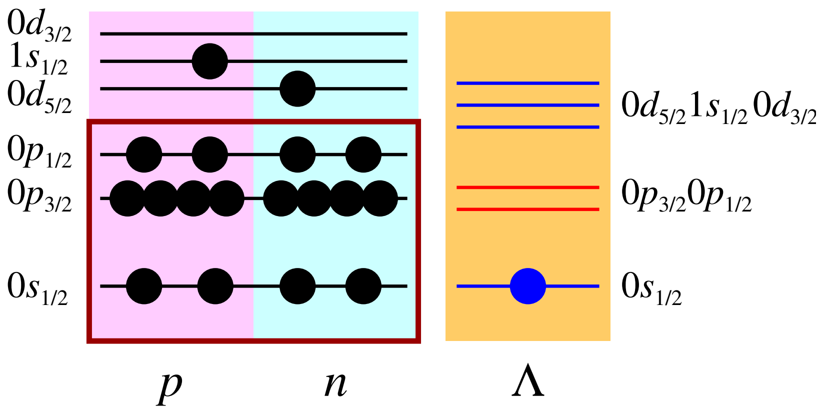
(1) $J^+_{\rm core}\otimes j^+_{\Lambda}$ **positive** **(2)** $J^+_{\rm core}\otimes j^-_{\Lambda}$ **negative**

(3) $J^-_{\rm core}\otimes j^+_{\Lambda}$ **negative** **(4)** $J^-_{\rm core}\otimes j^-_{\Lambda}$ **positive**

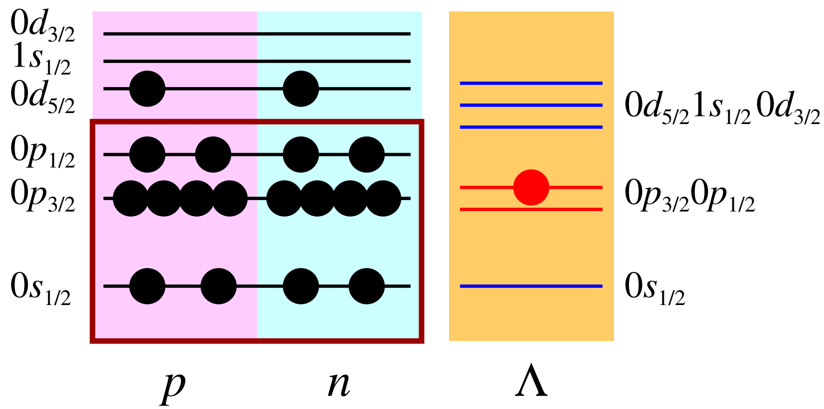
Shell-model wave functions (2)

4 types of basis states (For example, basis states of $^{19}_{\Lambda}\mathrm{F}$)

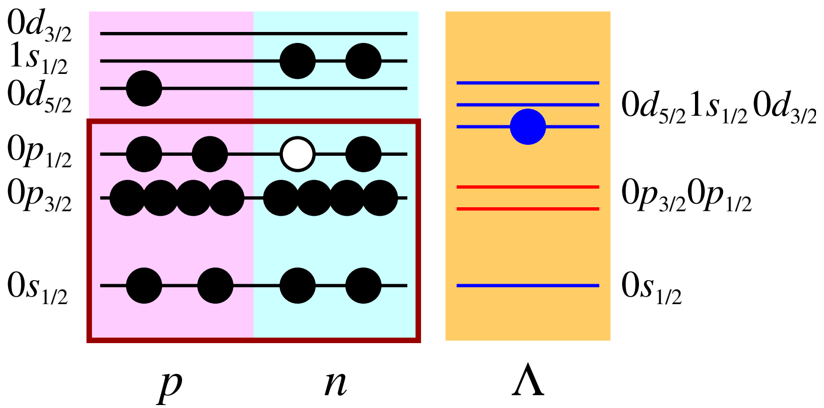
$J^{+}_{\mathrm{core}} \otimes j^{+}_{\Lambda}$ **positive**



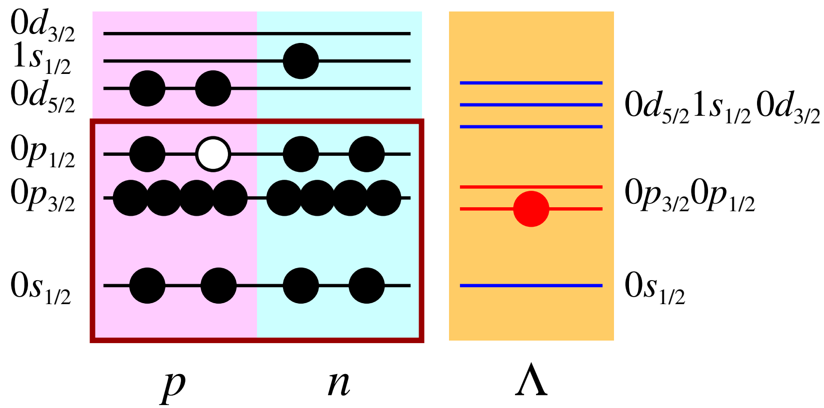
$J^{+}_{\mathrm{core}} \otimes j^{-}_{\Lambda}$ **negative**



$J^{-}_{\mathrm{core}} \otimes j^{+}_{\Lambda}$ **negative**



$J^{-}_{\mathrm{core}} \otimes j^{-}_{\Lambda}$ **positive**



Shell-model Hamiltonian

Two-body interaction

***NN* effective interaction**

$\langle (sd)^2 | V | (sd)^2 \rangle$

modified Kuo-Brown G-matrix

NP85, 40 (1966).

PTP52, 509 (1974).

$\langle p^{-1}\, sd | V | p^{-1}\, sd \rangle$

Warburton-Brown PSDT

PRC46, 923 (1992)

ΛN effective interaction

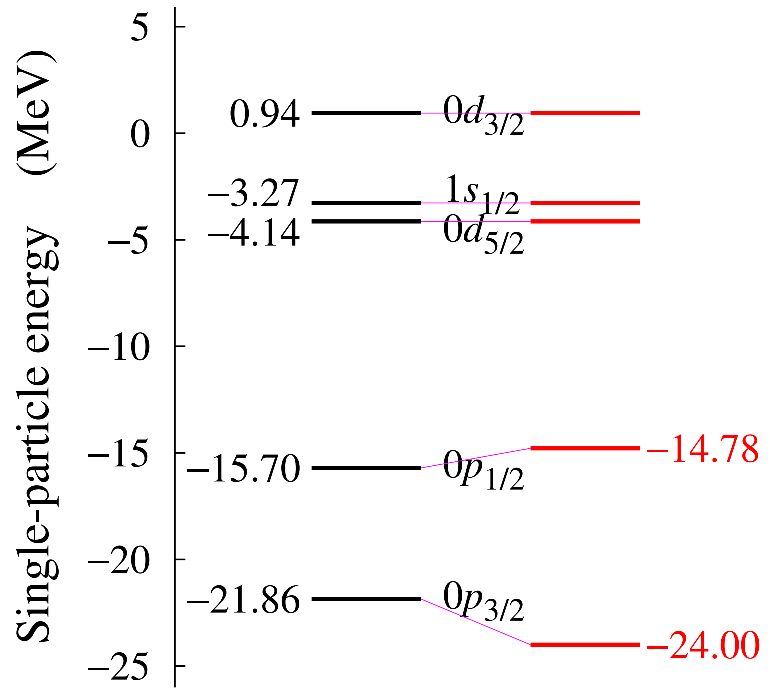
$\langle N\Lambda | V | N\Lambda \rangle$

NSC97f

PRC59, 21 (1999)

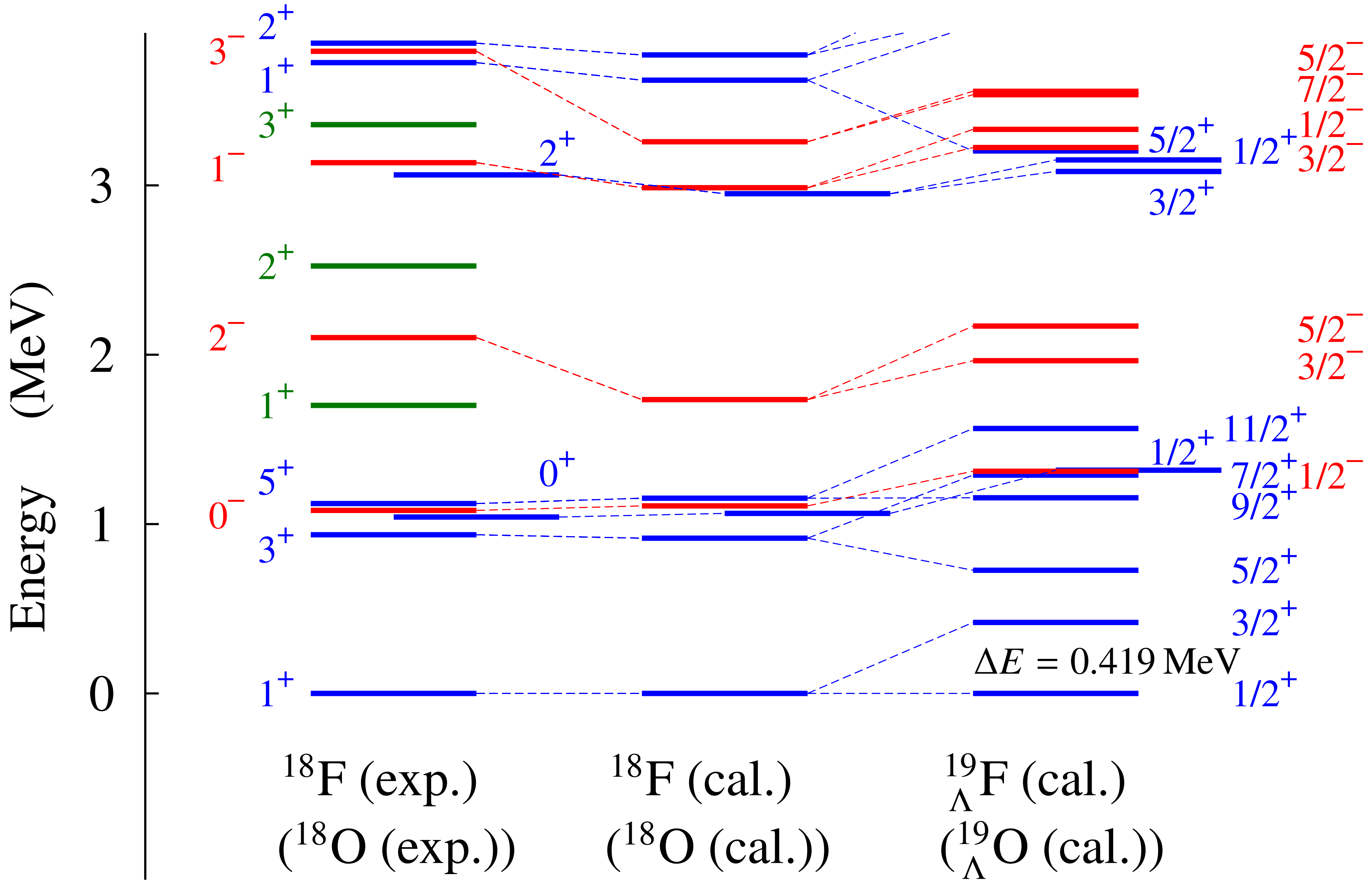
Using $2.5V_{\rm ALS}$ to adjust *LS* splitting

Single-particle energies for nucleon orbits with respect to ^{16}O core



Adjusting s.p.e. of $0p_{3/2}$ and $0p_{1/2}$ to reproduce the energy levels of the ^{19}F J^- states

Numerical Results : Energy levels for ${}^{19}_{\Lambda}$F and ^{18}F



Configuration of ground state of $^{19}\mathrm{F}$

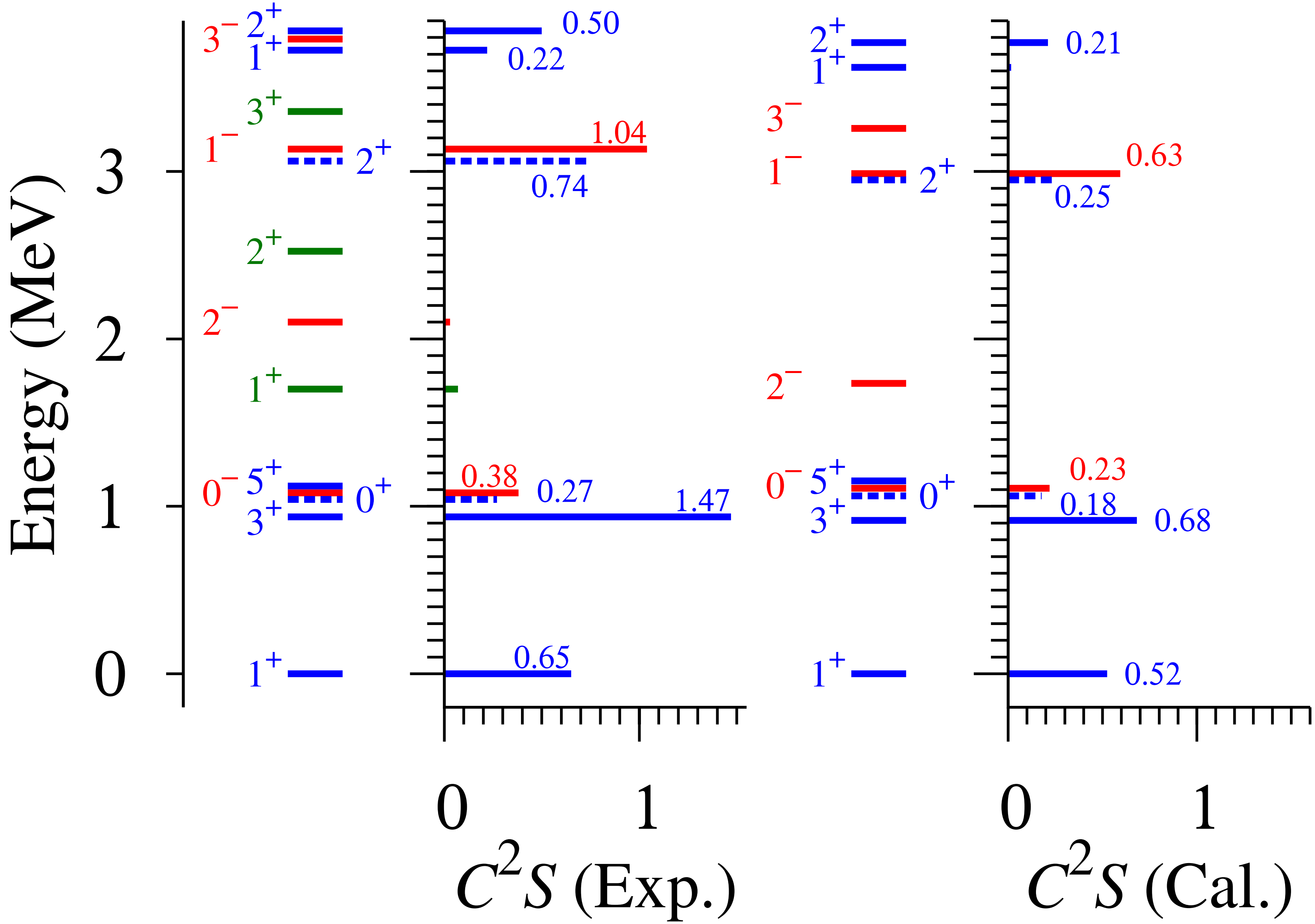
$$
\begin{aligned}
|\,^{19}\mathrm{F}; 1/2^+_{\mathrm{g.s.}}\rangle = & + \sqrt{0.11}\,|\,(^{16}\mathrm{O})(0d_{5/2})^3\rangle \\
& + \sqrt{0.31}\,|\,(^{16}\mathrm{O})(0d_{5/2})^2_{T=1,J=0}(1s_{1/2})\rangle \\
& - \sqrt{0.14}\,|\,(^{16}\mathrm{O})(0d_{5/2})^2_{T=0,J=1}(1s_{1/2})\rangle \\
& + \sqrt{0.11}\,|\,(^{16}\mathrm{O})(0d_{5/2})(0d_{3/2})(1s_{1/2})\rangle \\
& + \sqrt{0.17}\,|\,(^{16}\mathrm{O})(1s_{1/2})^3\rangle \\
& + \cdots
\end{aligned}
$$

The ground state of $^{19}\mathrm{F}$ is not described by a simple configuration due to the $1s_{1/2}$ orbit.

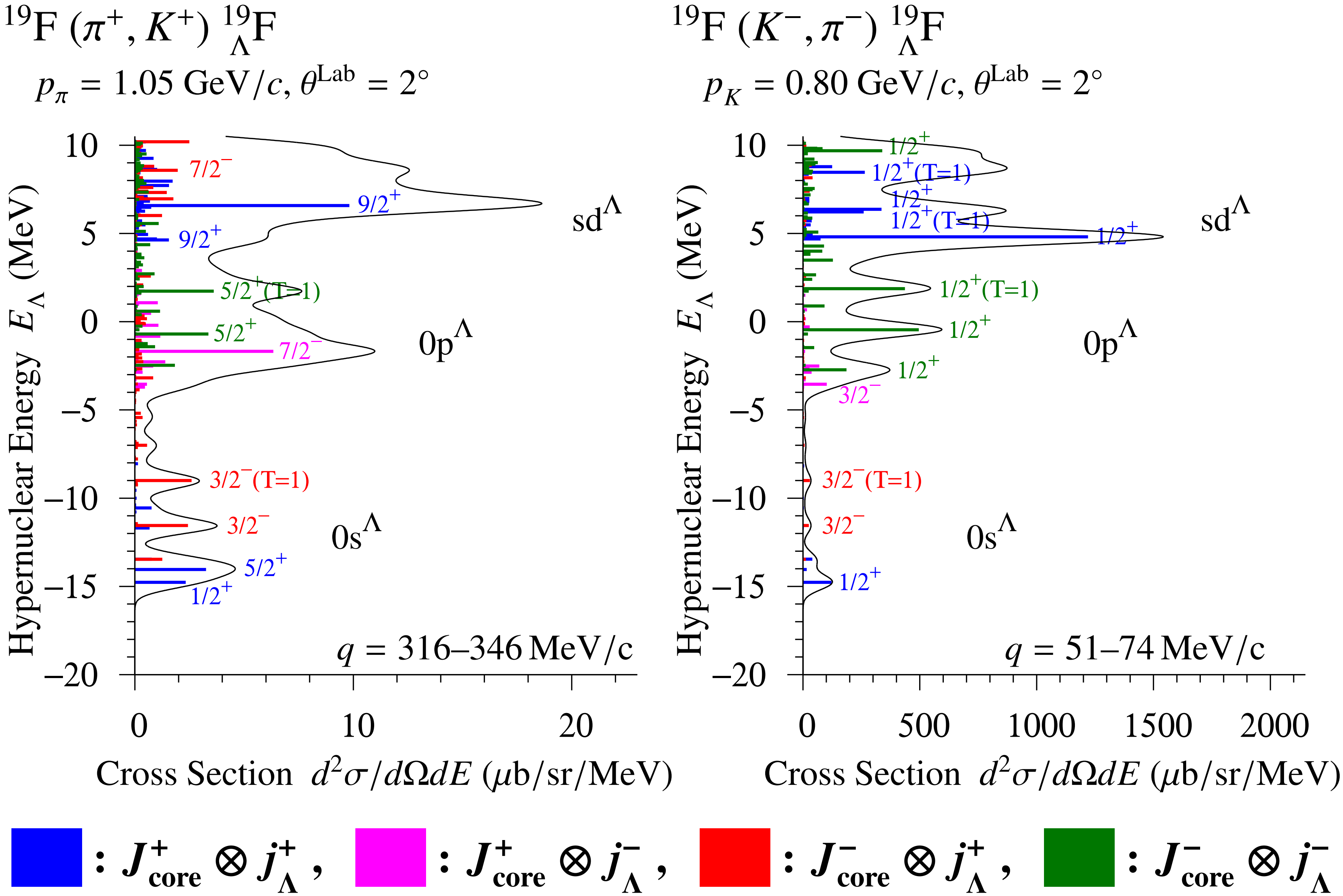
$\Longrightarrow$ In the production of $^{19}_{\Lambda}\mathrm{F}$, transition strengths are fragmented among several states and have small values.

(Magnetic moment of $^{19}\mathrm{F}$ cal. $2.89\mu_N$, exp. $2.62\mu_N$)

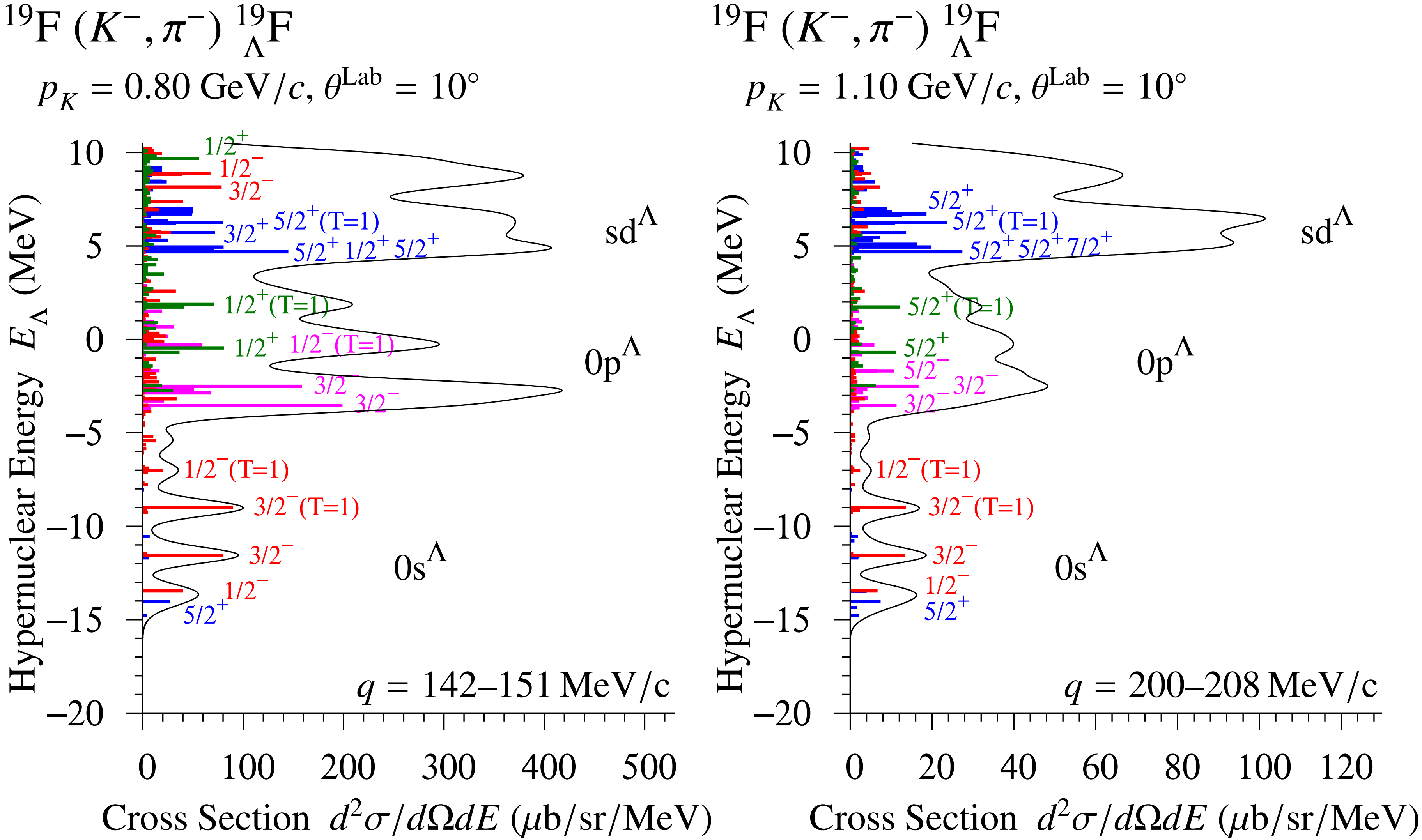
Spectroscopic factors of pickup reaction from ^{19}F

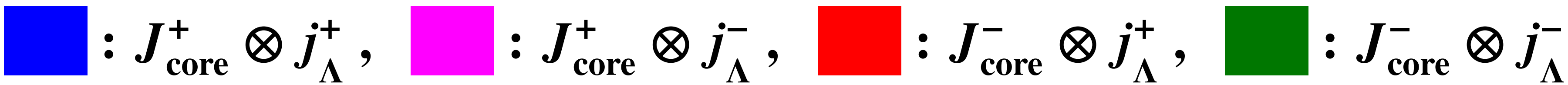


Cross sections of $^{19}\mathrm{F}(\pi^+, K^+)$ and $^{19}\mathrm{F}(K^-, \pi^-)$

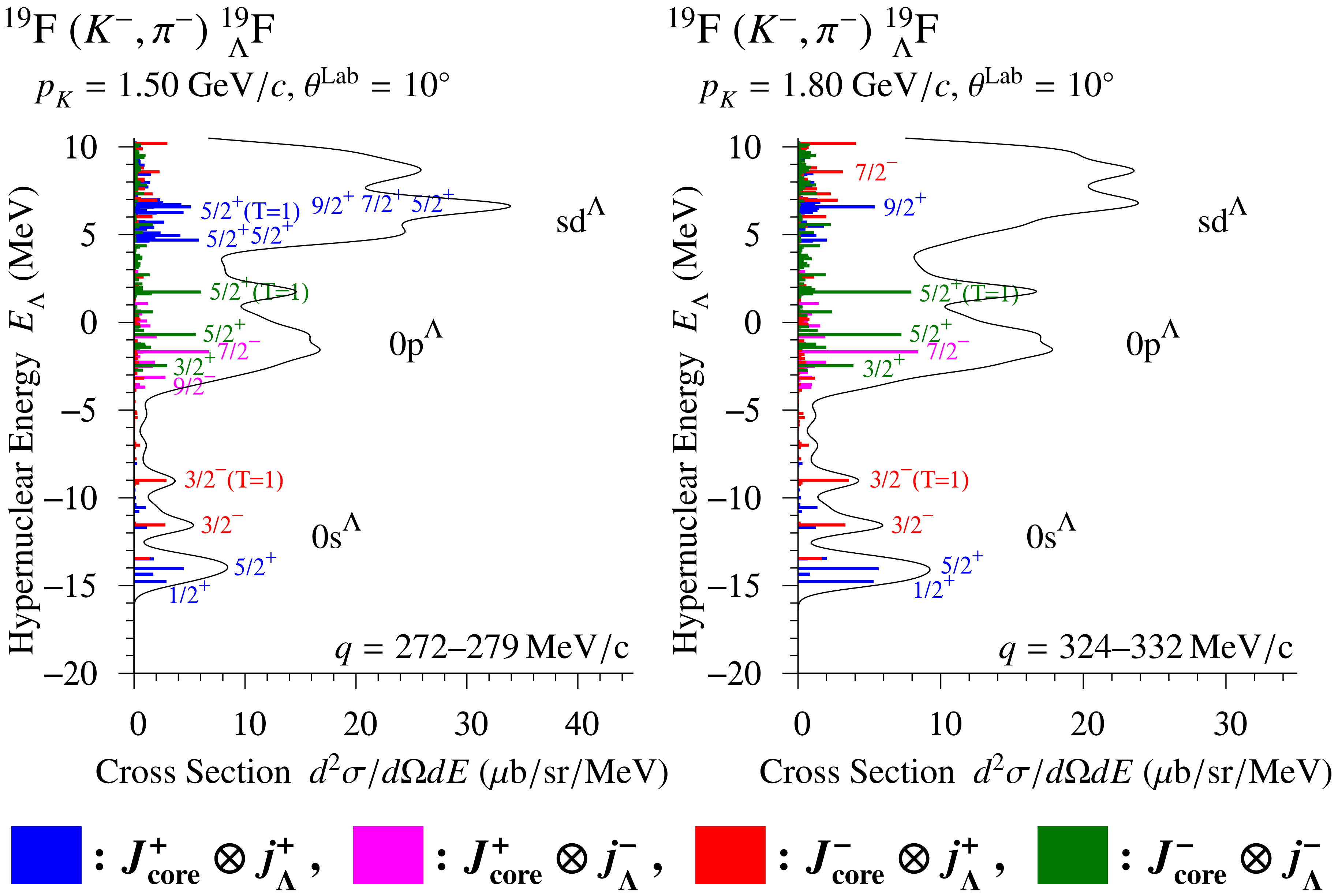


Cross sections of $^{19}\mathrm{F}(K^-, \pi^-)$ at different incident momemta (1)

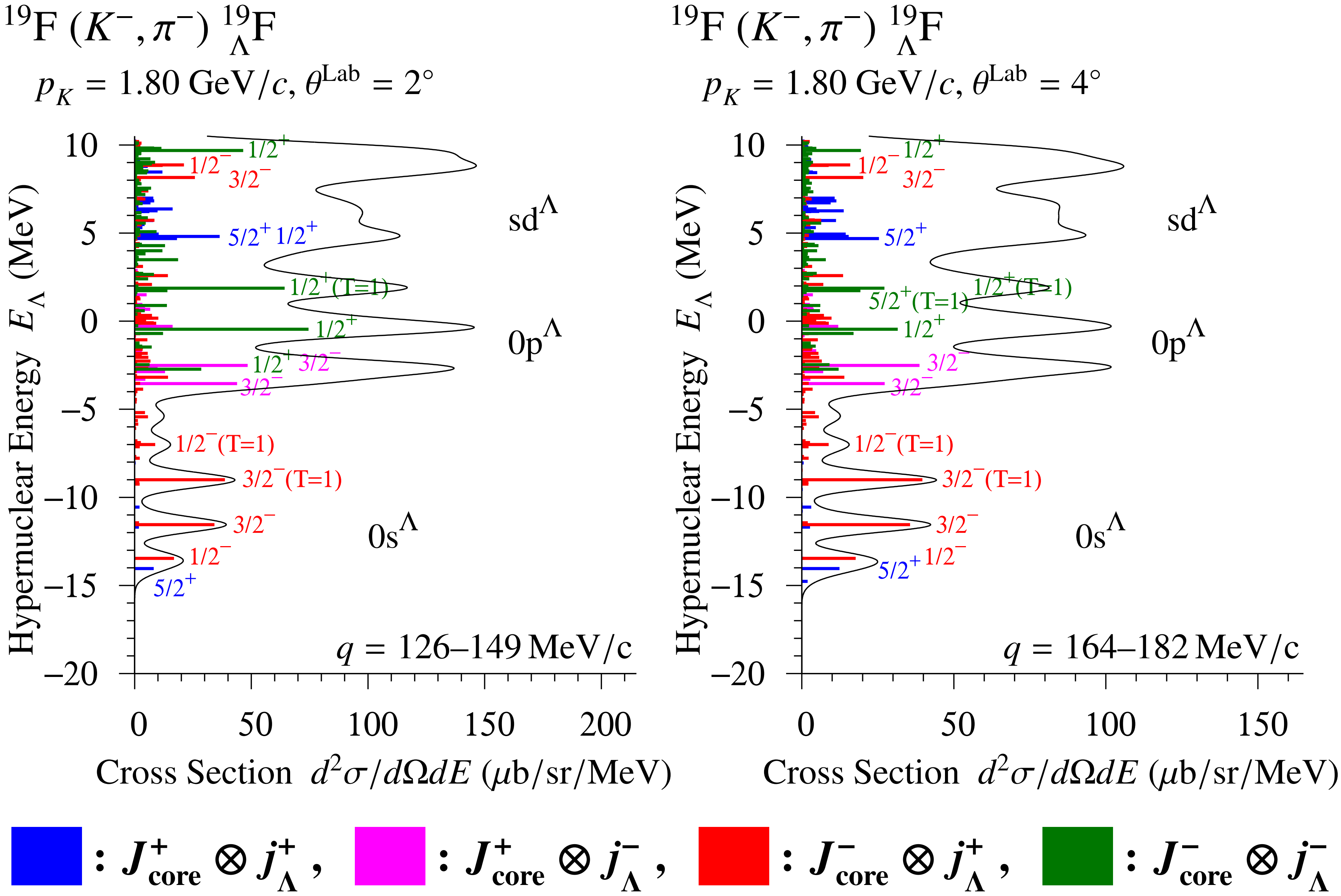




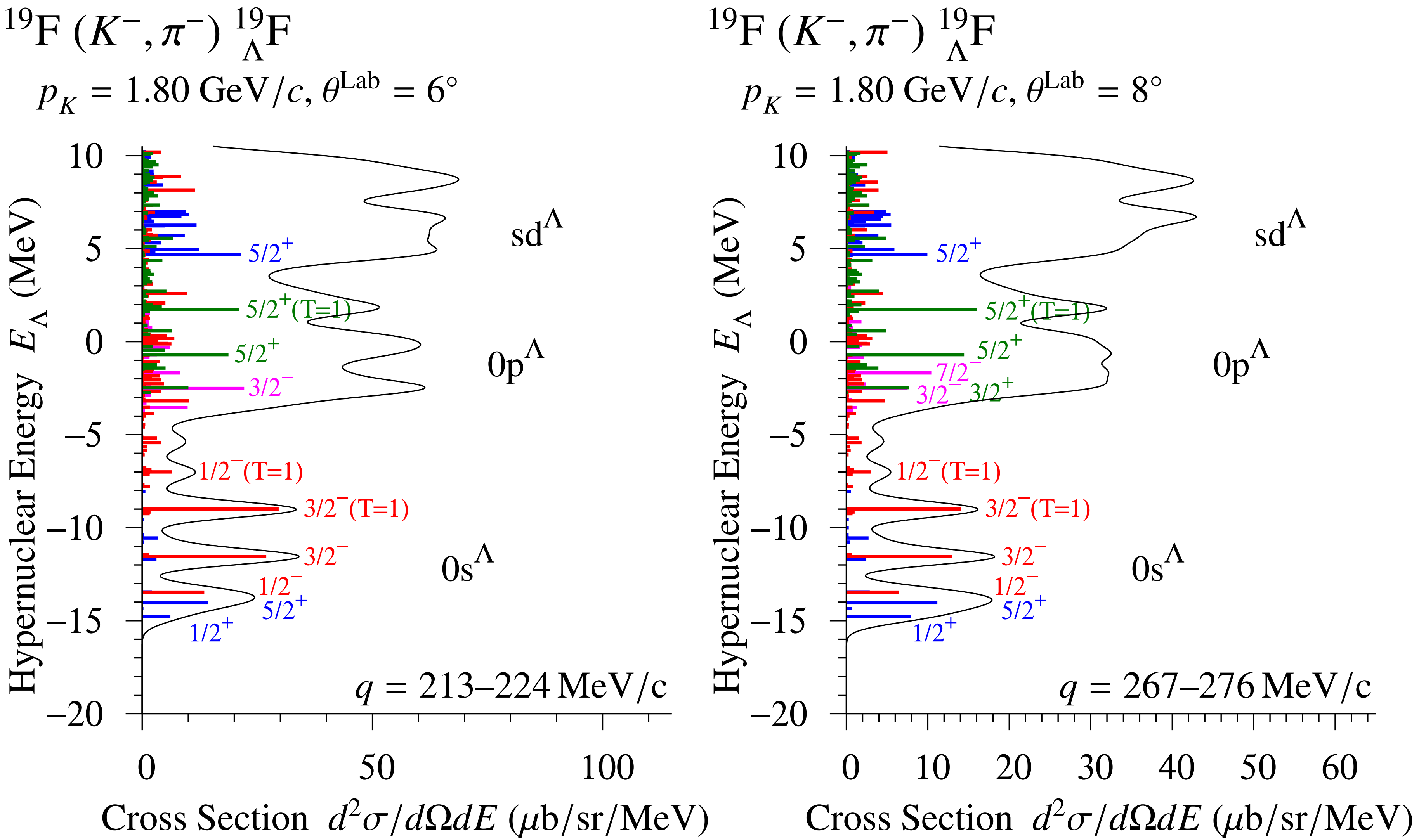
Cross sections of $^{19}\mathrm{F}(K^-,\pi^-)$ at different incident momemta (2)



Cross sections of $^{19}\mathrm{F}(K^-, \pi^-)$ at different scattering angles (1)

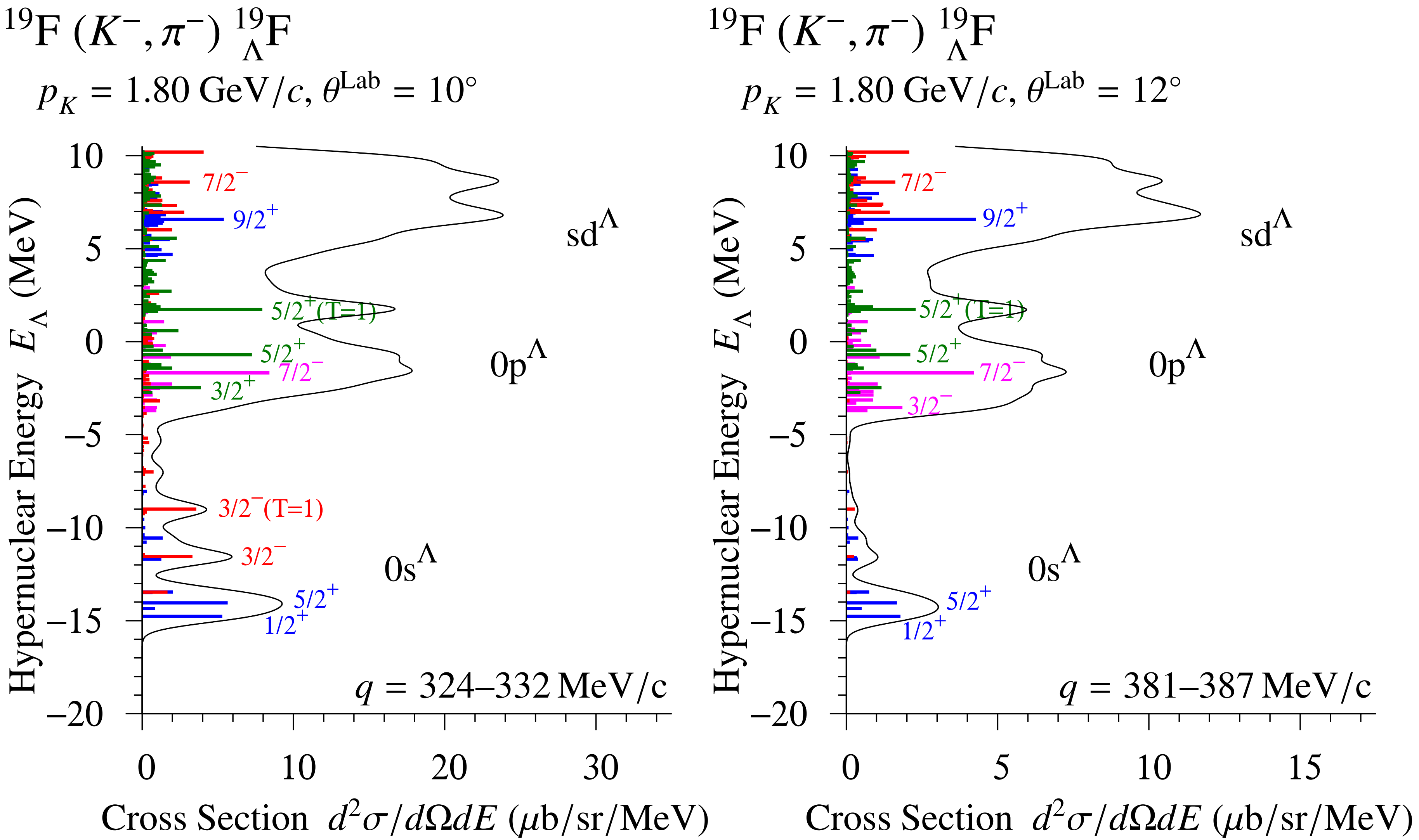


Cross sections of $^{19}\mathrm{F}(K^-,\pi^-)$ at different scattering angles (2)



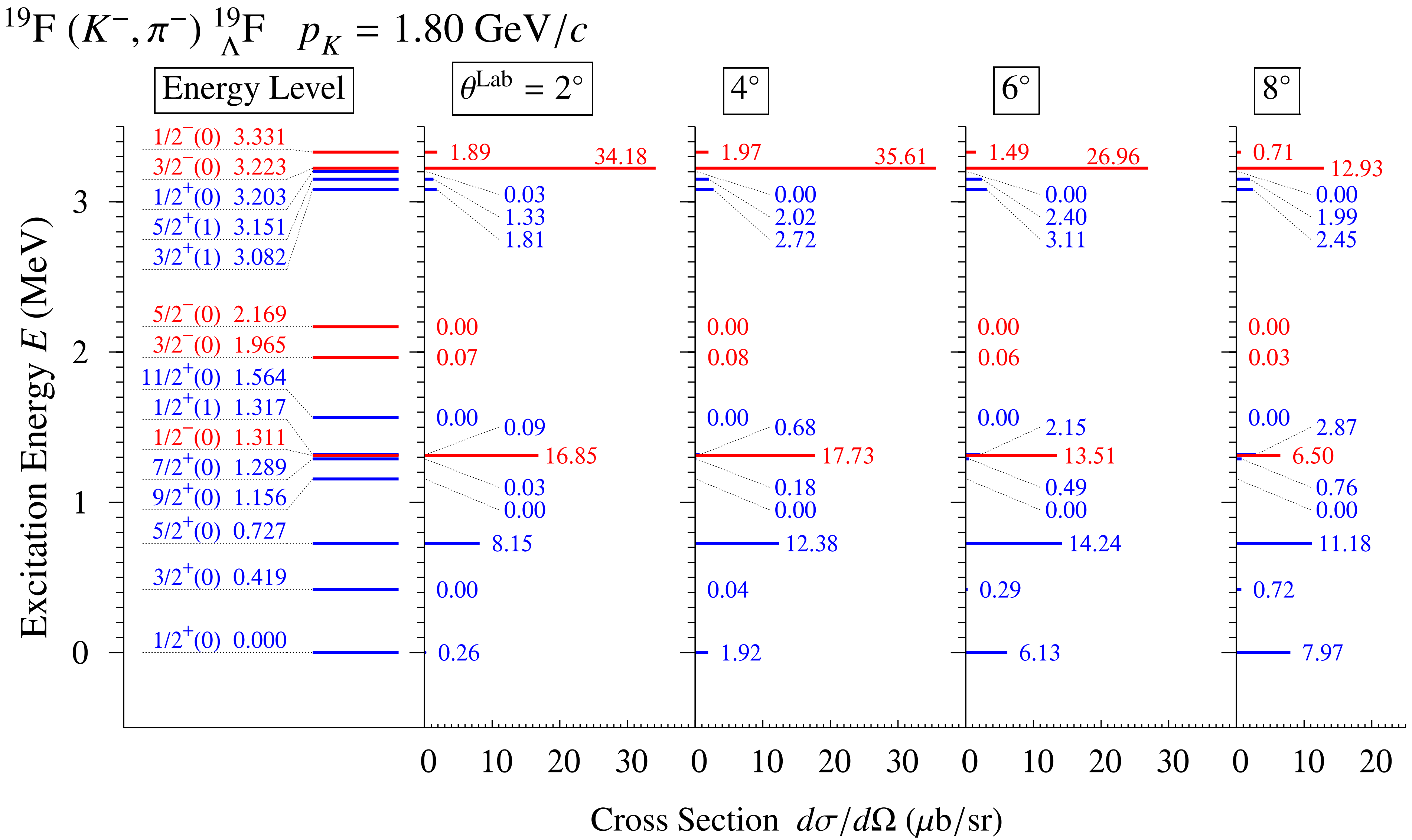
Blue: $J^+_{\mathrm{core}} \otimes j^+_\Lambda$, Magenta: $J^+_{\mathrm{core}} \otimes j^-_\Lambda$, Red: $J^-_{\mathrm{core}} \otimes j^+_\Lambda$, Green: $J^-_{\mathrm{core}} \otimes j^-_\Lambda$

Cross sections of $^{19}\mathrm{F}(K^-,\pi^-)$ at different scattering angles (3)

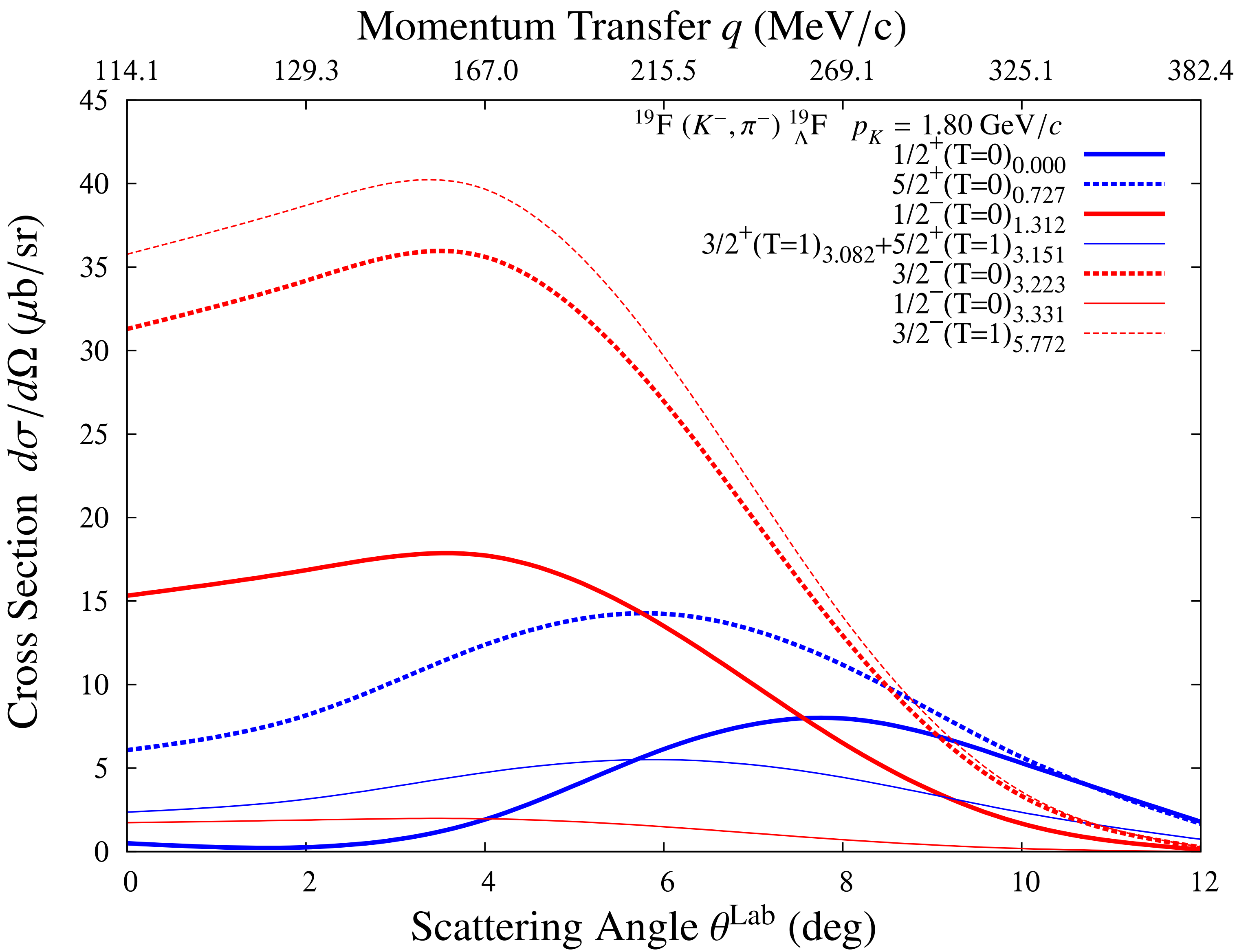


: $J^+_{\mathrm{core}} \otimes j^+_\Lambda$, : $J^+_{\mathrm{core}} \otimes j^-_\Lambda$, : $J^-_{\mathrm{core}} \otimes j^+_\Lambda$, : $J^-_{\mathrm{core}} \otimes j^-_\Lambda$

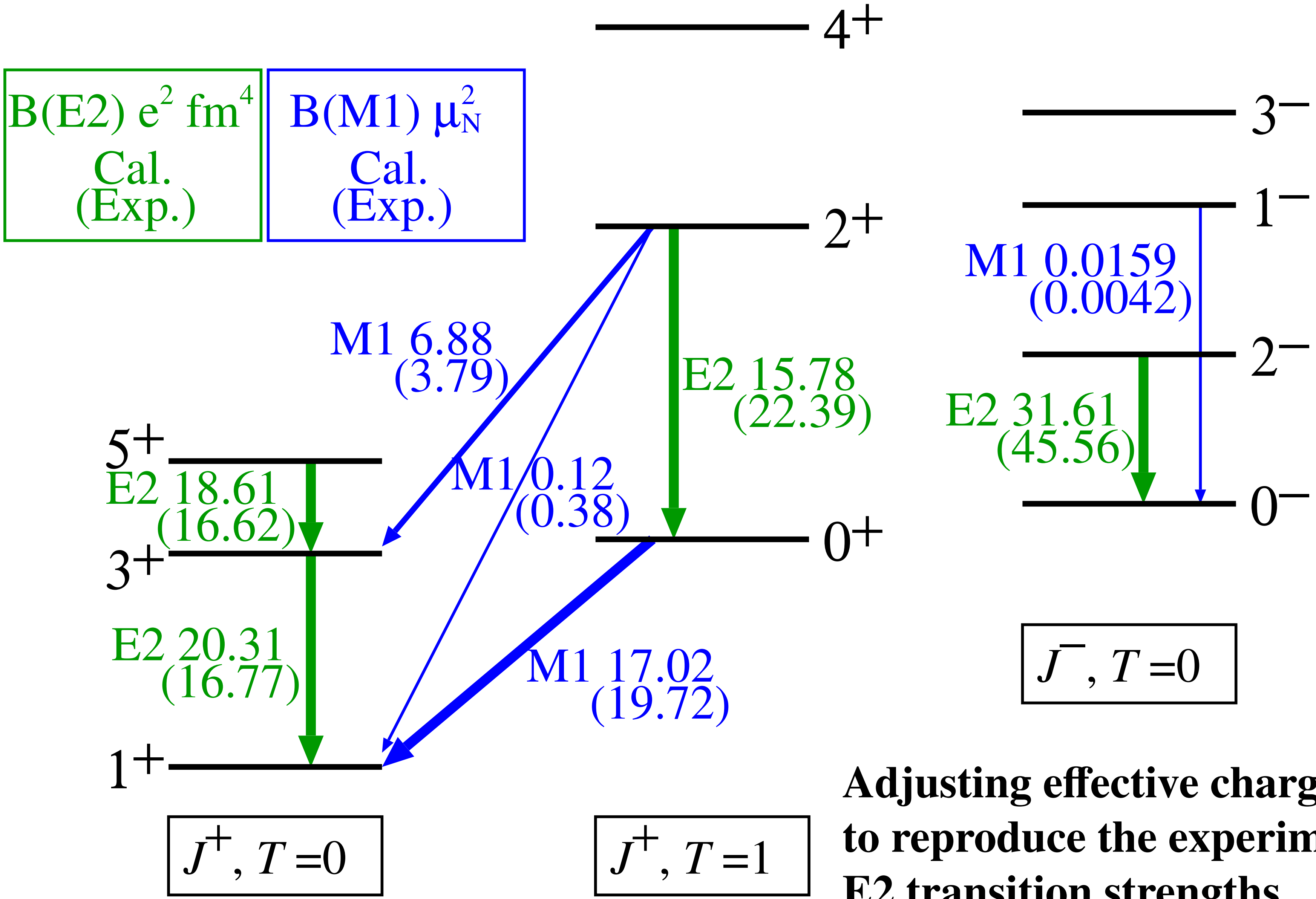
Cross sections of $^{19}F(K^-,\pi^-)$ for low-lying states (1)



Cross sections of $^{19}\mathrm{F}(K^-, \pi^-)$ for low-lying states (2)

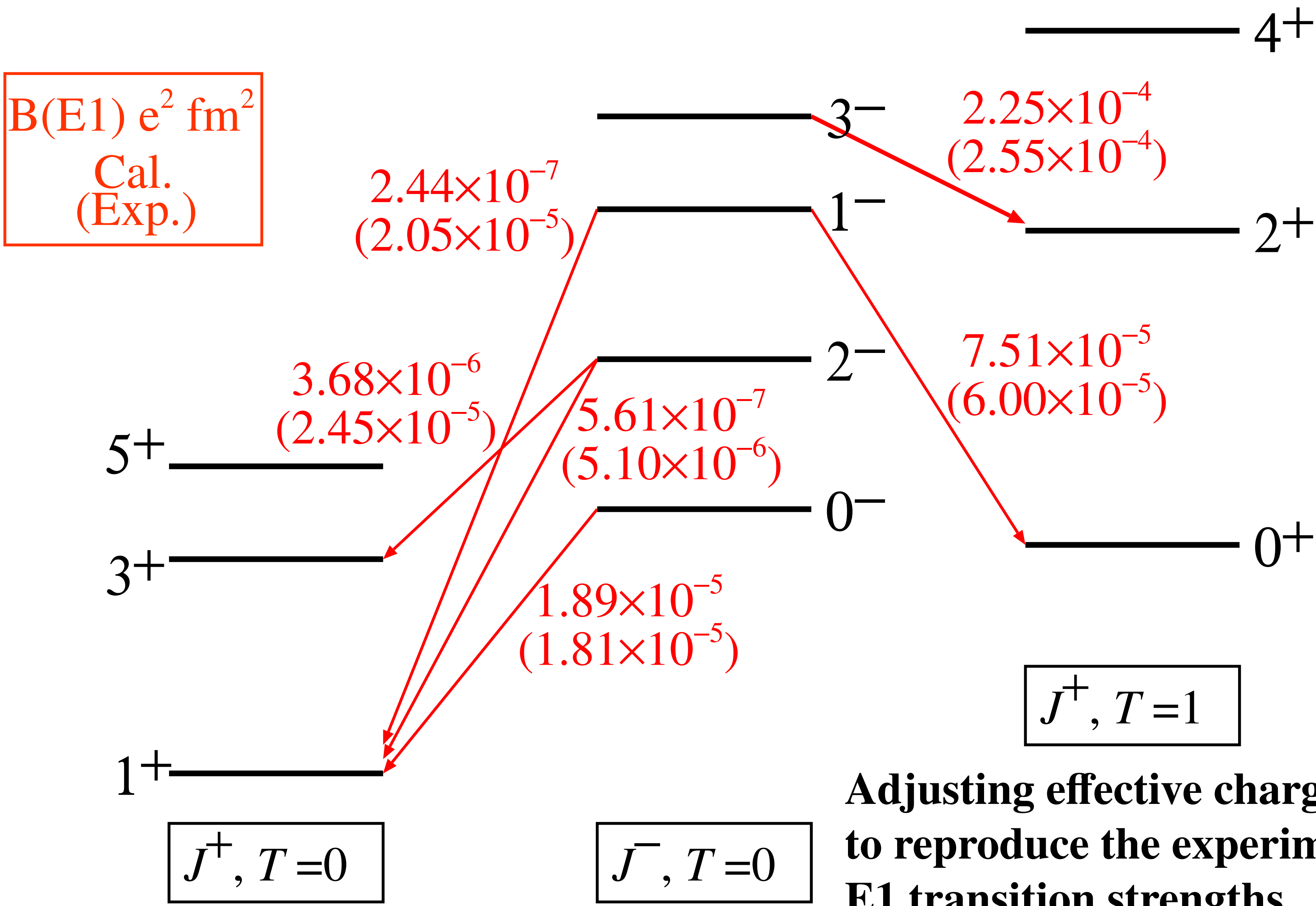


M1 and E2 transitions of ^{18}F



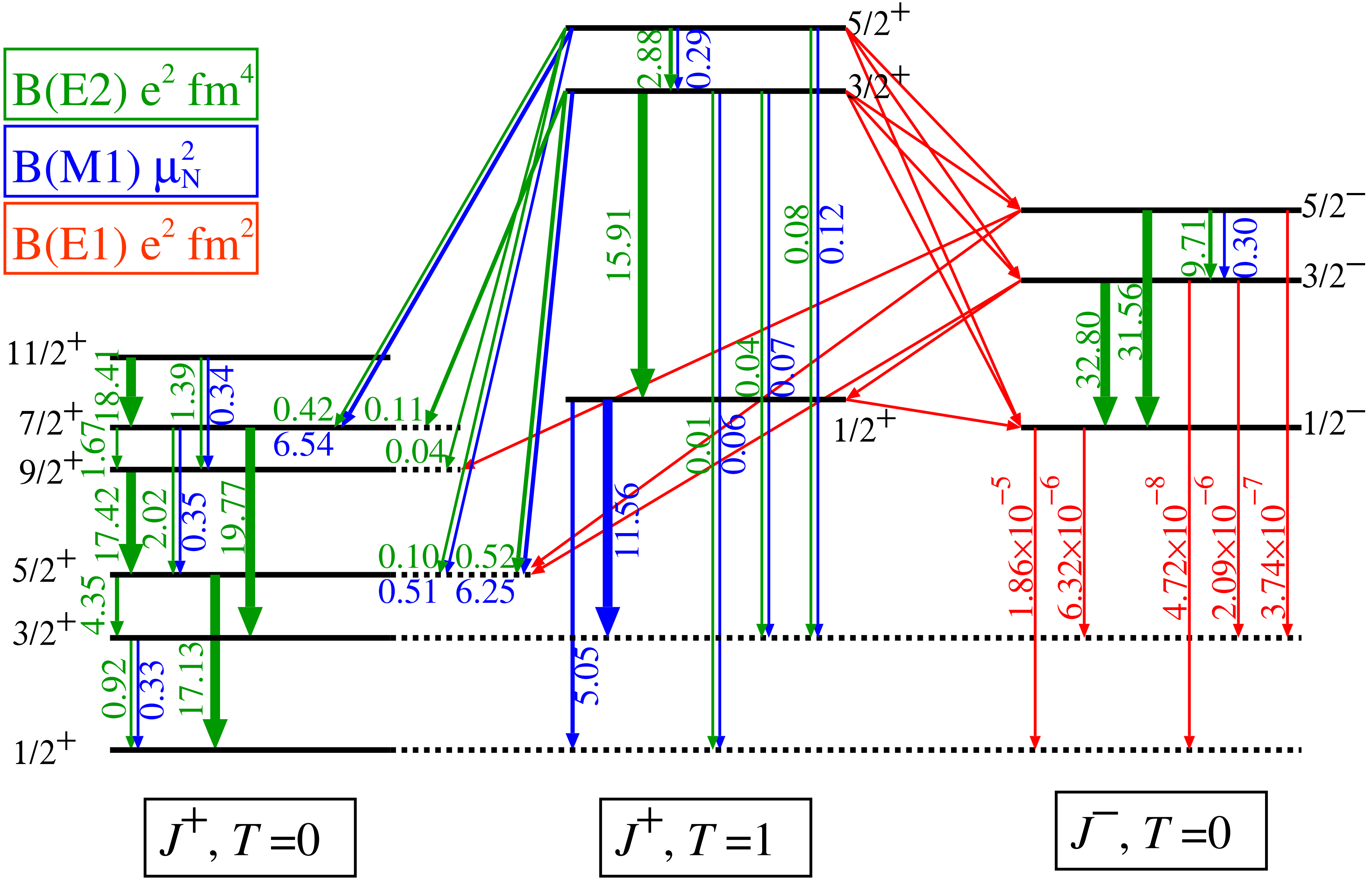
Adjusting effective charges to reproduce the experimental E2 transition strengths

E1 transitions of ^{18}F



Adjusting effective charges to reproduce the experimental E1 transition strengths

E2, M1 and E1 transitions of $^{19}_{\Lambda}F$



Summary

As a typical gate to medium-heavy *sd*-shell hypernuclei, we have calculated the energy levels, the production cross sections and electro-magnetic transition strengths of $^{19}_{\Lambda}$F by using the multi-configuration shell model.

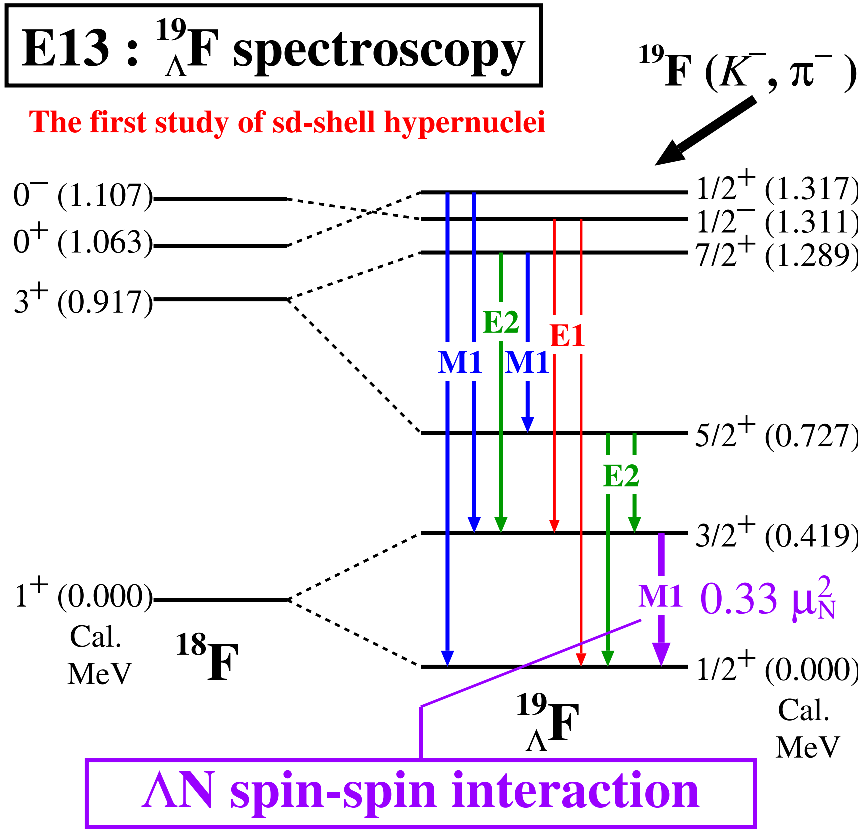
$\Delta E(3/2^+ - 1/2^+_{g.s.}) = 0.419$ MeV

$B(\mathrm{M1}; 3/2^+ \rightarrow 1/2^+_{g.s.}) = 0.33\,\mu_N^2$

However the cross section of $3/2^+$ states is the small value of

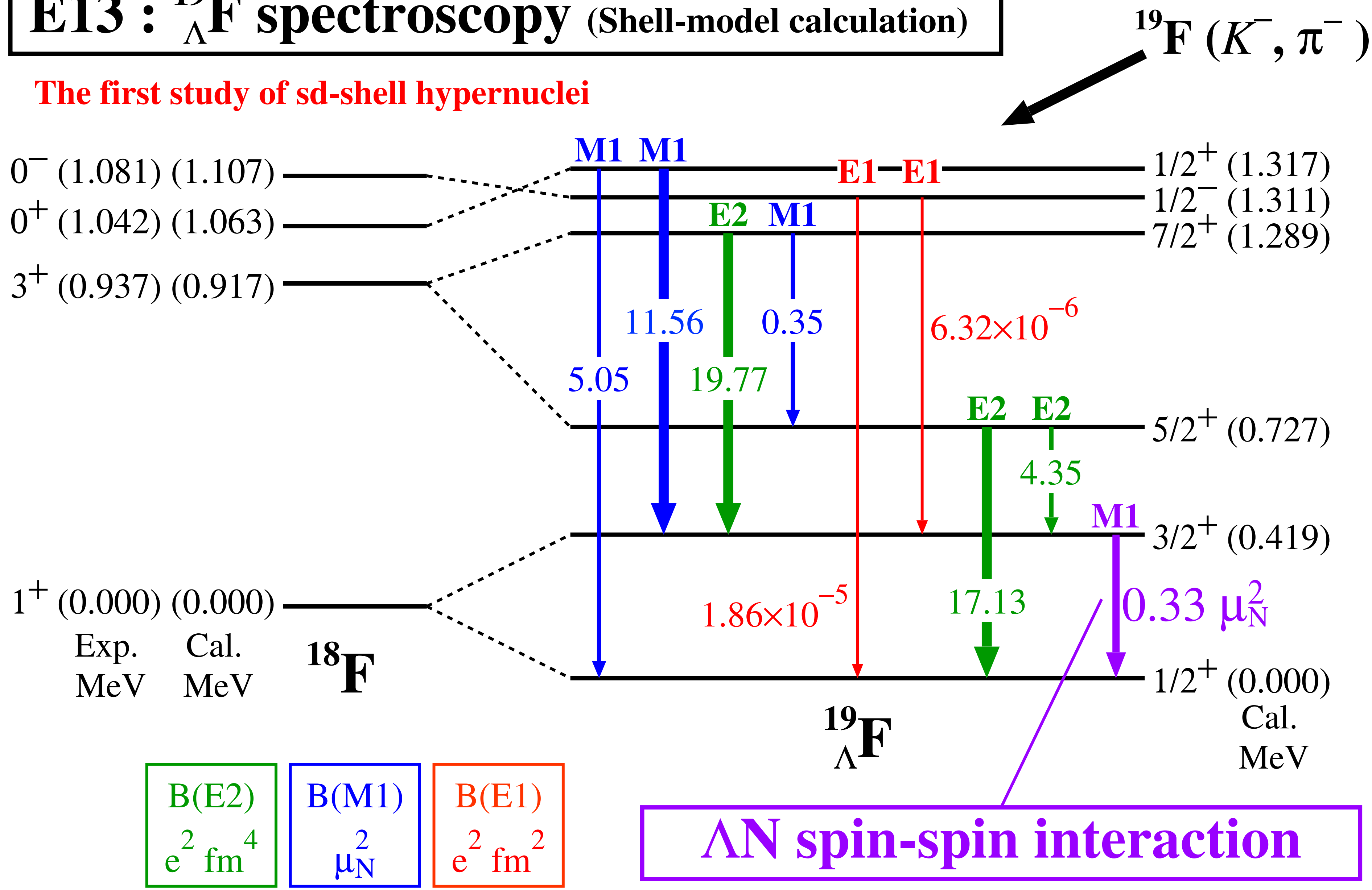
$d\sigma/d\Omega = 0.29\,\mu$b/sr

in ^{19}F$(K^-, \pi^-)^{19}_{\Lambda}$F with $p_K = 1.80$ GeV$/c$ and $\theta^{\mathrm{Lab}} = 6°$.



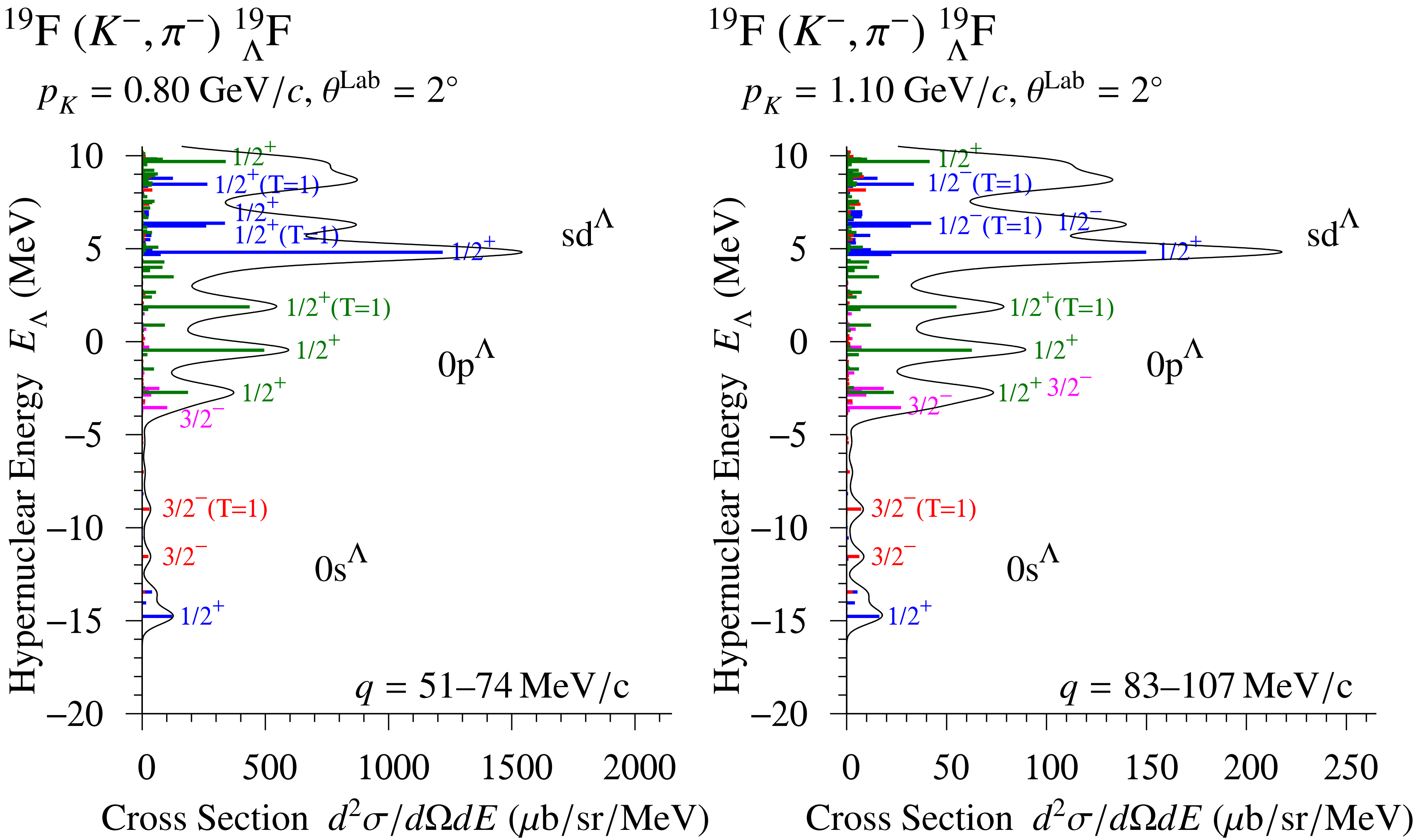
E13 : $^{19}_{\Lambda}$F spectroscopy (Shell-model calculation)

The first study of sd-shell hypernuclei



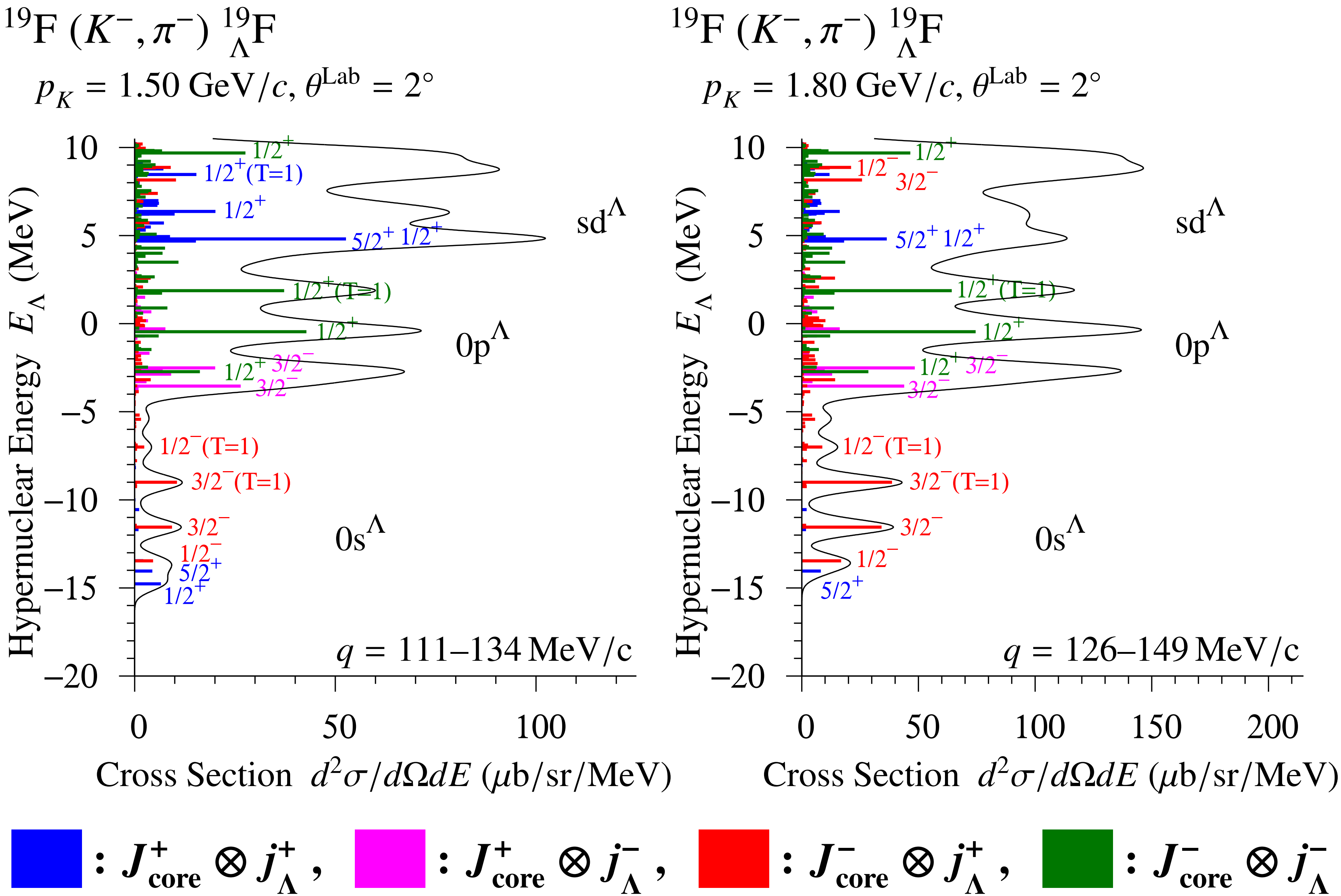
Backup

Cross sections of $^{19}\mathrm{F}(K^-,\pi^-)$ at different incident momemta (a)



■ : $J^+_{\mathrm{core}} \otimes j^+_\Lambda$, ■ : $J^+_{\mathrm{core}} \otimes j^-_\Lambda$, ■ : $J^-_{\mathrm{core}} \otimes j^+_\Lambda$, ■ : $J^-_{\mathrm{core}} \otimes j^-_\Lambda$

Cross sections of $^{19}\mathrm{F}(K^-, \pi^-)$ at different incident momemta (b)



Cross section of $^{19}F(\gamma, K^+)$