Fluorine isotope systematics: comparing *ab initio* approaches

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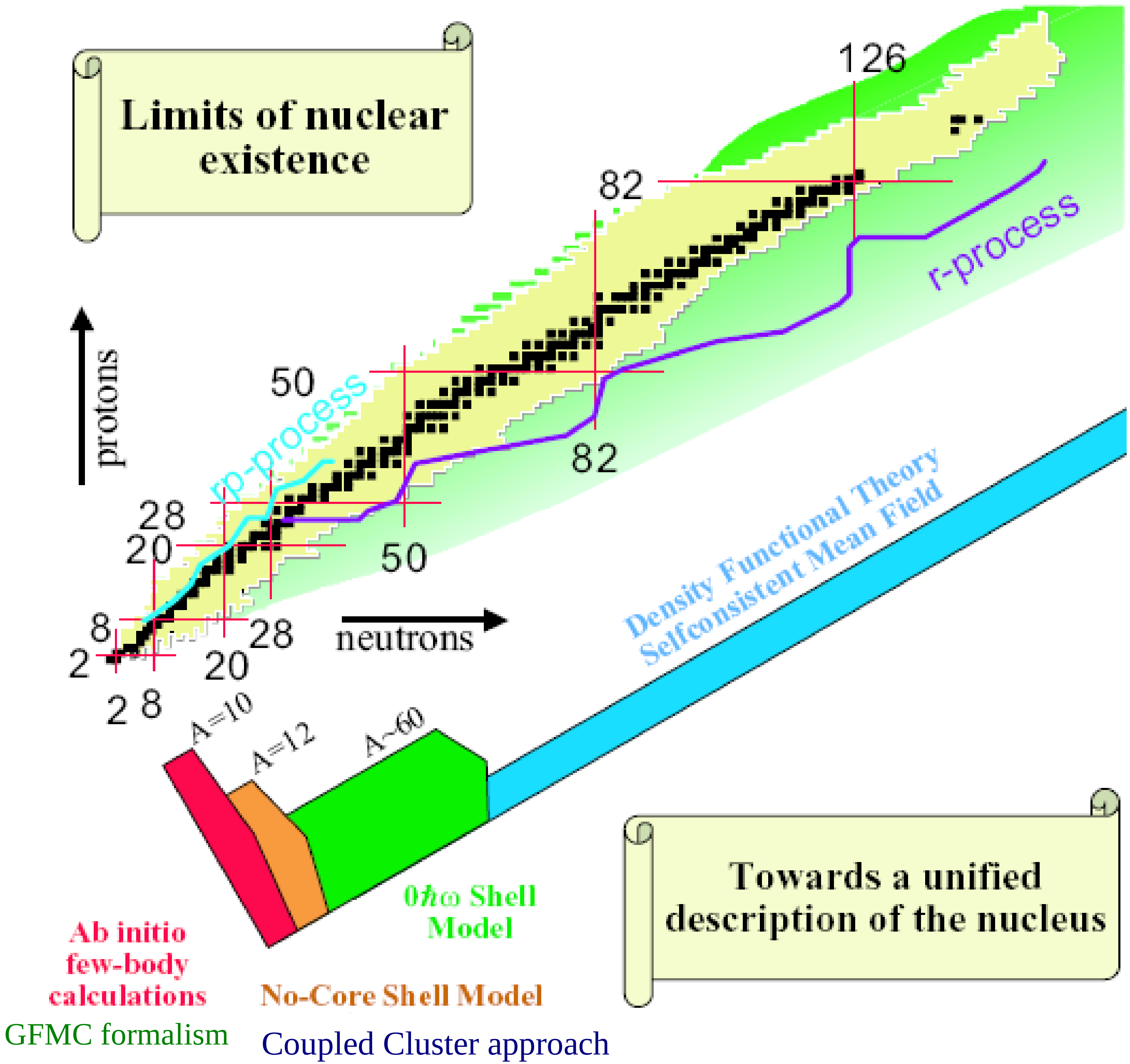


Limits of nuclear existence
126
82
50
rp-process
r-process
protons
neutrons
28
20
8
2
2 8
20
28
50
82
Density Functional Theory
Selfconsistent Mean Field
A=10
A=12
A~60
0ħω Shell Model
Ab initio few-body calculations
No-Core Shell Model
Towards a unified description of the nucleus
GFMC formalism
Coupled Cluster approach

OUTLINE

I. Overview of the *Ab Initio* Shell Model with a Core Approach

II. Results:

- a.) General sd-shell
- b.) Fluorine isotopes

III. Summary/Outlook

I. Overview of the *Ab Initio* Shell Model with a Core Approach

From few-body to many-body

Using the NCSM to calculate the shell model input

Ab initio
No Core Shell Model

Core Shell Model

Realistic NN & NNN forces

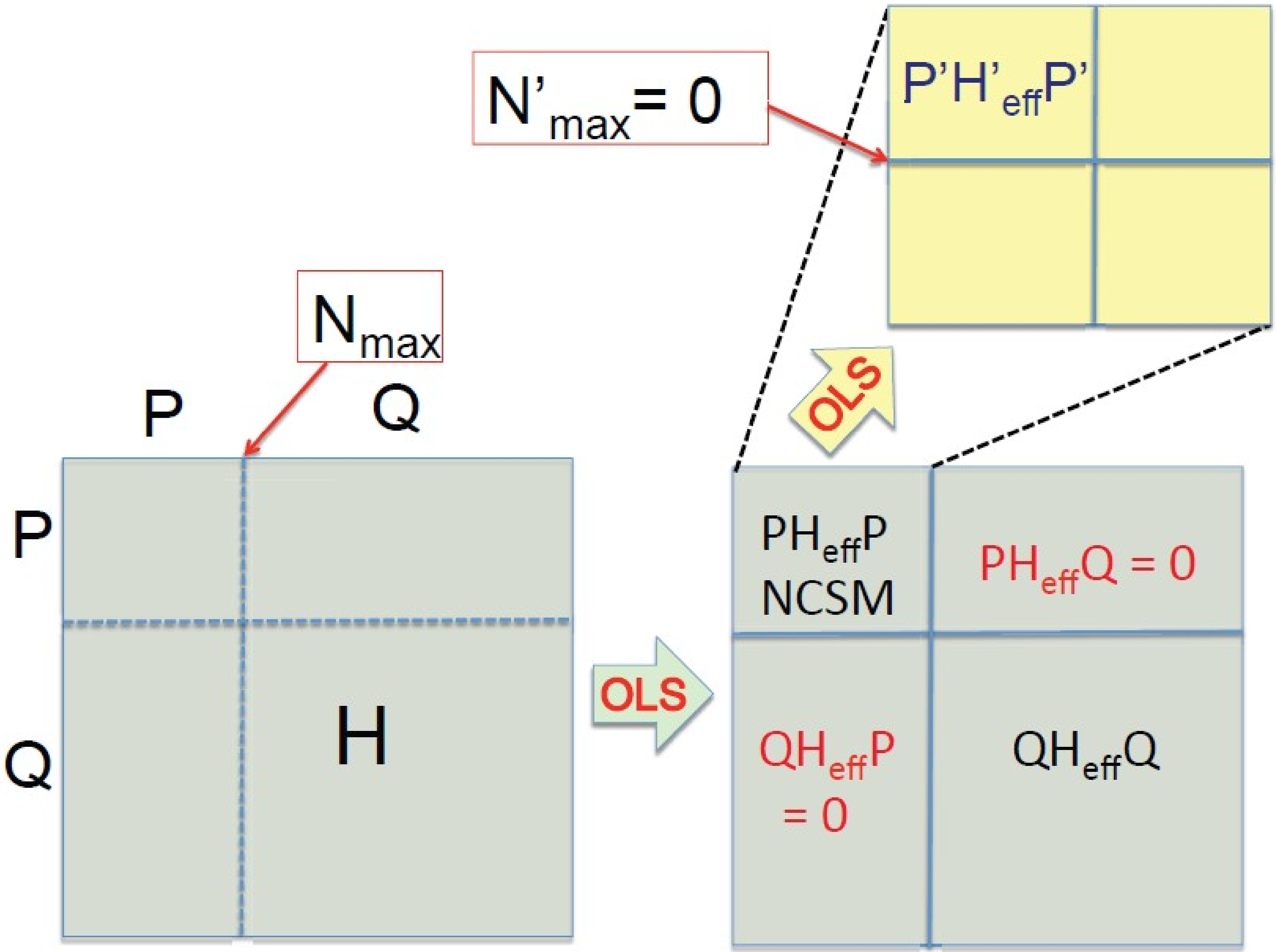
Effective interactions in cluster approximation

effective interactions for valence nucleons

Diagonalization of many- body Hamiltonian

Diagonalization of the Hamiltonian for valence nucleons

Many-body experimental data


N’max= 0
P’H’effP’
Nmax
P
Q
P
Q
H
OLS
OLS
PHeffP
NCSM
PHeffQ = 0
QHeffP
= 0
QHeffQ

Effective interaction in a projected model space

$$H\Psi_\alpha = E_\alpha \Psi_\alpha \quad \text{where} \quad H = \sum_{i=1}^{A} t_i + \sum_{i\leq j}^{A} v_{ij}.$$

$$\mathcal{H}\Phi_\beta = E_\beta \Phi_\beta$$

$$\Phi_\beta = P\Psi_\beta$$

P is a projection operator from S into $\mathcal{S}$

$$< \tilde{\Phi}_\gamma | \Phi_\beta >= \delta_{\gamma\beta}$$

$$\mathcal{H} = \sum_{\beta \epsilon \mathcal{S}} |\Phi_\beta > E_\beta < \tilde{\Phi}_\beta|$$

Effective Hamiltonian for NCSM

Solving $H^{\Omega}_{A,\,a=2}\Psi_{a=2} = E^{\Omega}_{A,\,a=2}\Psi_{a=2}$ in "infinite space" 2n+l = 450 relative coordinates

P + Q = 1; P – model space; Q – excluded space;

$$E^{\Omega}_{A,2} = U_2 H^{\Omega}_{A,2} U_2^{\dagger}$$

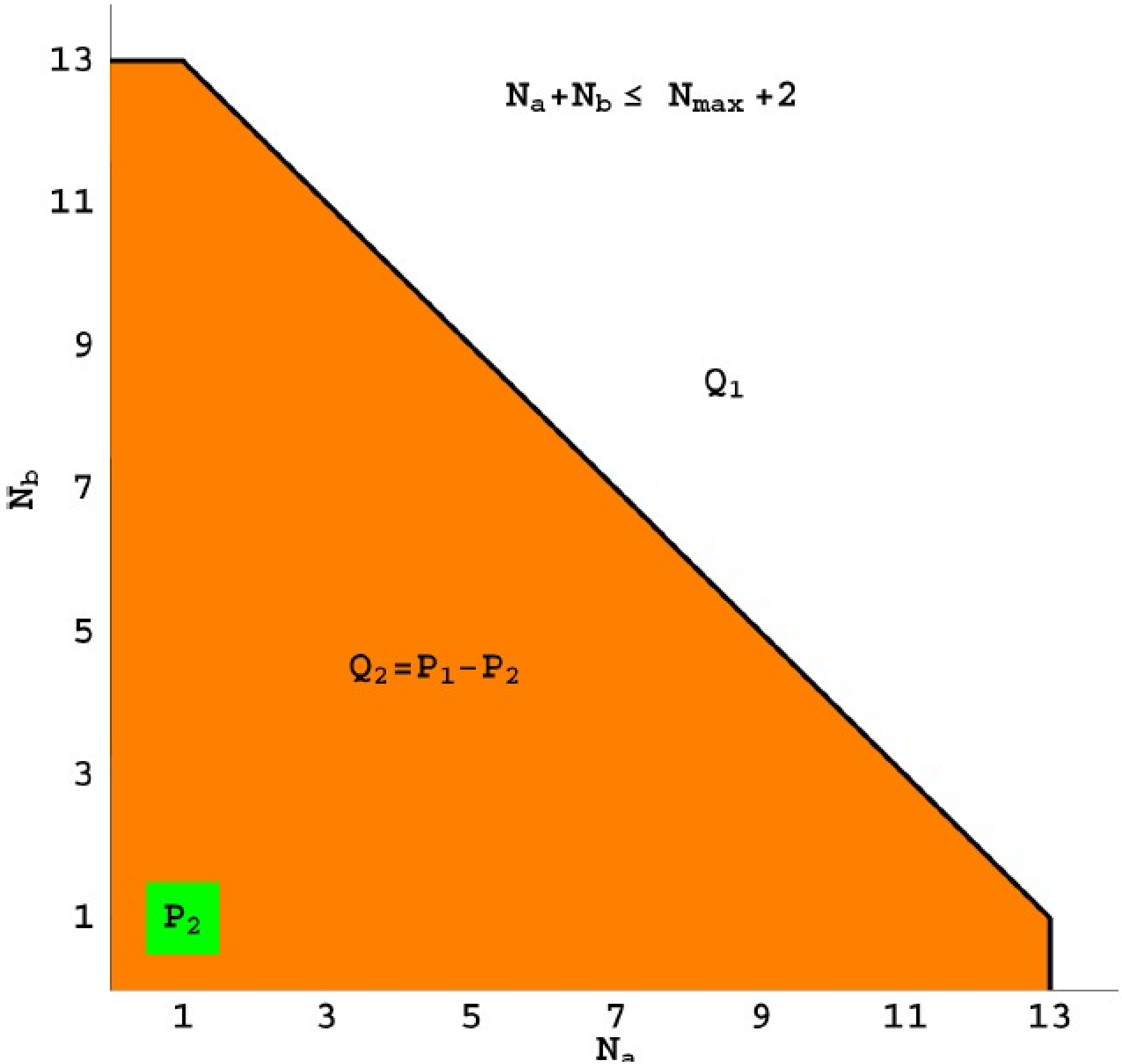
$$U_2 = \begin{pmatrix} U_{2,P} & U_{2,PQ} \\ U_{2,QP} & U_{2,Q} \end{pmatrix} \qquad E^{\Omega}_{A,2} = \begin{pmatrix} E^{\Omega}_{A,2,P} & 0 \\ 0 & E^{\Omega}_{A,2,Q} \end{pmatrix}$$

$$H^{N_{\max},\Omega,\mathrm{eff}}_{A,2} = \frac{U^{\dagger}_{2,P}}{\sqrt{U^{\dagger}_{2,P}U_{2,P}}} E^{\Omega}_{A,2,P} \frac{U_{2,P}}{\sqrt{U^{\dagger}_{2,P}U_{2,P}}}$$

Two ways of convergence:

1) For P → 1 and fixed a: $H^{\mathrm{eff}}_{A,a=2} \rightarrow H_A$

2) For a → A and fixed P: $H^{\mathrm{eff}}_{A,a} \rightarrow H_A$


13
11
9
7
5
3
1
N_b
$N_a + N_b \leq N_{max} + 2$
Q_1
$Q_2 = P_1 - P_2$
P_2
1
3
5
7
9
11
13
N_a

PHYSICAL REVIEW C **78**, 044302 (2008)

Ab-initio shell model with a core

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(Received 20 June 2008; published 10 October 2008)

We construct effective two- and three-body Hamiltonians for the p-shell by performing $12\hbar\Omega$ *ab initio* no-core shell model (NCSM) calculations for $A = 6$ and 7 nuclei and explicitly projecting the many-body Hamiltonians onto the $0\hbar\Omega$ space. We then separate these effective Hamiltonians into inert core, one- and two-body contributions (also three-body for $A = 7$) and analyze the systematic behavior of these different parts as a function of the mass number A and size of the NCSM basis space. The role of effective three- and higher-body interactions for $A > 6$ is investigated and discussed.

DOI: 10.1103/PhysRevC.78.044302 PACS number(s): 21.10.Hw, 21.60.Cs, 23.20.Lv, 27.20.+n

P. Navratil, M. Thoresen and B.R.B., Phys. Rev. C 55, R573 (1997)

FORMALISM

1. Perform a large basis NCSM for a core + 2N system, e.g., 18^F.

2. Use Okubo-Lee-Suzuki transformation to project these results into a single major shell to obtain effective 2-body matrix elements.

3. Separate these 2-body matrix elements into a core term, single-particle energies and residual 2-body interactions, i.e., the standard input for a normal Shell Model calculation.

4. Use these values for performing SM calculations in that shell.

Effective Hamiltonian for SSM

How to calculate the Shell Model 2-body effective interaction:

Two ways of convergence:

1) For $P \rightarrow 1$ and fixed a: $H^{eff}_{A,a=2} \rightarrow H_A$: previous slide

2) For $a_1 \rightarrow A$ and fixed P_1: $H^{eff}_{A,a1} \rightarrow H_A$

$P_1 + Q_1 = P$; P_1 - small model space; Q_1 - excluded space;

$$\mathcal{H}^{N_{1,\max},N_{\max}}_{A,a_1} = \frac{U^{A,\dagger}_{a_1,P_1}}{\sqrt{U^{A,\dagger}_{a_1,P_1} U^{A}_{a_1,P_1}}} E^{N_{\max},\Omega}_{A,a_1,P_1} \frac{U^{A}_{a_1,P_1}}{\sqrt{U^{A,\dagger}_{a_1,P_1} U^{A}_{a_1,P_1}}}$$

Valence Cluster Expansion

$N_{1,max} = 0$ space (p-space) ; $a_1 = A_C + a_V$; a_1 - order of cluster;

A_C - number of nucleons in core; a_V - order of valence cluster;

$$\mathcal{H}^{0,N_{\max}}_{A,a_1} = \sum_{k}^{a_v} V_k^{A,A_c+k}$$

II. Results: a.) sd-shell nuclei

Phys. Rev. C 91, 064301 (2015)

Ab initio effective interactions for *sd*-shell valence nucleons

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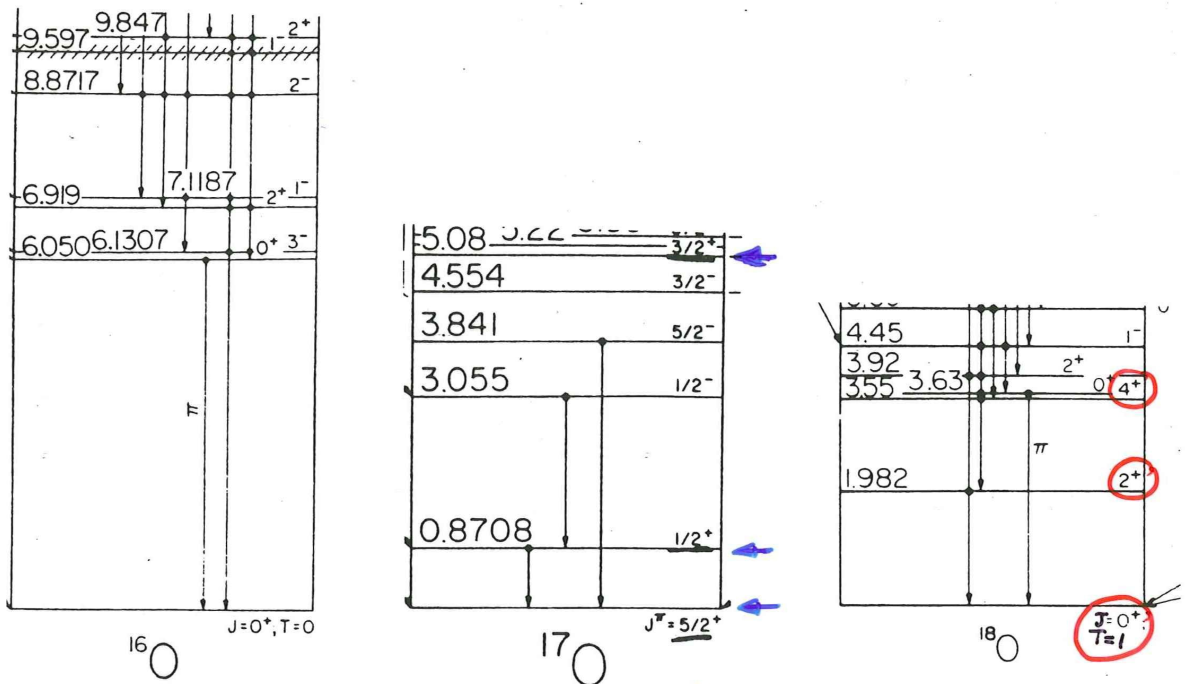
(Dated: February 3, 2015)

We perform *ab initio* no core shell model calculations for $A = 18$ and 19 nuclei in a $4\hbar\Omega$, or $N_{\text{max}} = 4$, model space using the effective JISP16 and chiral N3LO nucleon-nucleon potentials and transform the many-body effective Hamiltonians into the $0\hbar\Omega$ model space to construct the A-body effective Hamiltonians in the *sd*-shell. We separate the A-body effective Hamiltonians with $A = 18$ and $A = 19$ into inert core, one- and two-body components. Then, we use these core, one- and two-body components to perform standard shell model calculations for the $A = 18$ and $A = 19$ systems with valence nucleons restricted to the *sd*-shell. Finally, we compare the standard shell model results in the $0\hbar\Omega$ model space with the exact no core shell model results in the $4\hbar\Omega$ model space for the $A = 18$ and $A = 19$ systems and find good agreement.

ArXiv: Nucl-th 1502.00700

Empirical Single-Particle Energies



$$\varepsilon_{0d_{5/2}} = 0.0 \text{ MeV}$$

$$\varepsilon_{1s_{1/2}} = 0.87 \text{ MeV}$$

$$\varepsilon_{0d_{3/2}} = 5.08 \text{ MeV}$$

$$H^{sd}(P\Psi)^{sd} = \left\{ \sum_i^{sd} \varepsilon_i + v_{eff}^{sd} \right\} (P\Psi)^{sd}$$

$$\left\{ H_0 + V_{eff}^{sd} \right\} (P\Psi)^{sd} = E^{sd}(P\Psi)^{sd}$$

Input: The results of N_max = 4 and hw = 14 MeV NCSM calculations

TABLE II: Proton and neutron single-particle energies (in MeV) for JISP16 effective interaction obtained for the mass of $A = 18$ and $A = 19$.

	$A = 18$, $E_{\text{core}} = -115.529$			$A = 19$, $E_{\text{core}} = -115.319$		
j_i	$\frac{1}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{5}{2}$	$\frac{3}{2}$
$\epsilon^n_{j_i}$	-3.068	-2.270	6.262	-3.044	-2.248	6.289
$\epsilon^p_{j_i}$	0.603	1.398	9.748	0.627	1.419	9.774

TABLE III: Proton and neutron single-particle energies (in MeV) for chiral N3LO effective interaction obtained for the mass of $A = 18$ and $A = 19$.

	$A = 18$, $E_{\text{core}} = -118.469$			$A = 19$, $E_{\text{core}} = -118.306$		
j_i	$\frac{1}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{5}{2}$	$\frac{3}{2}$
$\epsilon^n_{j_i}$	-3.638	-3.042	3.763	-3.625	-3.031	3.770
$\epsilon^p_{j_i}$	0.044	0.690	7.299	0.057	0.700	7.307

	A = 18	A = 19	
Coupled Cluster, E_core: Idaho NN N3LO + 3N N2LO	-130.462	-130.056	from G.R. Jansen et al. PRL 113, 142502 (2014)
IM-SRG, E_core: Idaho NN N3LO + 3N N2LO	-130.132	-129.637	from H. Hergert private comm.

No-Core Shell-Model Approach

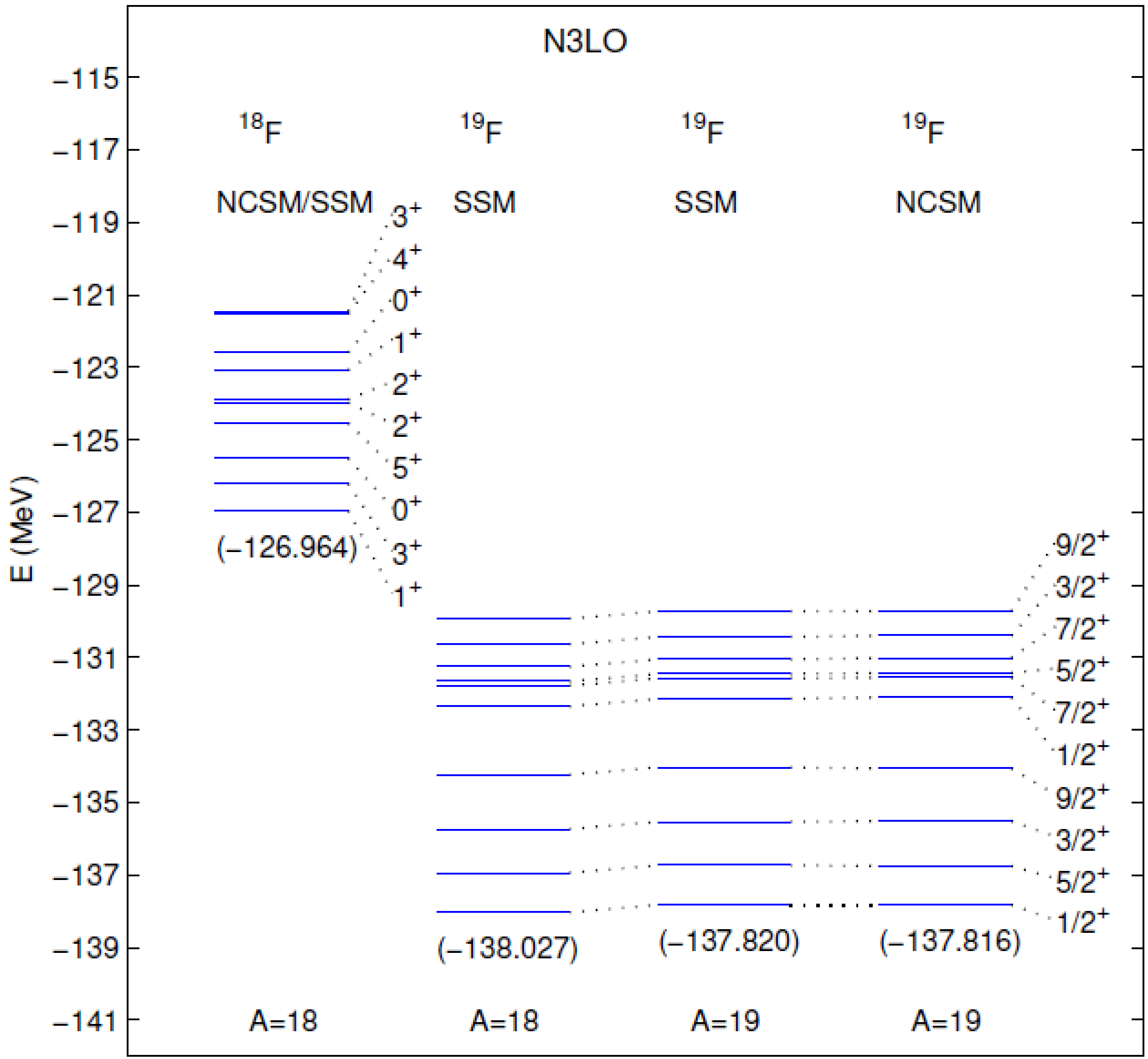
- Next, add CM harmonic-oscillator Hamiltonian

$$H_{CM}^{HO} = \frac{\vec{P}^{\,2}}{2Am} + \frac{1}{2} A m \Omega^2 \vec{R}^{\,2} ; \quad \vec{R} = \frac{1}{A}\sum_{i=1}^{A} \vec{r}_i \,, \quad \vec{P} = Am\dot{\vec{R}}$$

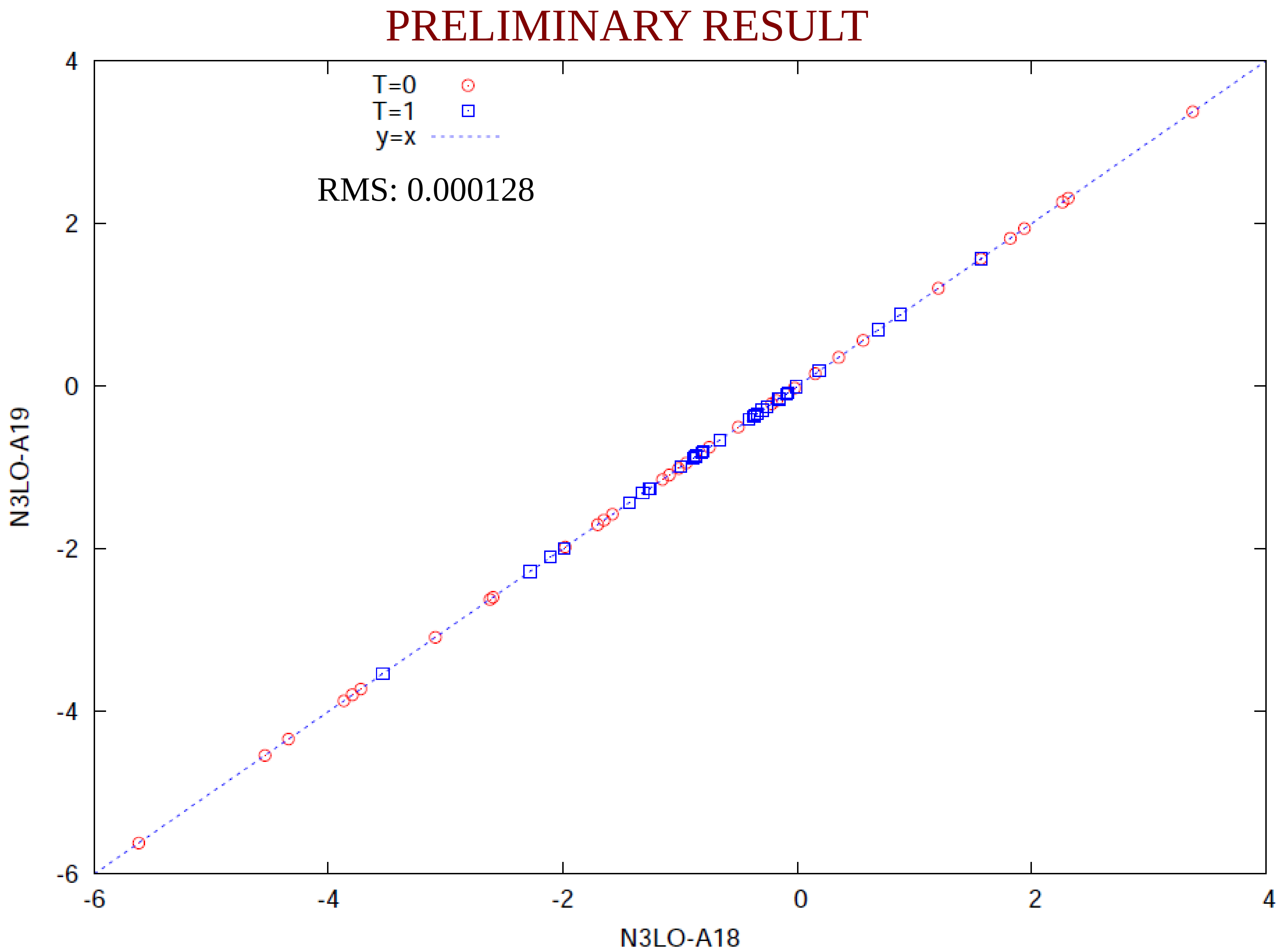
To H_A, yielding

$$H_A^{\Omega} = \sum_{i=1}^{A}\left[\frac{\vec{p}_i^{\,2}}{2m} + \frac{1}{2} m\Omega^2 \vec{r}_i^{\,2}\right] + \underbrace{\sum_{i<j=1}^{A}\left[V_{NN}(\vec{r}_i - \vec{r}_j) - \frac{m\Omega^2}{2A}(\vec{r}_i - \vec{r}_j)^2\right]}_{V_{ij}}$$

Defines a basis (*i.e.* HO) for evaluating V_{ij}



N3LO
E (MeV)
−115
−117
−119
−121
−123
−125
−127
−129
−131
−133
−135
−137
−139
−141
18F
19F
19F
19F
NCSM/SSM
SSM
SSM
NCSM
3+
4+
0+
1+
2+
2+
5+
0+
3+
1+
(−126.964)
9/2+
3/2+
7/2+
5/2+
7/2+
1/2+
9/2+
3/2+
5/2+
1/2+
(−138.027)
(−137.820)
(−137.816)
A=18
A=18
A=19
A=19


PRELIMINARY RESULT
T=0
T=1
y=x
RMS: 0.000128
N3LO-A19
N3LO-A18
4
2
0
-2
-4
-6
-6
-4
-2
0
2
4

II. Results: b) Fluorine isotopes

Survey of the Fluorine isotopes

1. Calculate the Fluorine isotopes using the same set of effective TBMEs, which are very weakly A-dependent, e.g., those determined from the N3LO NN interaction, to test how well they reproduce data trends.

2. Approximate the effect of 3NFs by replacing our theoretical single-particle energies with the theoretical ones obtained in the IM-SRG calculations of S.R. Stroberg et al. *

3. Compare our results for 18,20,22,24 F with those obtained with the IM-SRG approach* using an EFT N3LO NN plus N2LO NNN interaction and with experiment.

* S.R. Stroberg et al., arXiv Nucl-th 1511.02802 (2015)

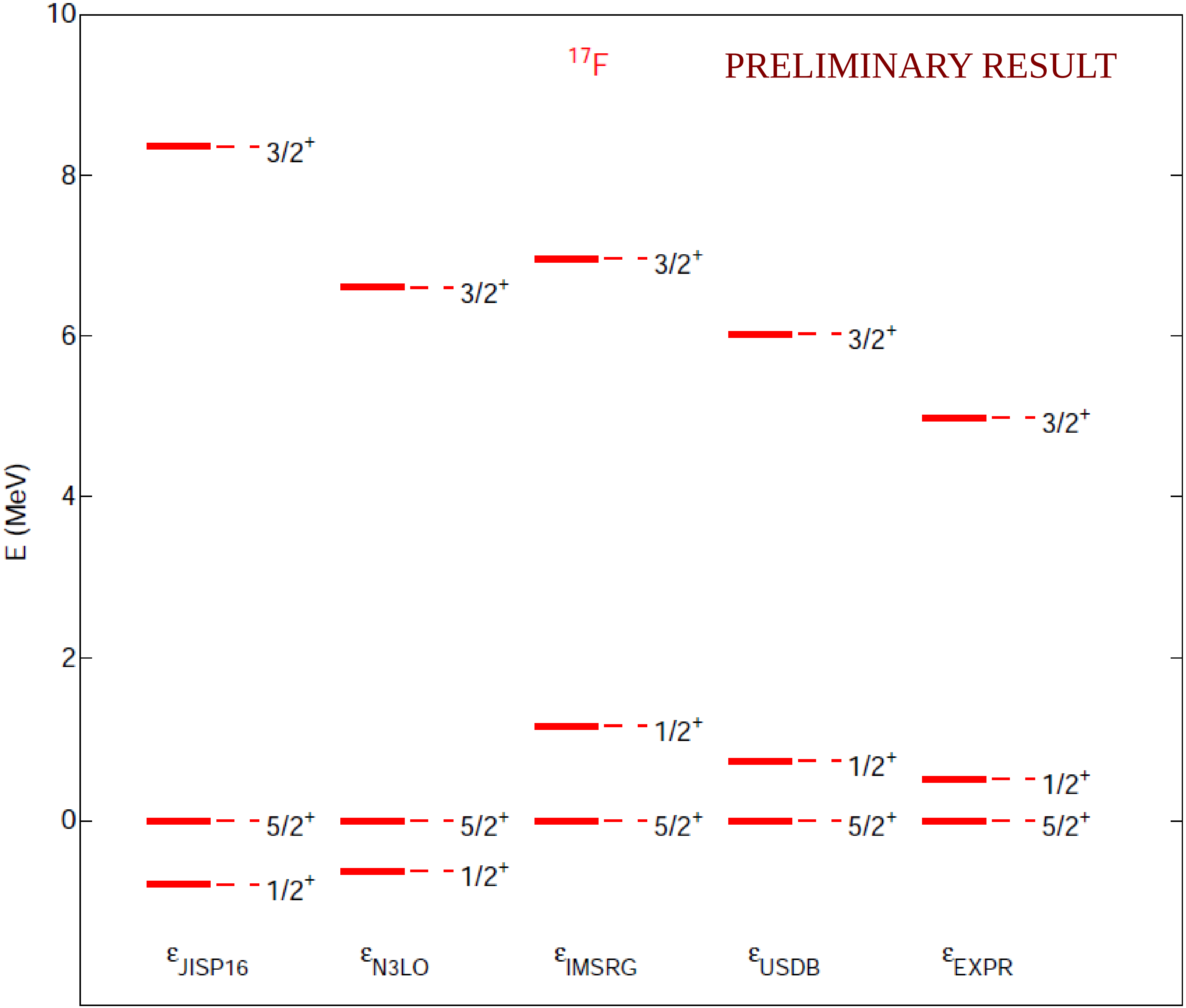
Preliminary Results

TABLE I: The single-particle energies (in MeV) used in the standard shell model calculations of F isotopes. (n) and (p) represent neutron and proton, respectively.

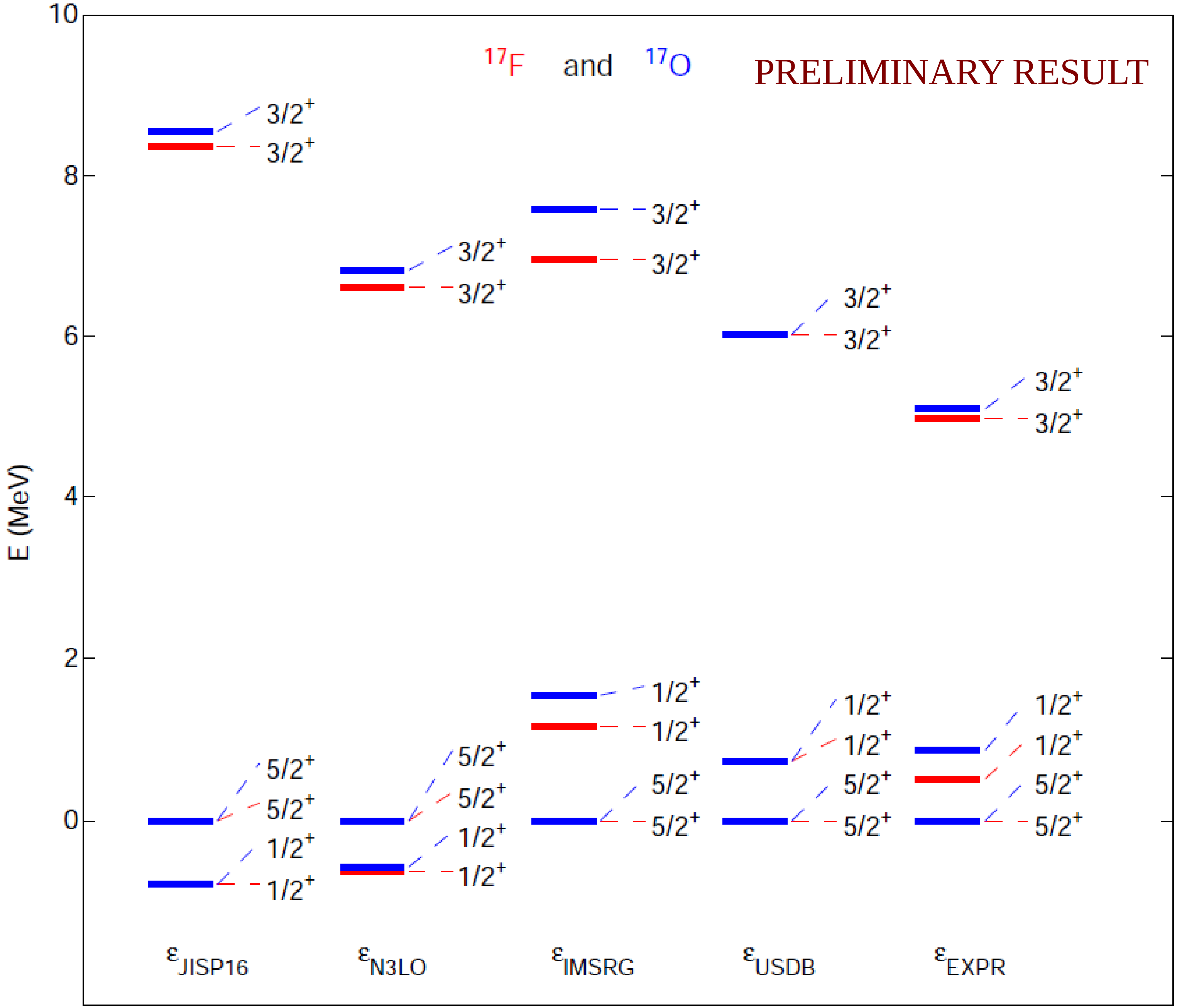
j_i	$\frac{1}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	
JISP16$_{A=18}$ (^{17}O) : (n)	-3.068	-2.270	6.262	
JISP16$_{A=18}$ (^{17}F) : (p)	0.603	1.398	9.748	
USDA	-3.0612	-3.9436	1.9798	
USDB	-3.2079	-3.9257	2.1117	*
IM-SRG (^{17}O) : (n)	-3.089	-4.643	2.940	**
IM-SRG (^{17}F) : (p)	0.255	-0.909	6.035	

* B.A. Brown & W.A. Richter, PRC 74, 034315 (2006)

** S.R. Stroberg, et al., arXiv Nucl-th 1511.02802

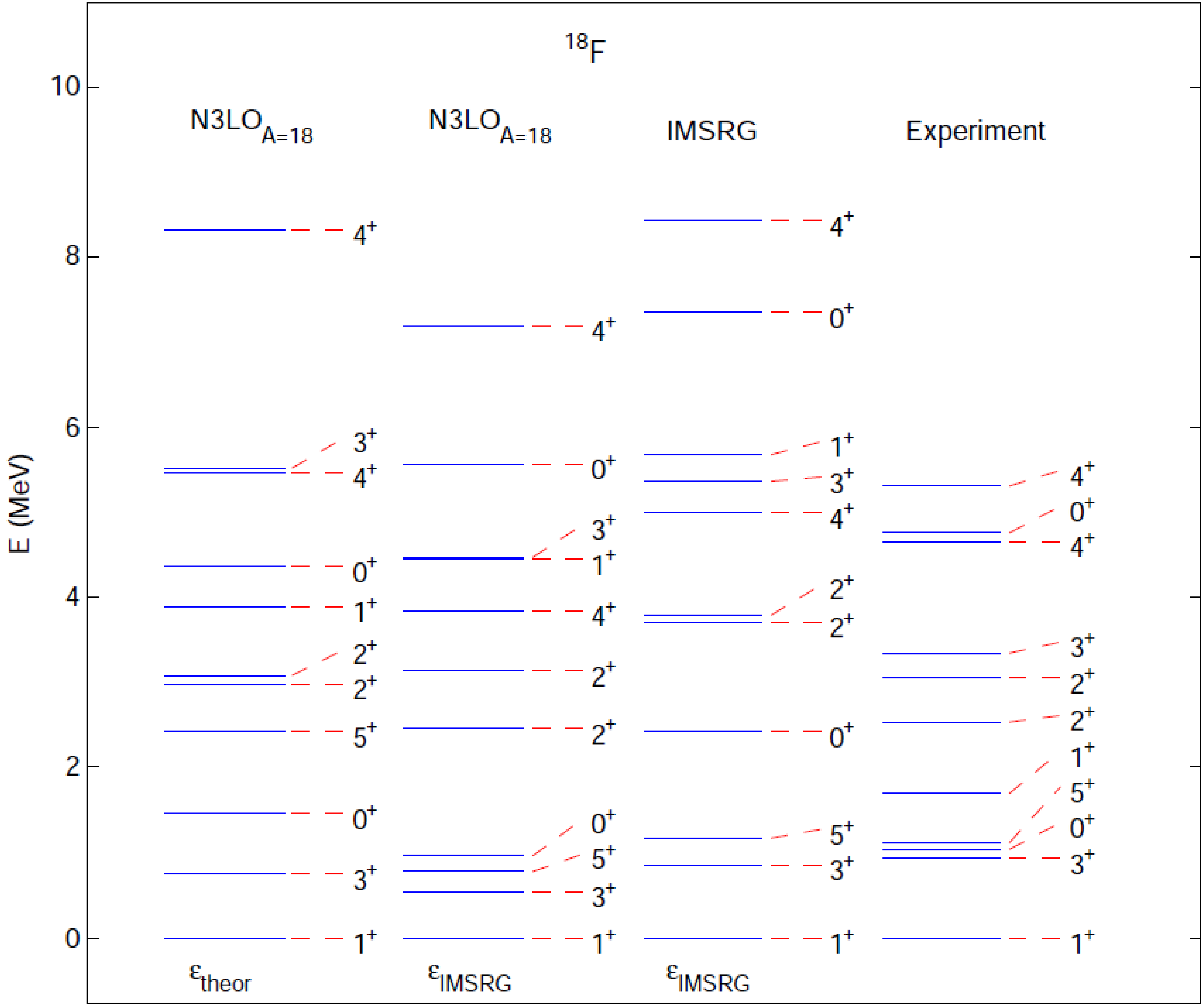


^{17}F
PRELIMINARY RESULT
E (MeV)
10
8
6
4
2
0
3/2⁺
1/2⁺
5/2⁺
ε_{JISP16}
ε_{N3LO}
ε_{IMSRG}
ε_{USDB}
ε_{EXPR}

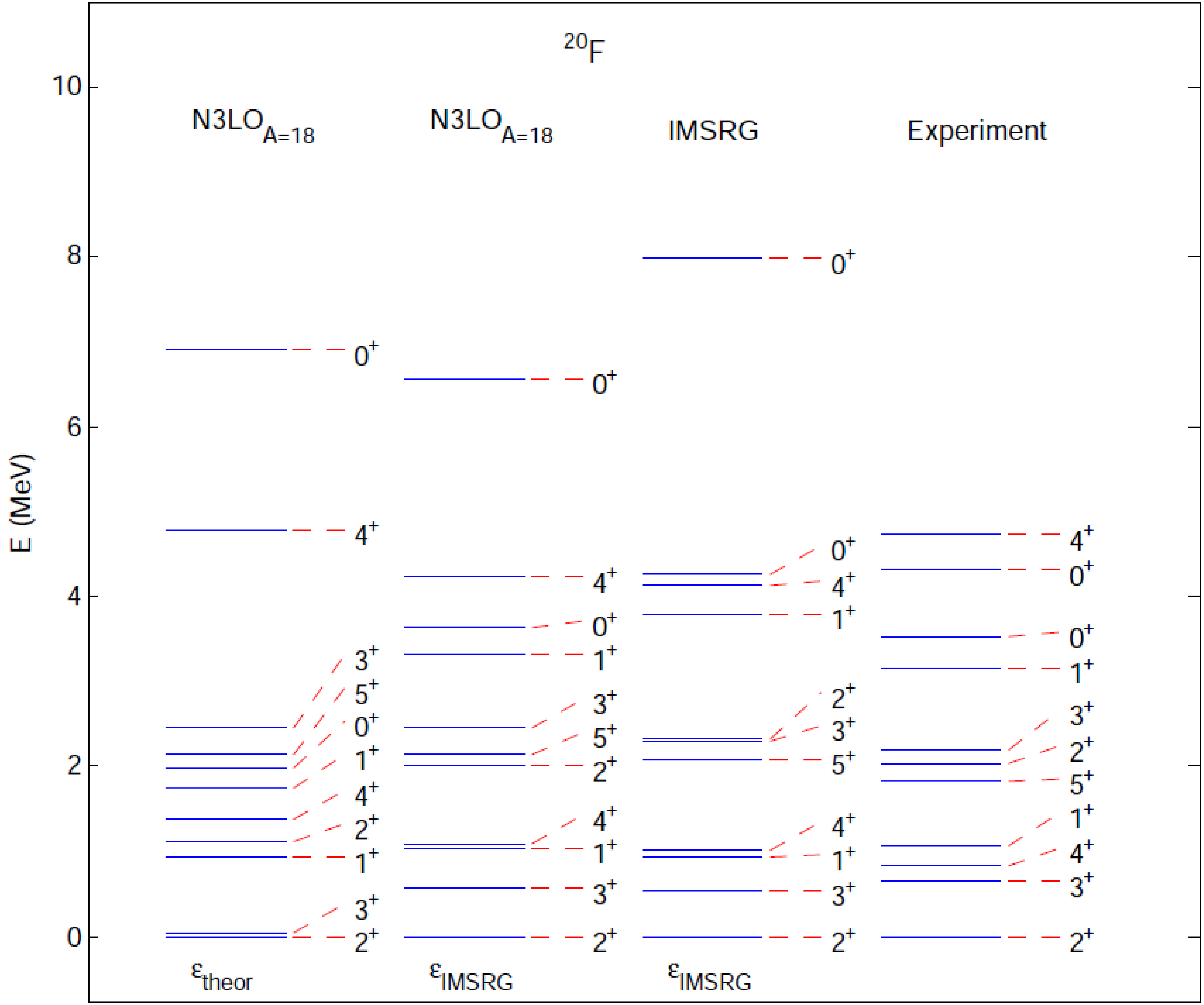


17F and 17O
PRELIMINARY RESULT
E (MeV)
10
8
6
4
2
0
3/2+
3/2+
5/2+
5/2+
1/2+
1/2+
1/2+
εJISP16
εN3LO
εIMSRG
εUSDB
εEXPR

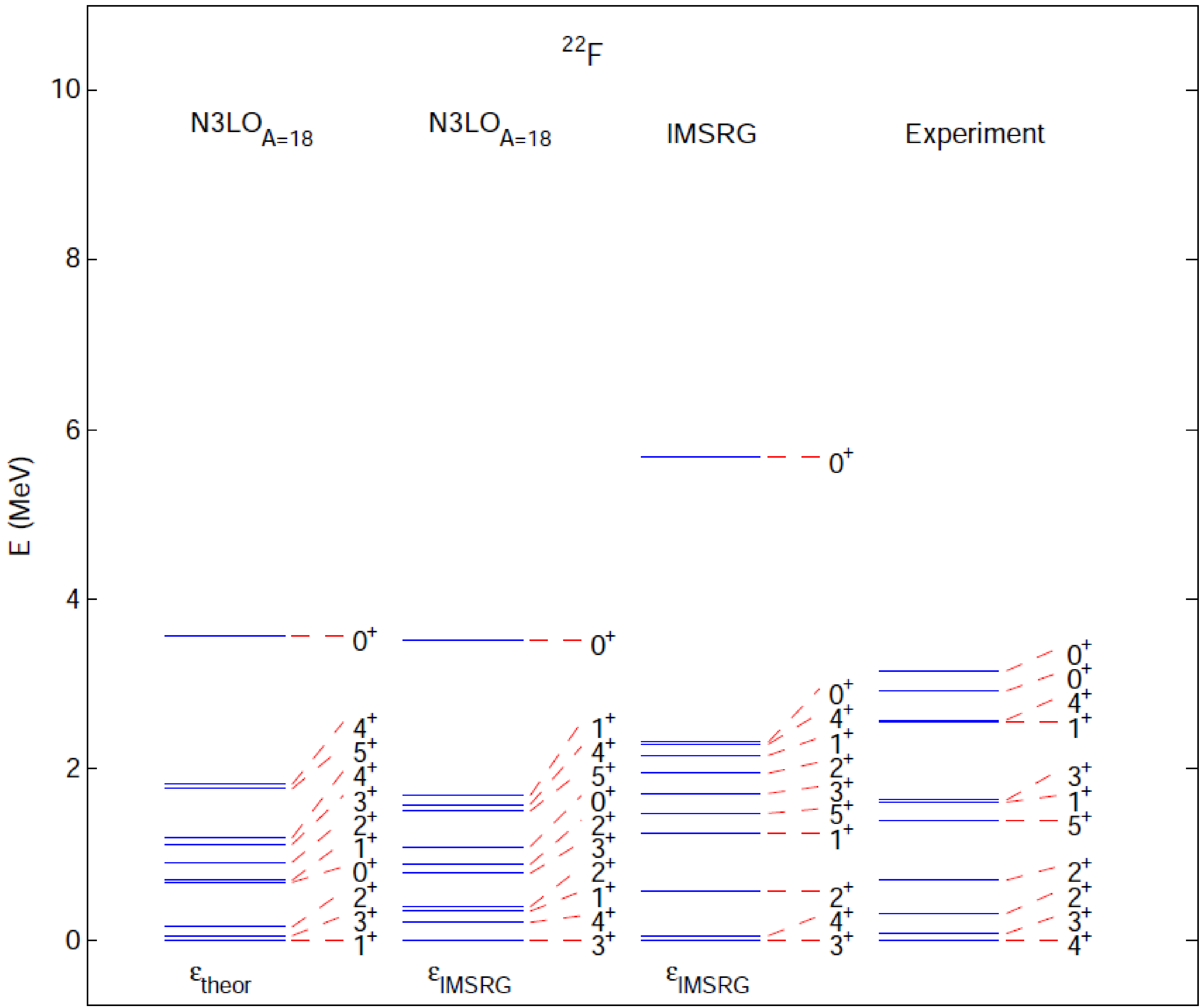
PRELIMINARY RESULT



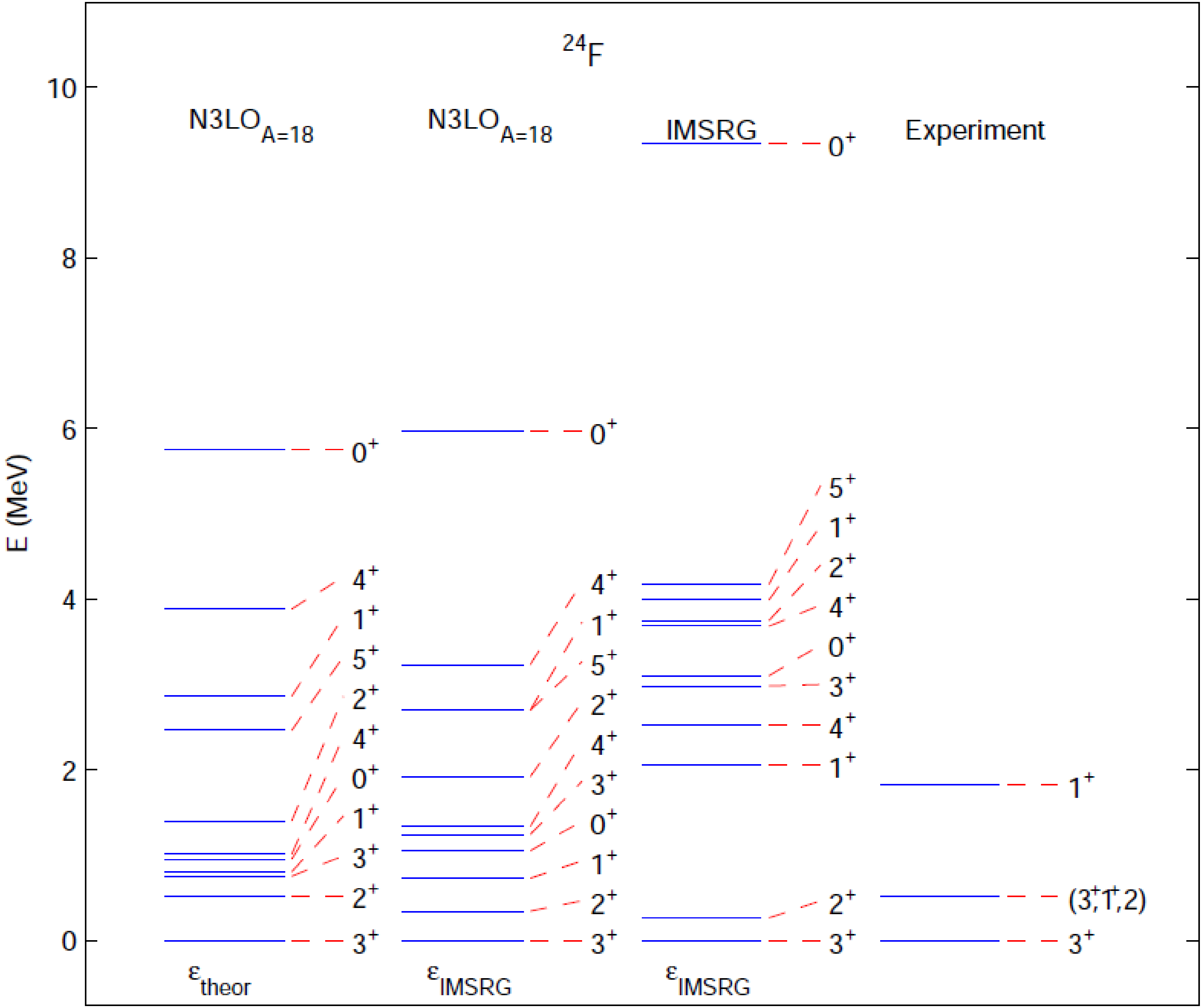
PRELIMINARY RESULT



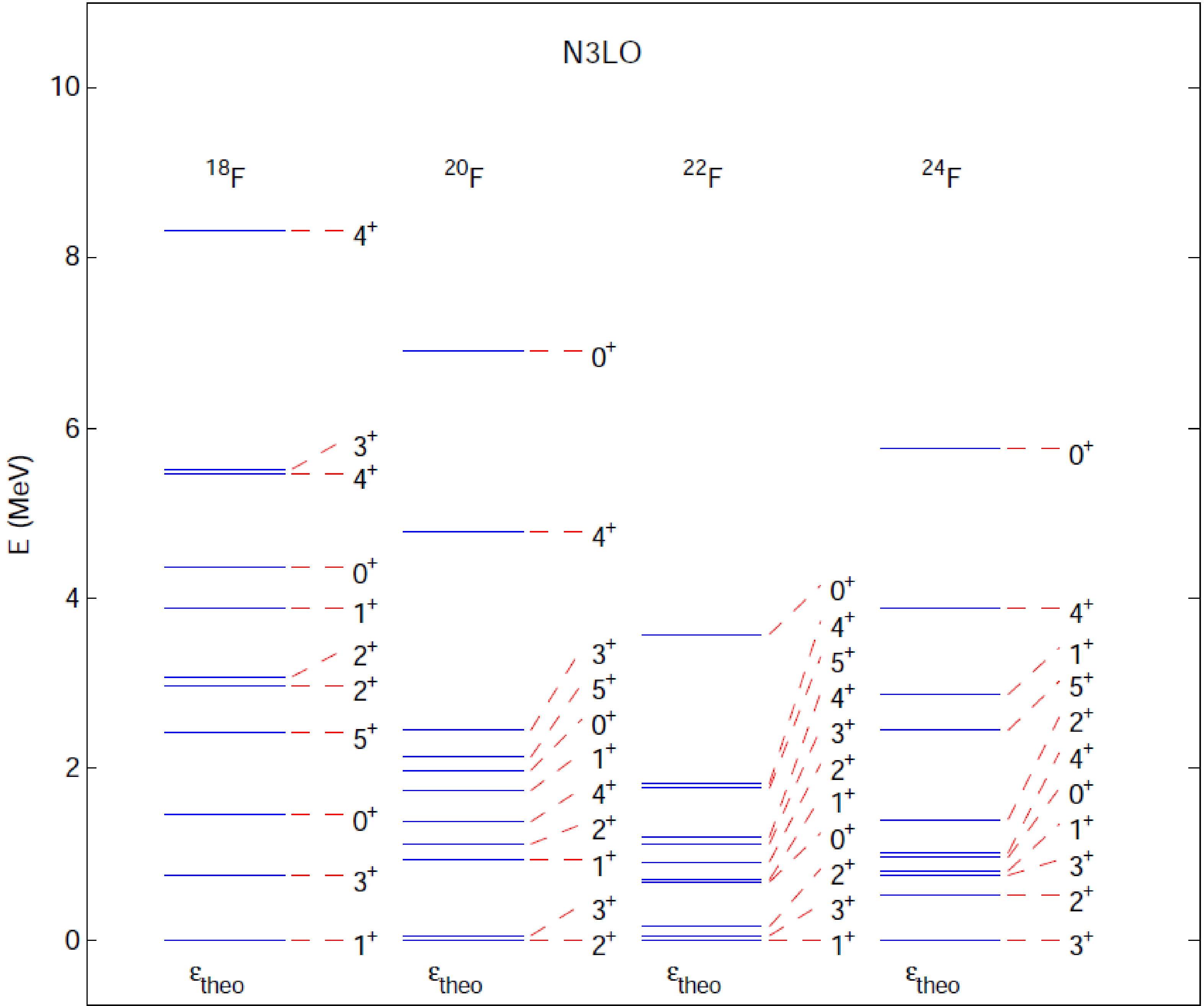
PRELIMINARY RESULT



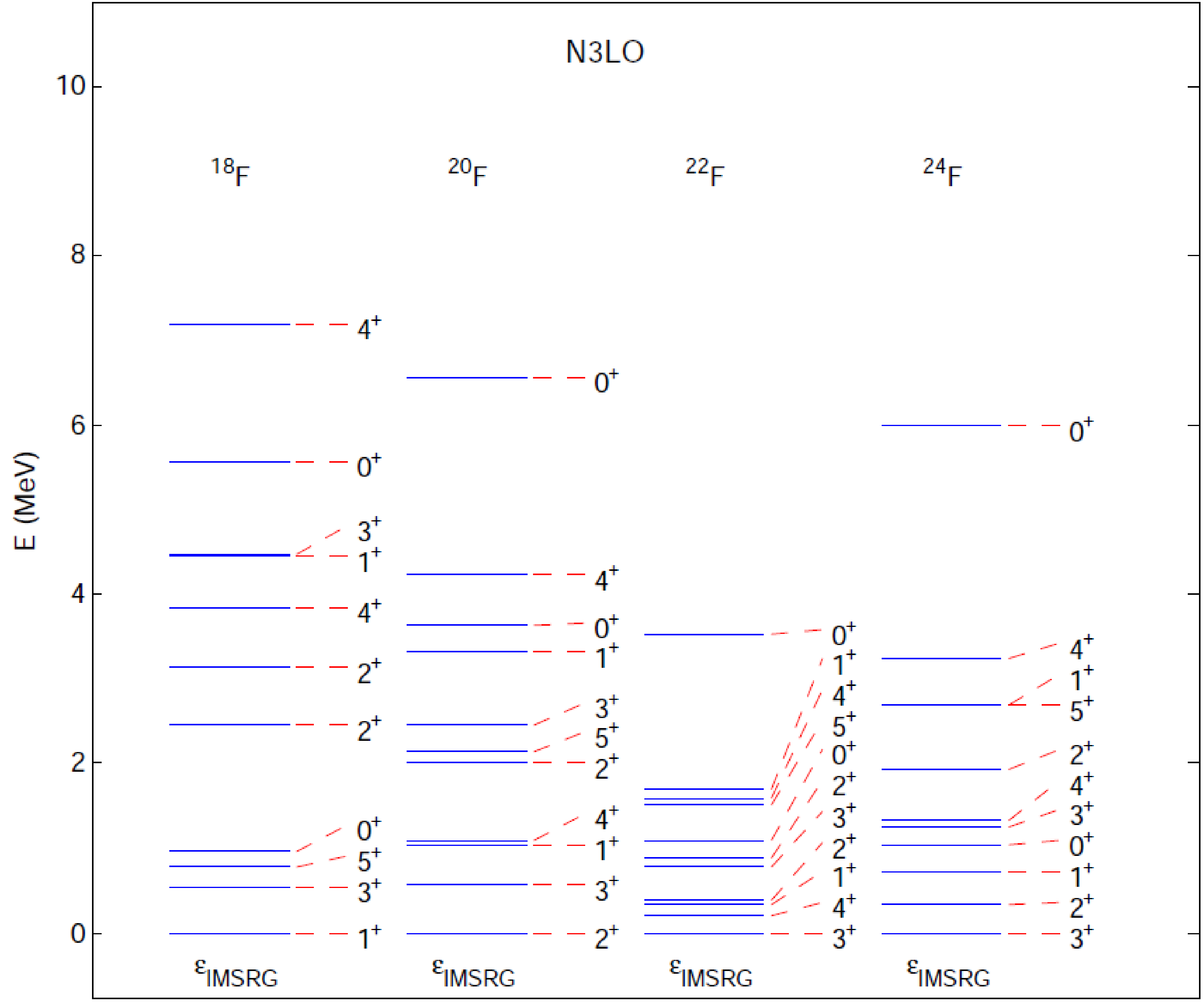
PRELIMINARY RESULT



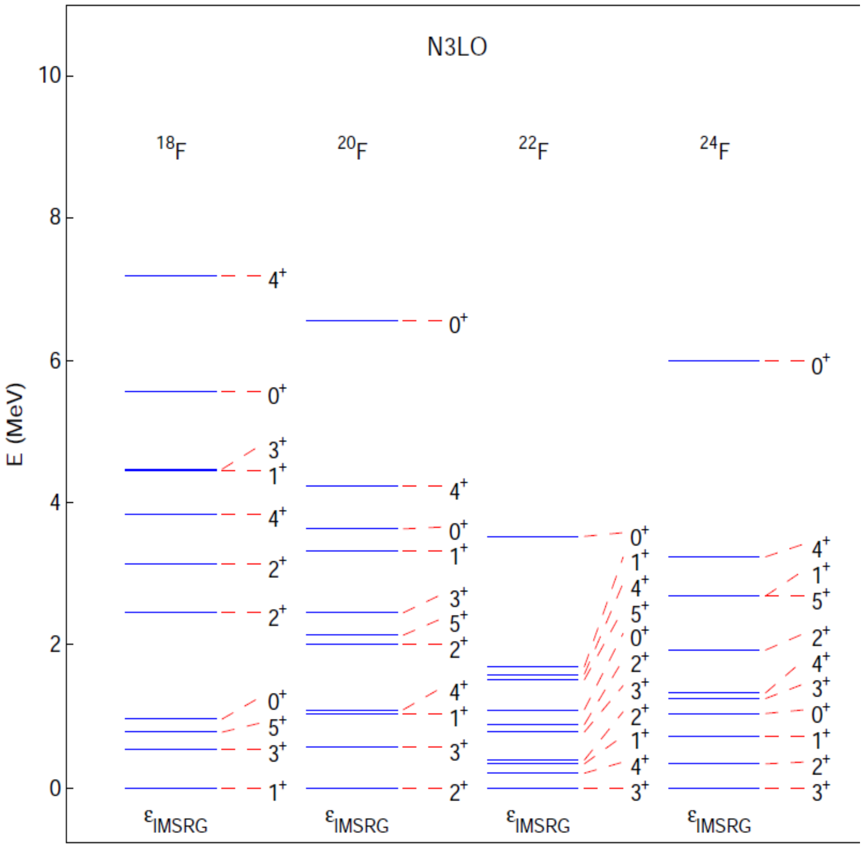
PRELIMINARY RESULT

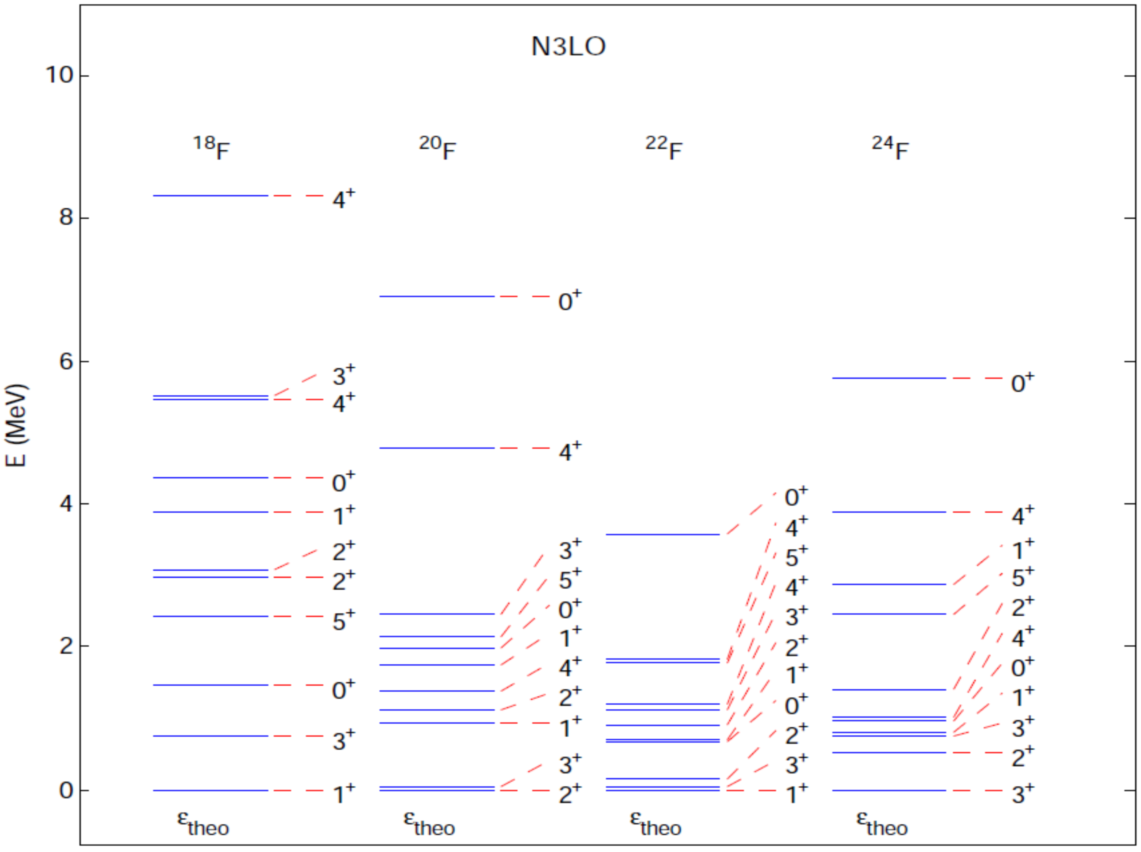


PRELIMINARY RESULT

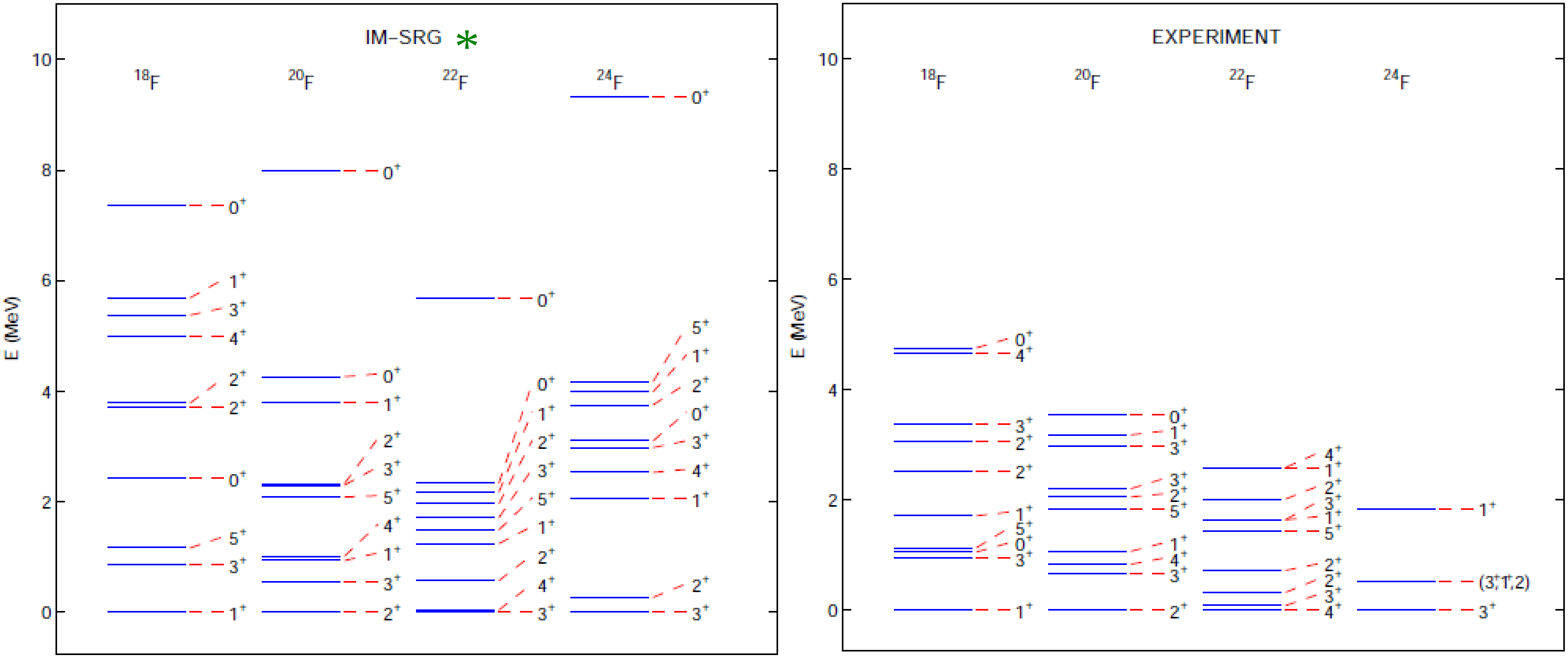


PRELIMINARY RESULTS



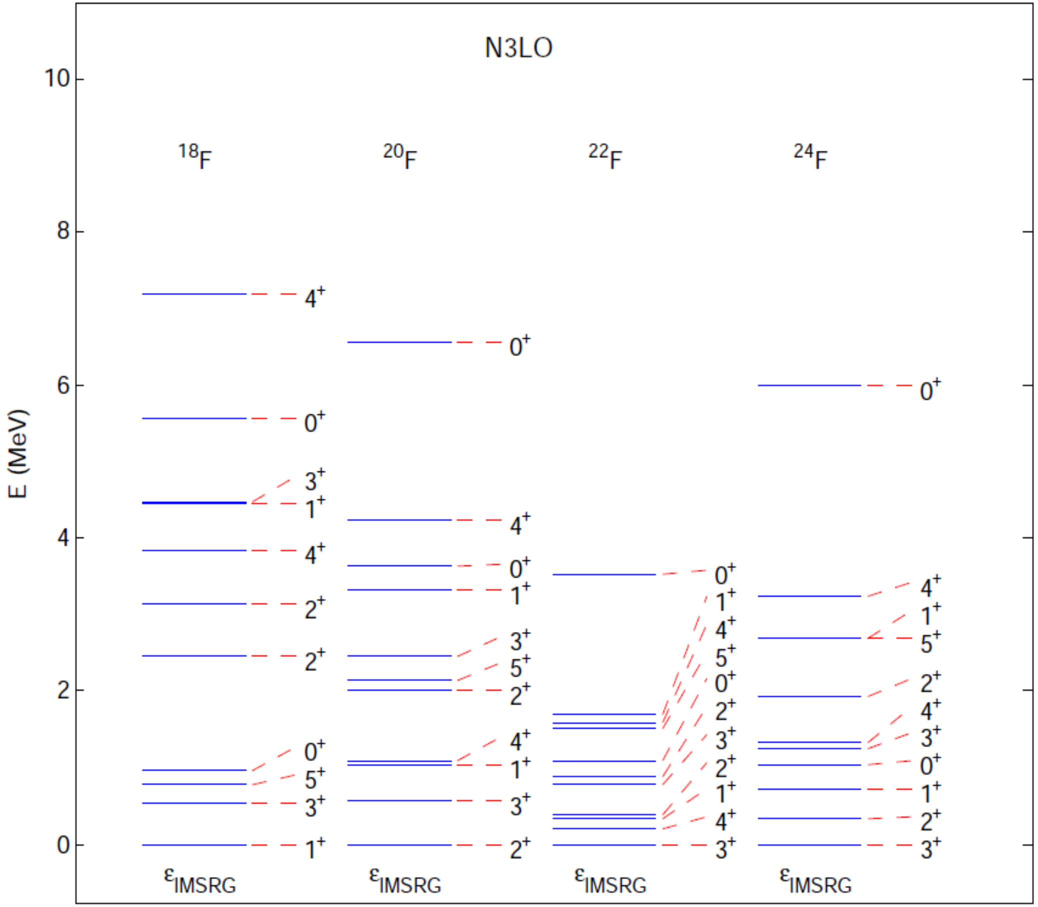


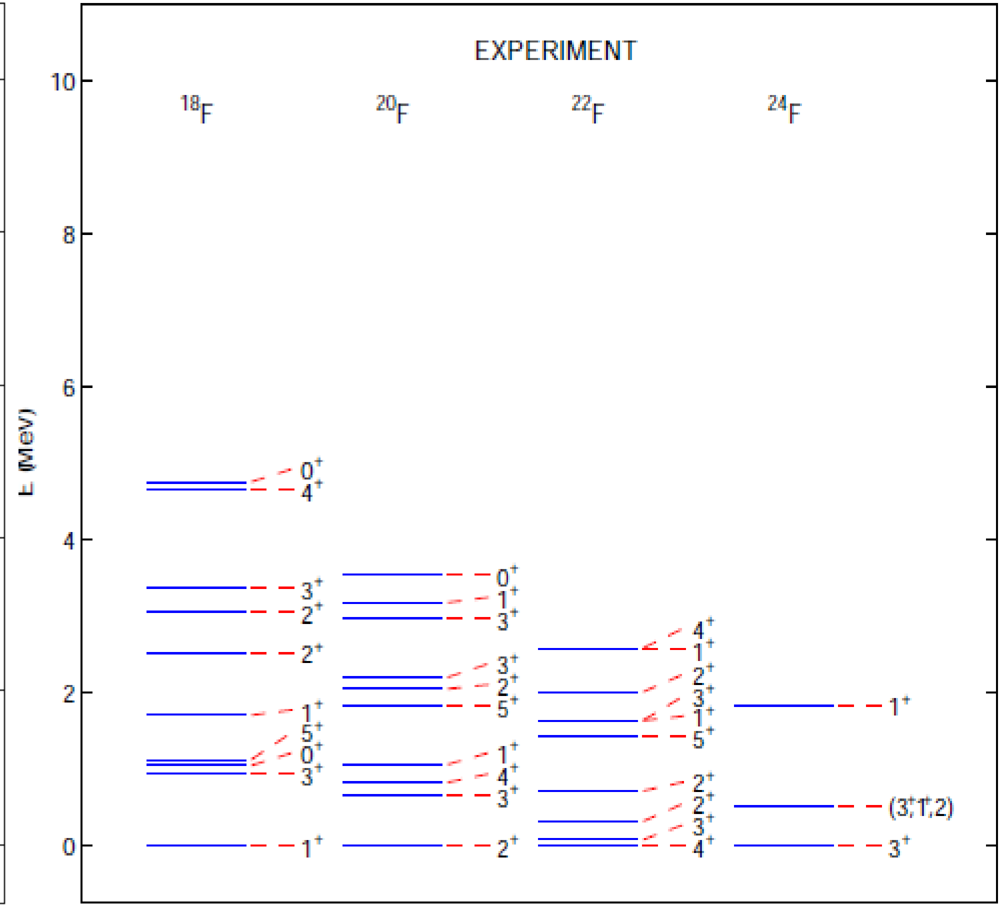
N3LO + IMSRG spe vs N3LO + theoretical spe



* S.R. Stroberg, et al., arXiv Nucl-th 1511.02802

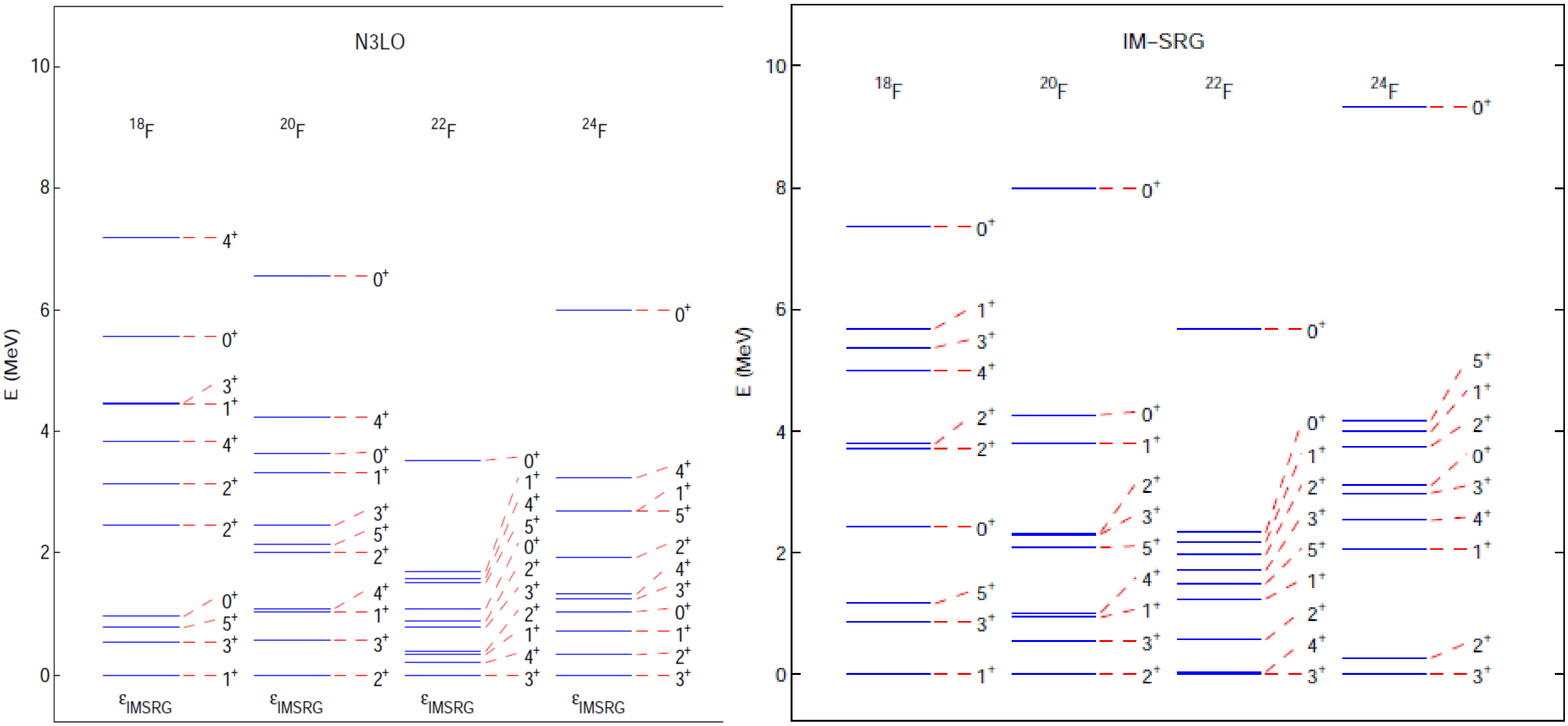
PRELIMINARY RESULTS





N3LO + IMSRG spe vs Experiment

PRELIMINARY RESULTS

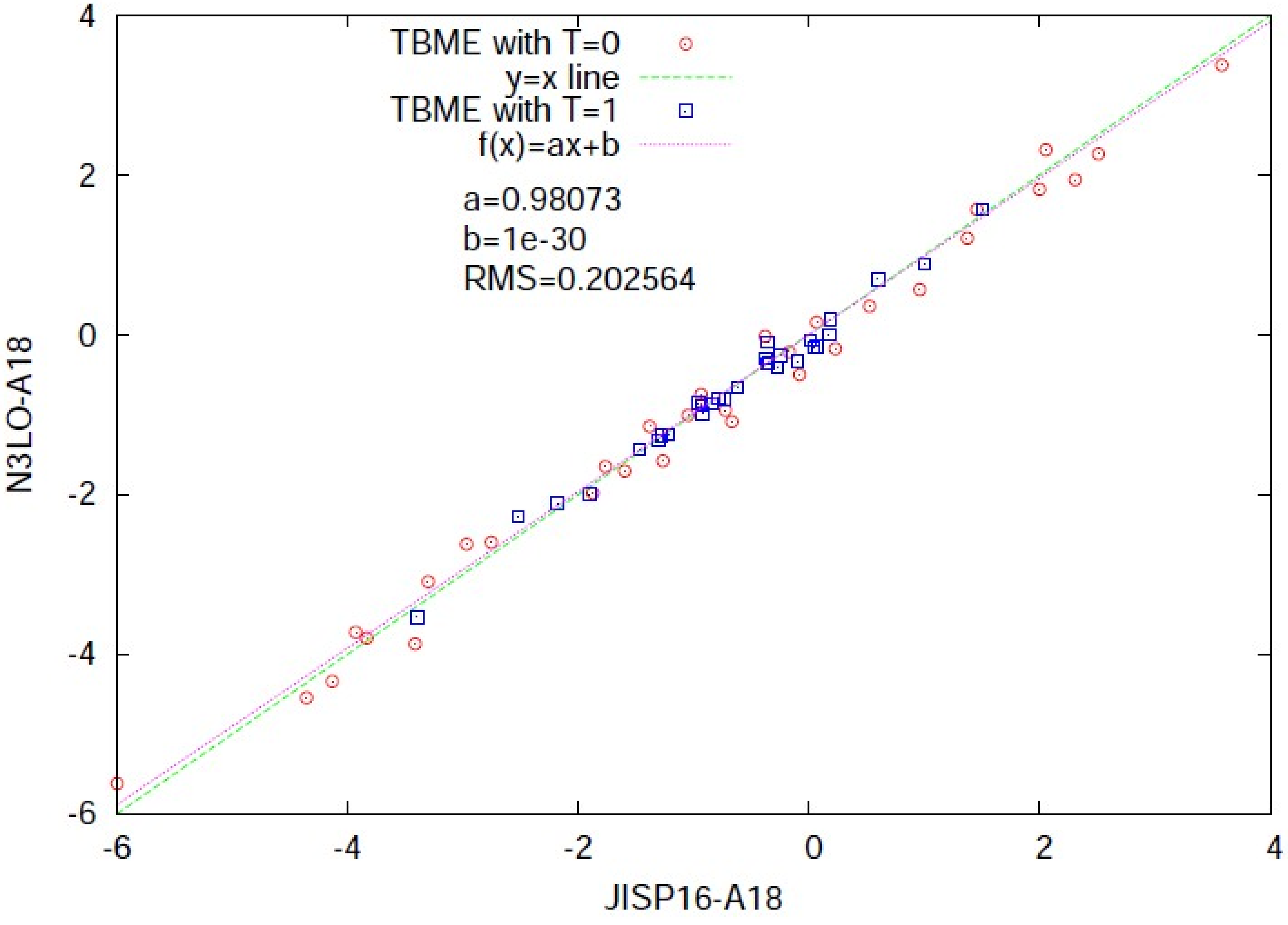


N3LO + IMSRG spe vs IM-SRG

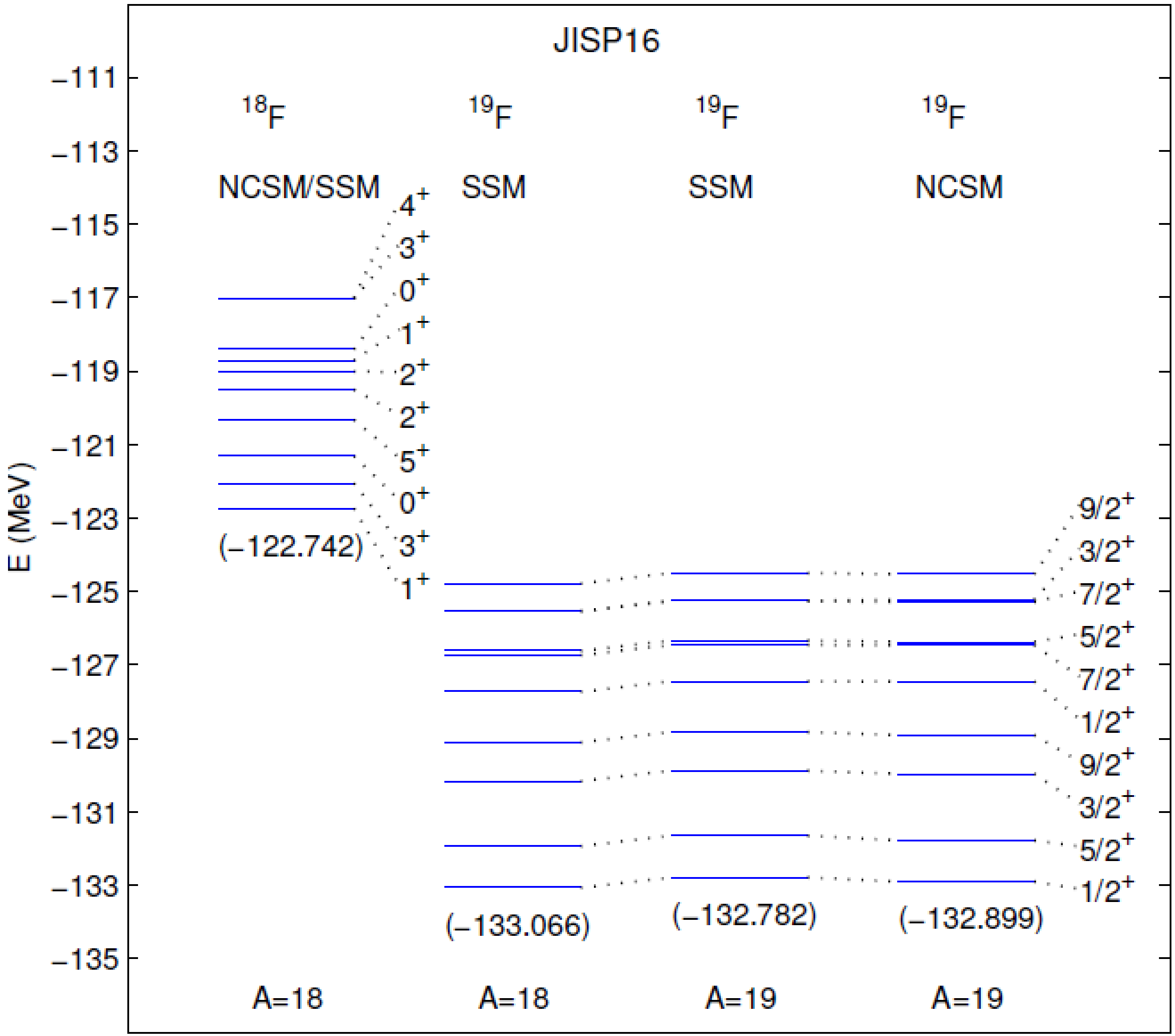
SUMMARY AND OUTLOOK

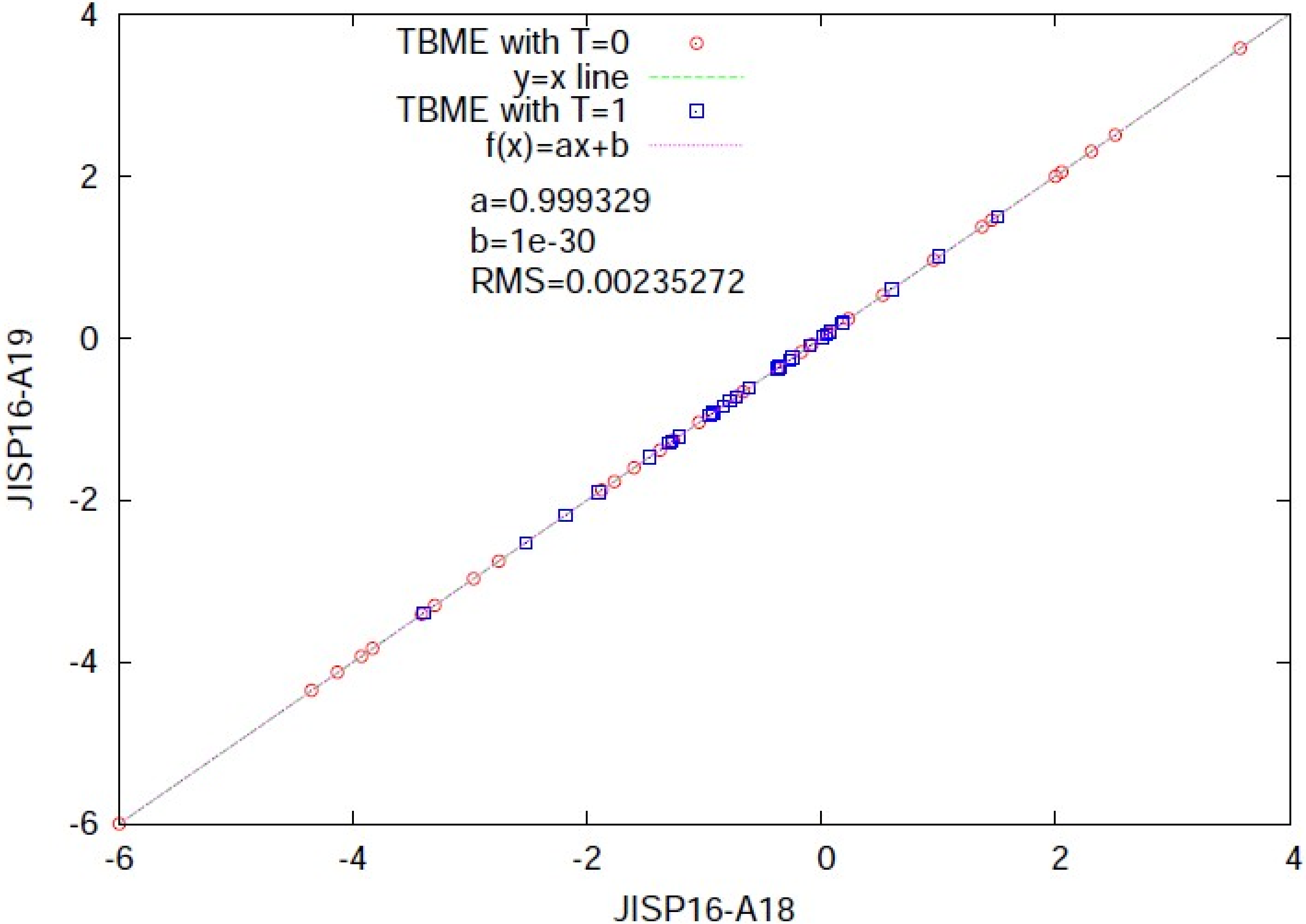
1. The interactions and approaches used in this study reproduced the gross trends and features of the experimental data for the 18,20,22,24 F isotopes.
2. Replacing our theoretical s.p. energies with those obtained in the IM-SRG calculations of Stroberg et al. to approximate the effects of a NNN interaction, in general, improved the agreement with experiment.
3. The overall, reasonable agreement with experiment obtained using the IM-SRG approach with an EFT N3LO NN and N2LO NNN suggests that the trends in our results should continue to improve as we improve the interactions used and increase the size of our model space for our NCSM calculations.
4. The current results support the hypothesis that a single A-independent set of effective TBMEs can explain the trends in the F isotopes.

OUTLOOK: Plan to perform further calculations implementing the changes outlined above.



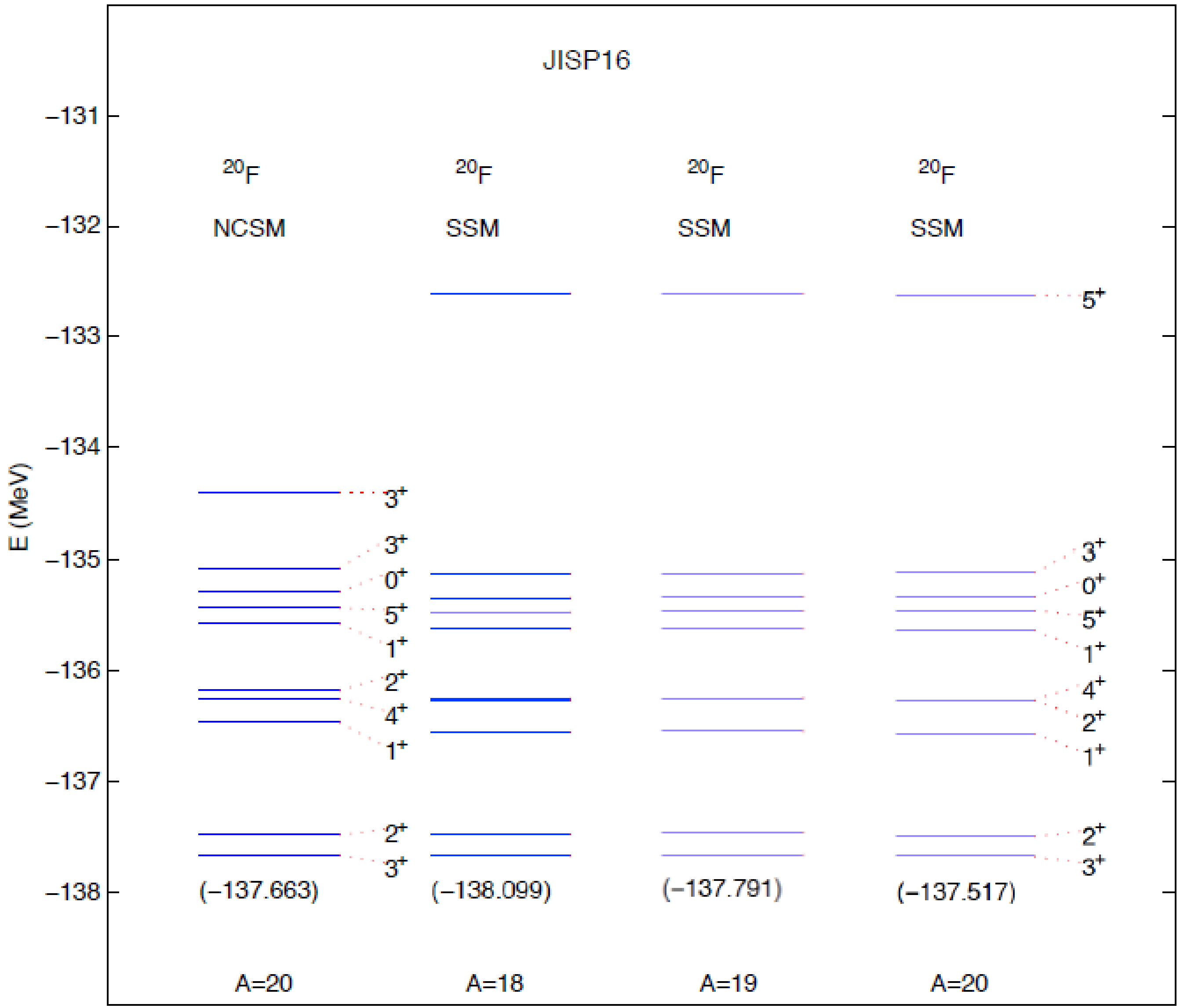
Preliminary Results


JISP16
E (MeV)
−111
−113
−115
−117
−119
−121
−123
−125
−127
−129
−131
−133
−135
^{18}F
NCSM/SSM
(−122.742)
A=18
^{19}F
SSM
(−133.066)
A=18
^{19}F
SSM
(−132.782)
A=19
^{19}F
NCSM
(−132.899)
A=19
4^+
3^+
0^+
1^+
2^+
2^+
5^+
0^+
3^+
1^+
$9/2^+$
$3/2^+$
$7/2^+$
$5/2^+$
$7/2^+$
$1/2^+$
$9/2^+$
$3/2^+$
$5/2^+$
$1/2^+$

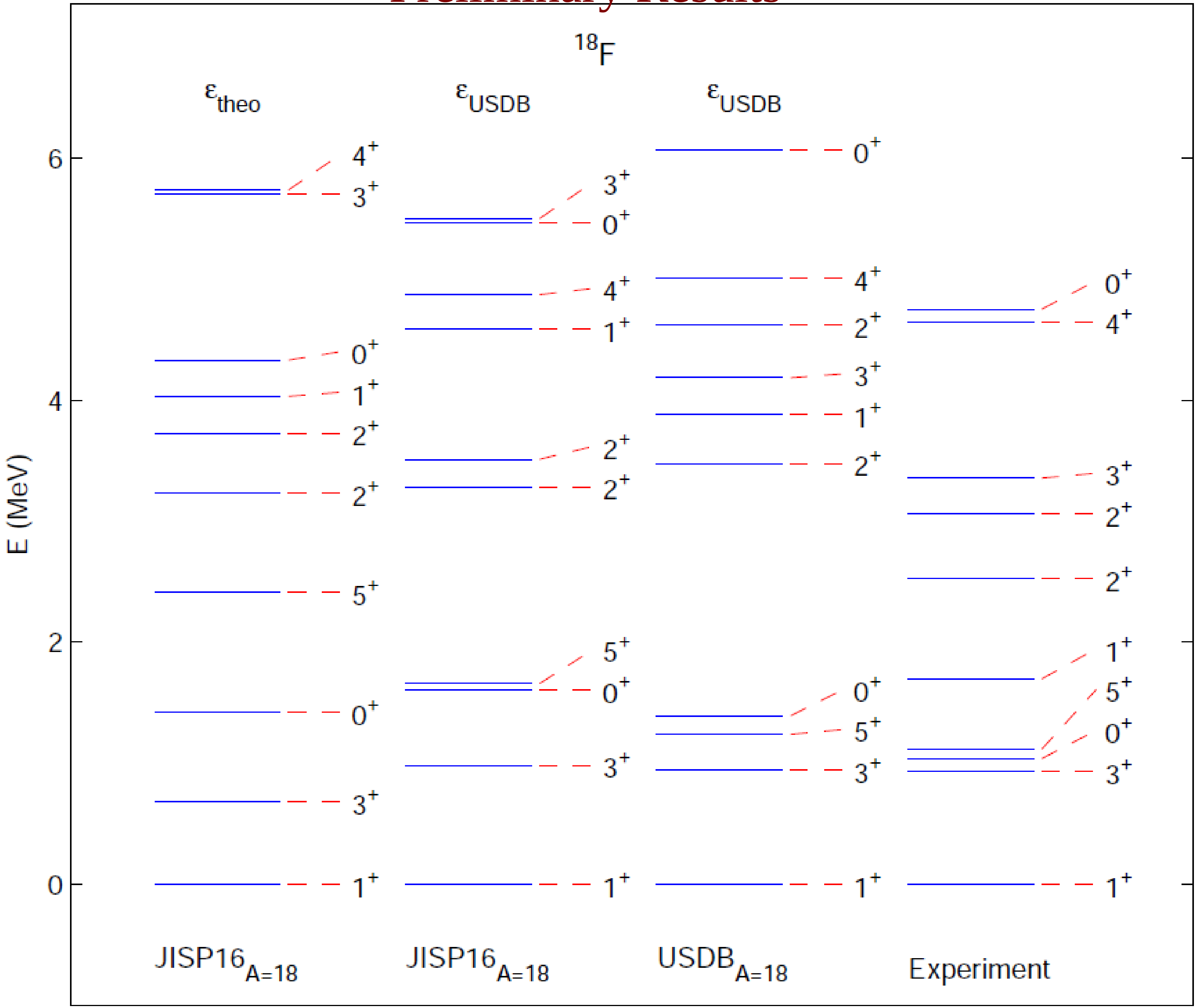


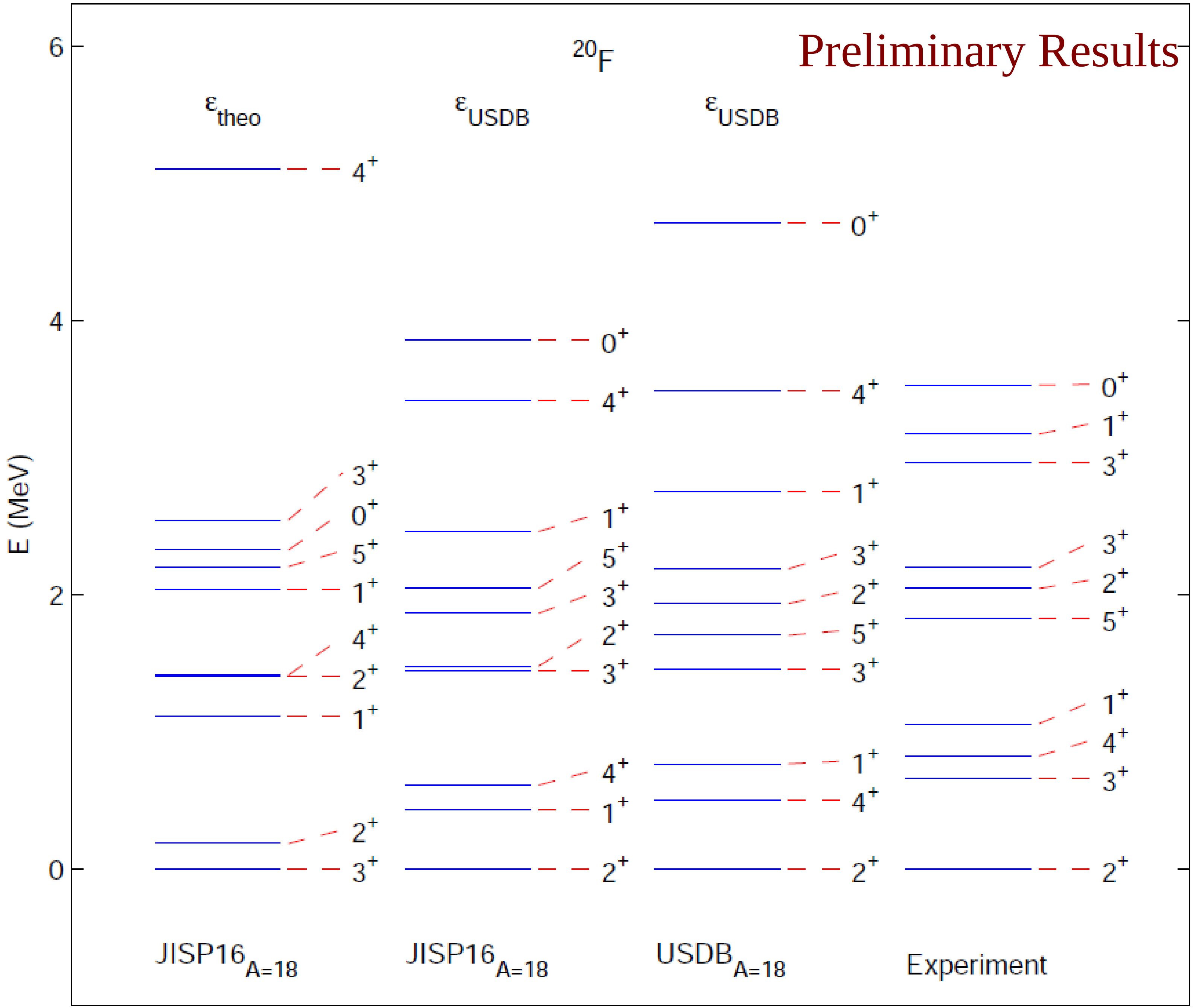
Preliminary Results

Preliminary Results

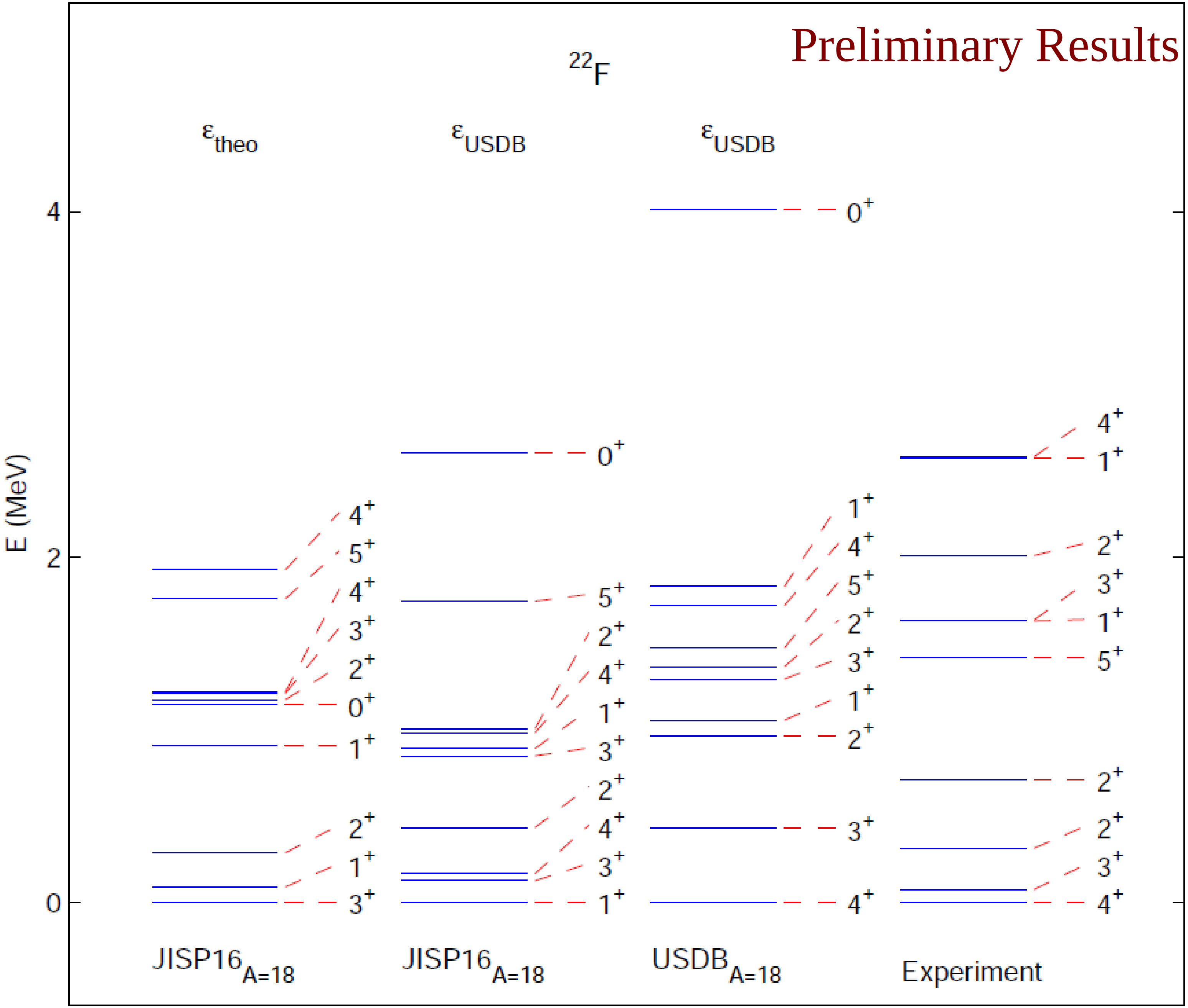


Preliminary Results

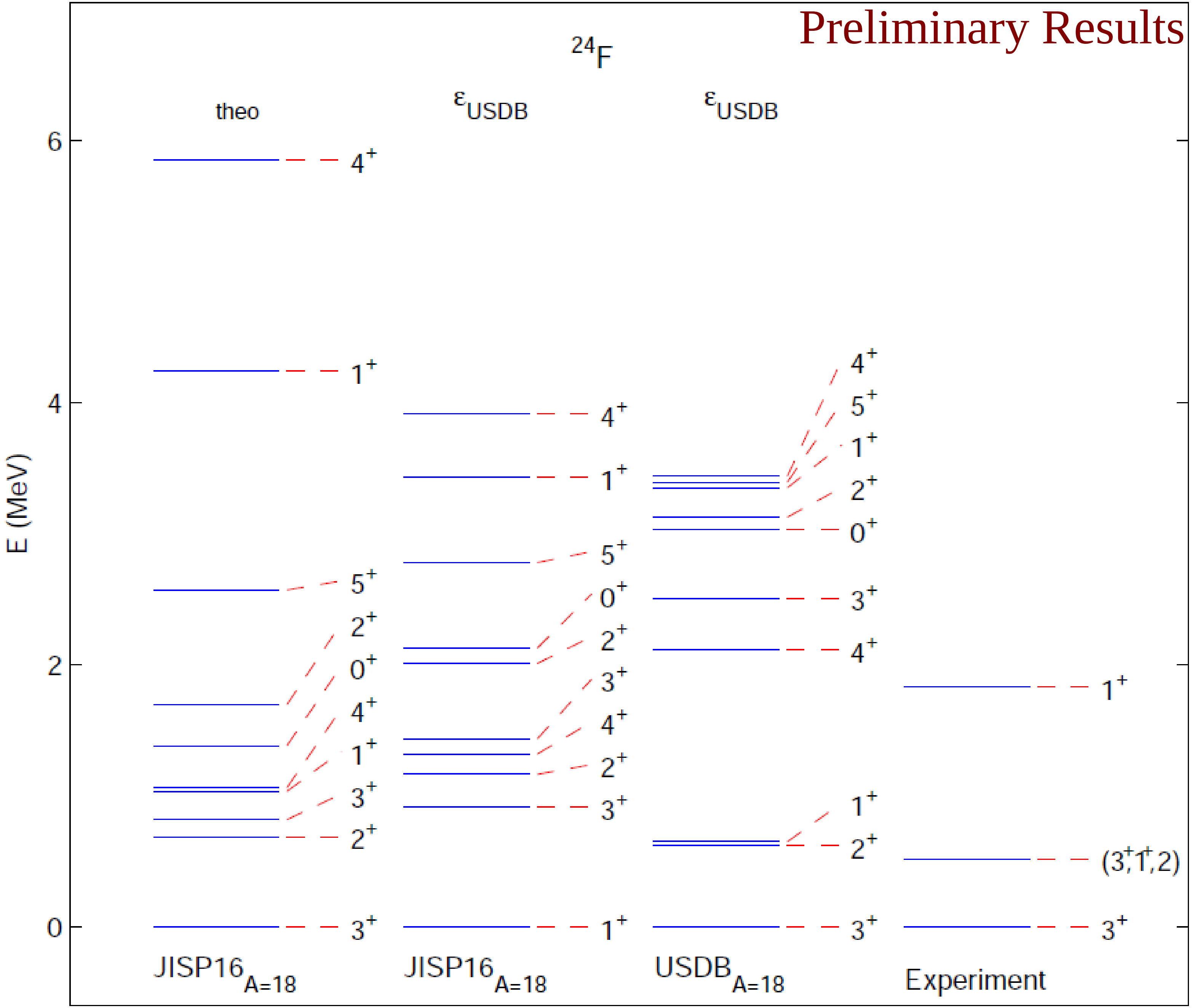




Preliminary Results
^{20}F
ε_{theo}
ε_{USDB}
ε_{USDB}
E (MeV)
6
4
2
0
4+
3+
0+
5+
1+
4+
2+
1+
2+
3+
0+
4+
1+
5+
3+
2+
3+
4+
1+
2+
0+
4+
1+
3+
2+
5+
3+
1+
4+
2+
0+
1+
3+
3+
2+
5+
1+
4+
3+
2+
JISP16$_{A=18}$
JISP16$_{A=18}$
USDB$_{A=18}$
Experiment

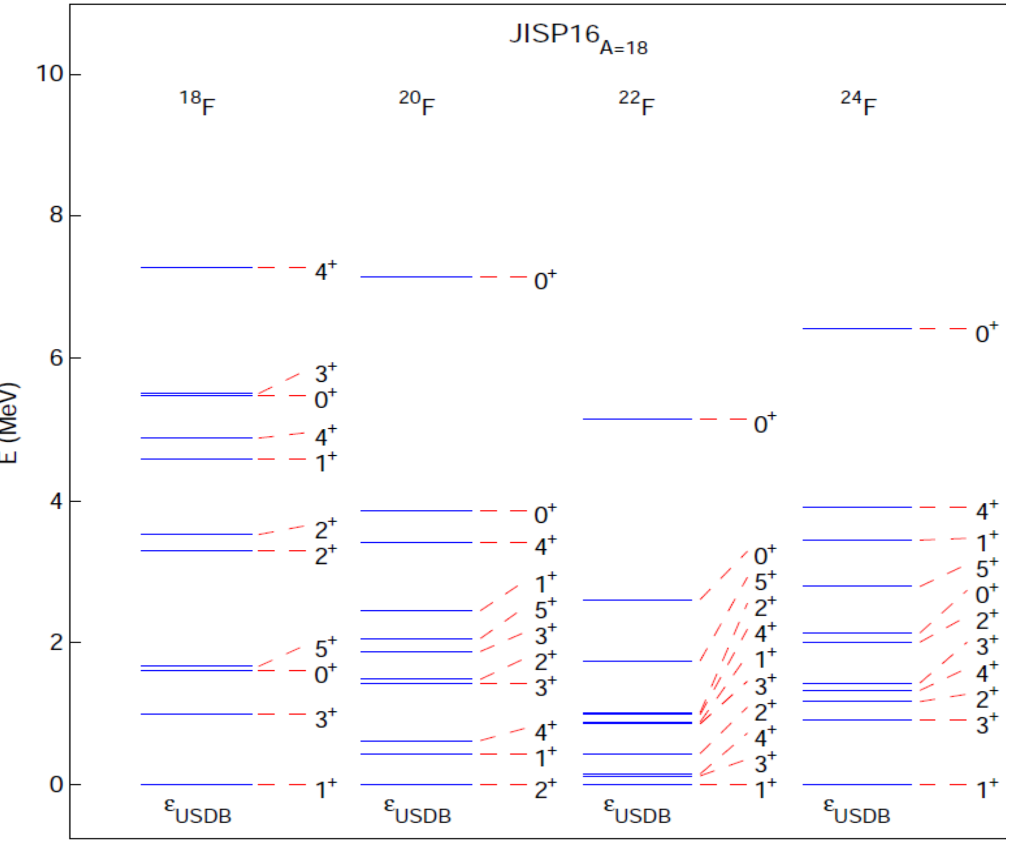


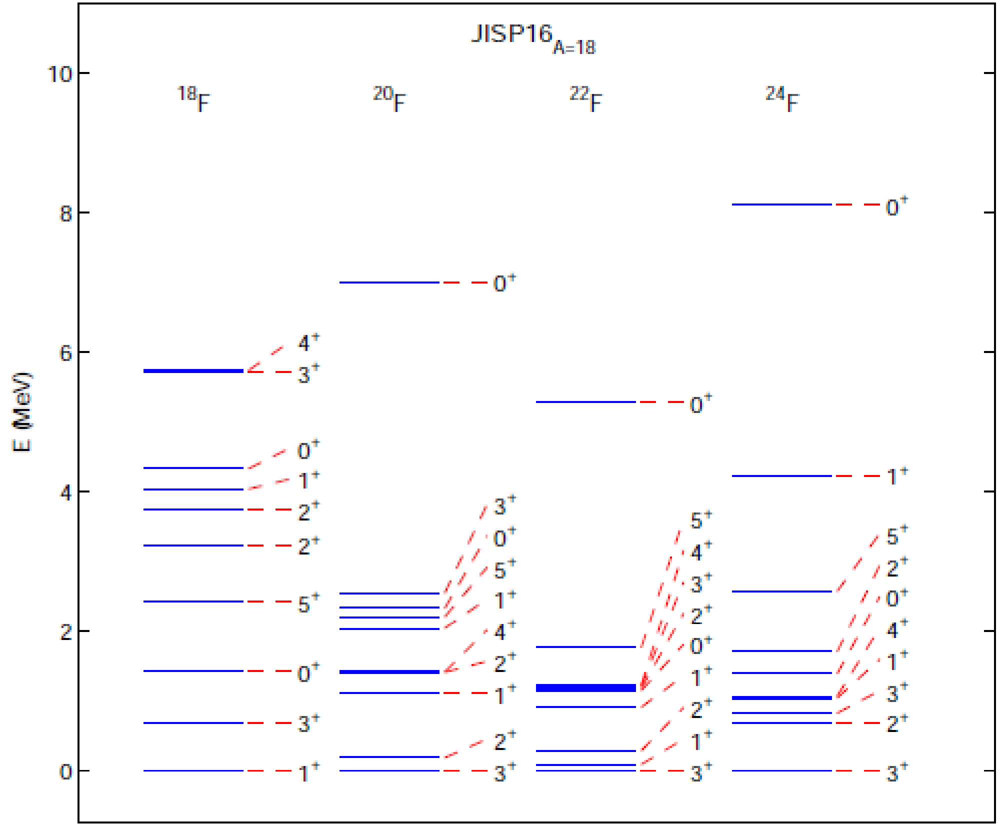
Preliminary Results
22F
ε theo
ε USDB
ε USDB
4
2
0
E (MeV)
4+
5+
4+
3+
2+
0+
1+
2+
1+
3+
0+
5+
2+
4+
1+
3+
2+
4+
3+
1+
0+
1+
4+
5+
2+
3+
1+
2+
3+
4+
4+
1+
2+
3+
1+
5+
2+
2+
3+
4+
JISP16 A=18
JISP16 A=18
USDB A=18
Experiment



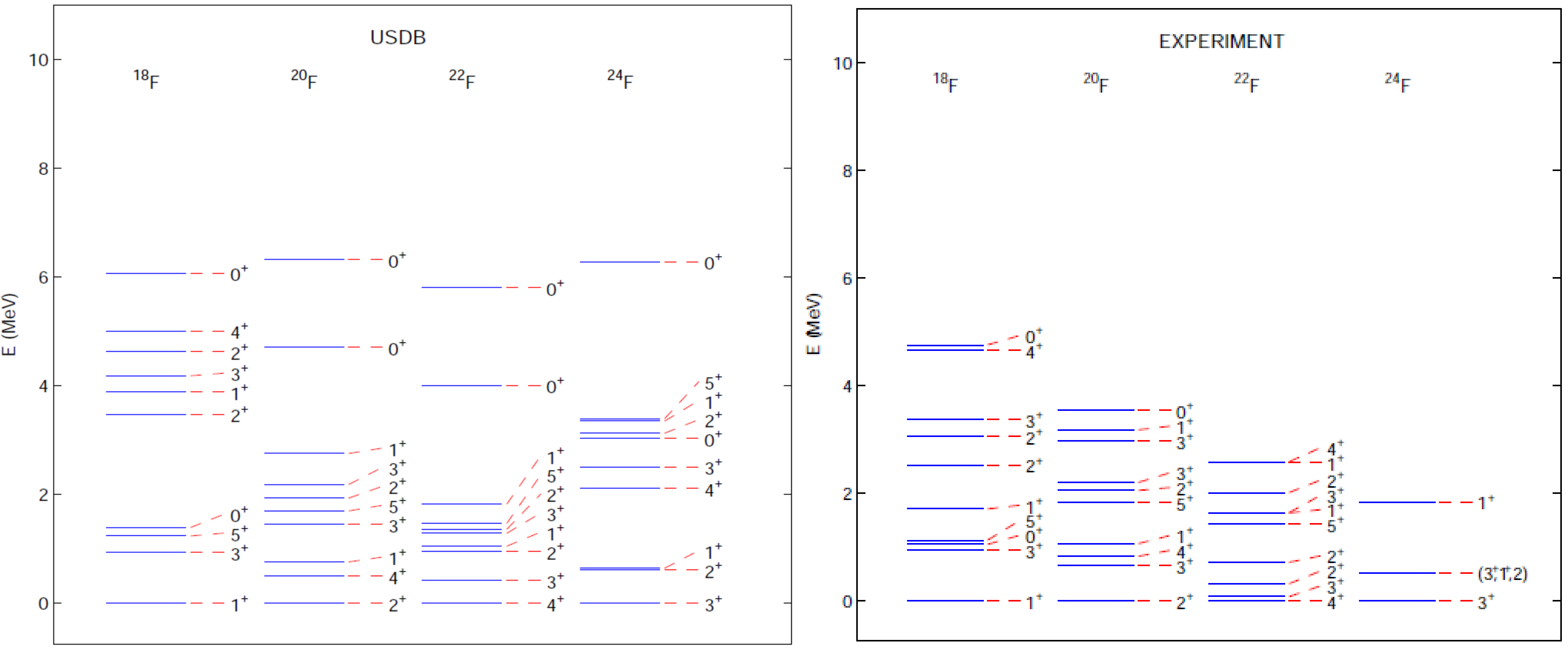
Preliminary Results
24F
theo
εUSDB
εUSDB
E (MeV)
6
4
2
0
4+
1+
5+
2+
0+
4+
1+
3+
2+
3+
4+
1+
5+
0+
2+
3+
4+
2+
3+
1+
4+
5+
1+
2+
0+
3+
4+
1+
2+
3+
1+
(3+,1+,2)
3+
JISP16A=18
JISP16A=18
USDBA=18
Experiment

Preliminary Results

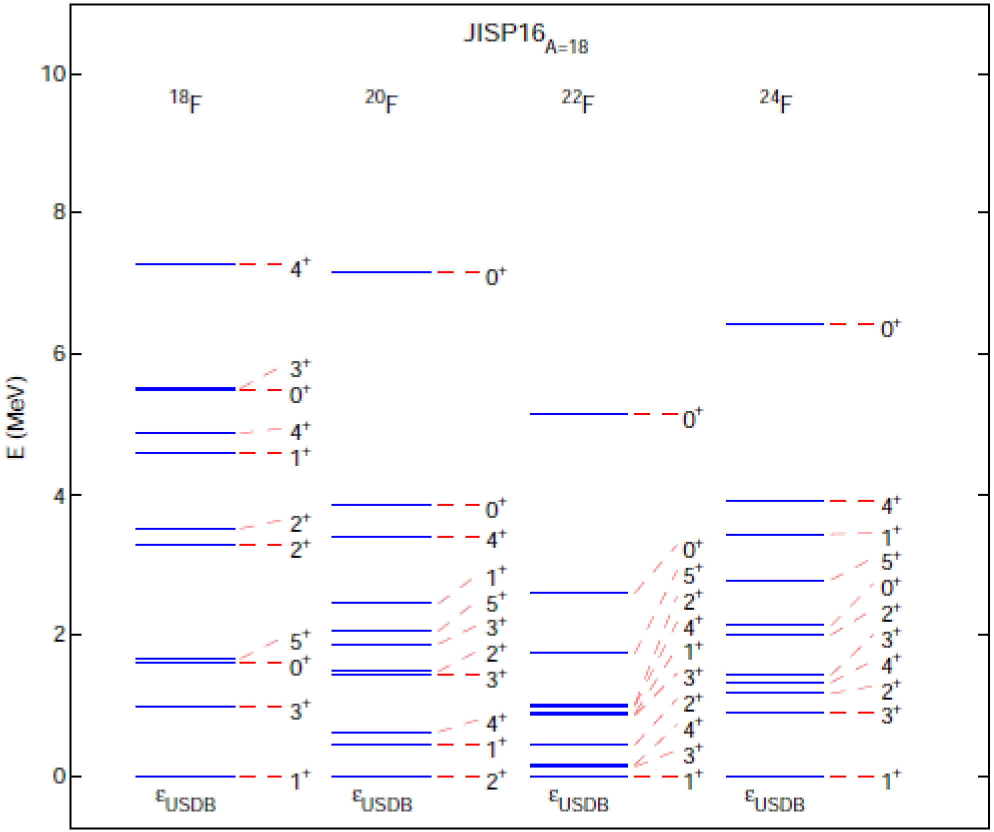


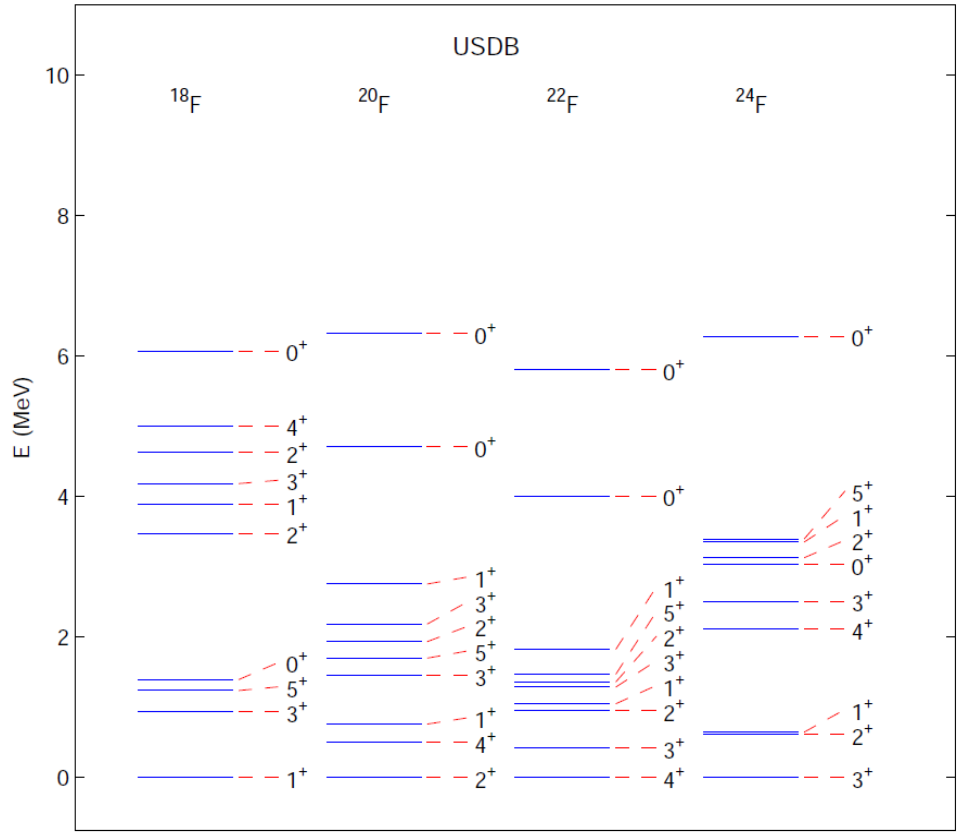


Preliminary Results

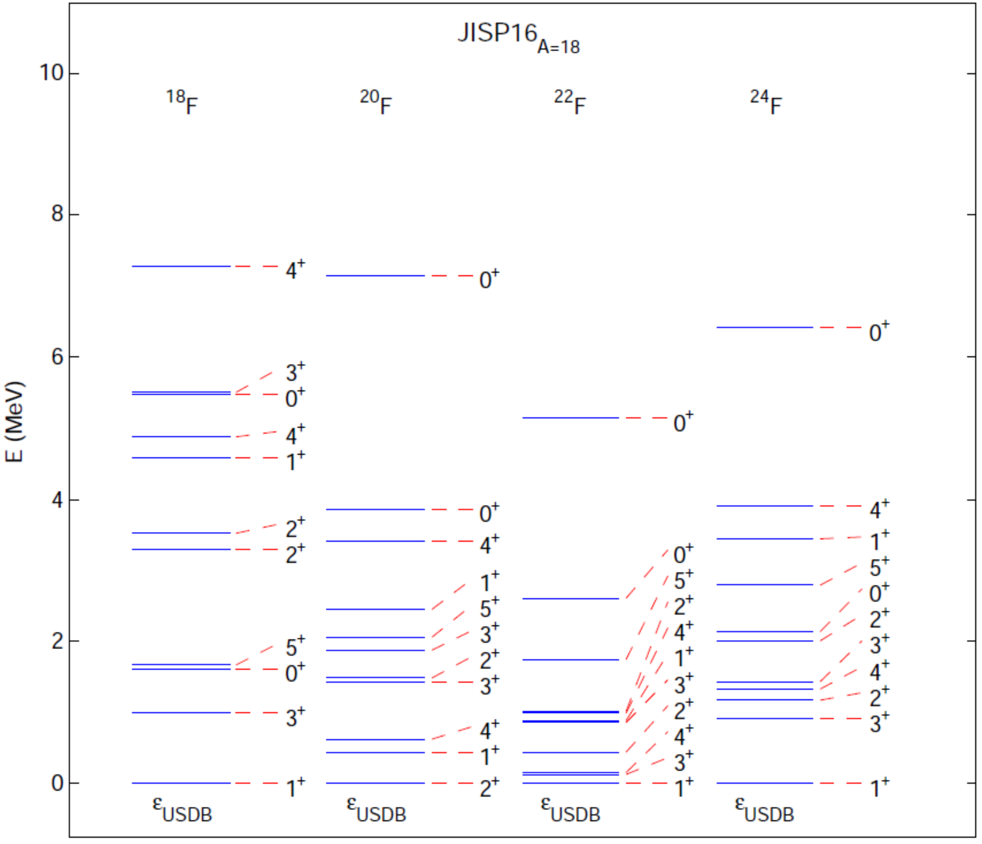


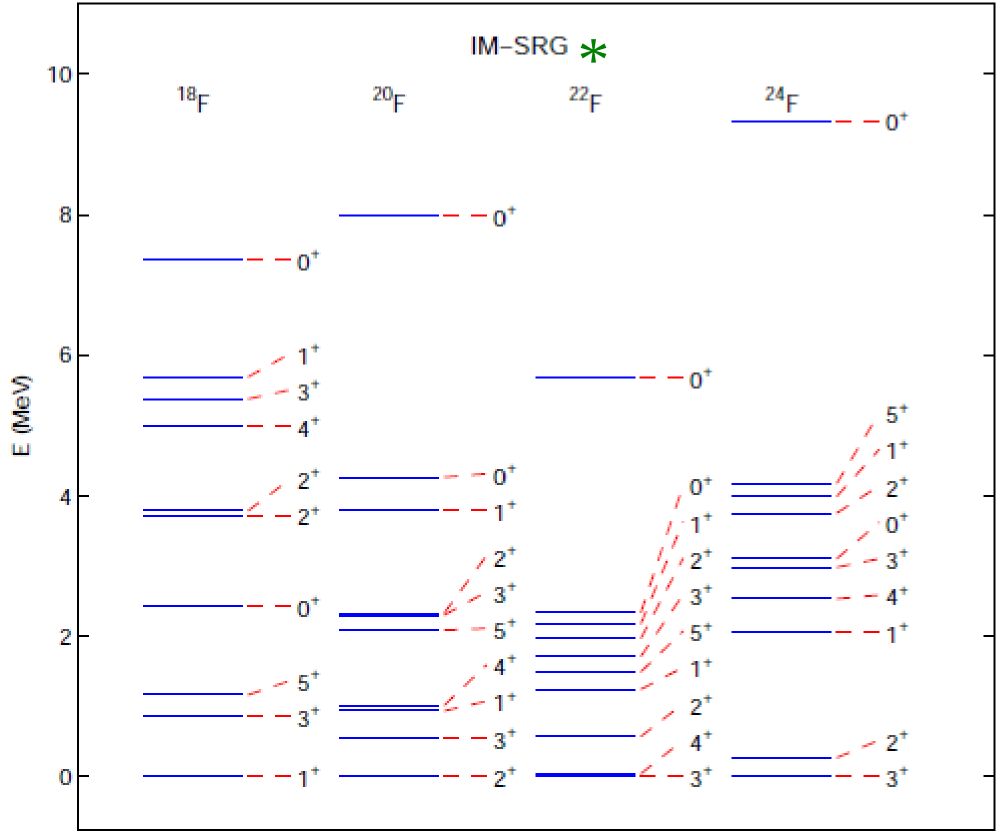
Preliminary Results





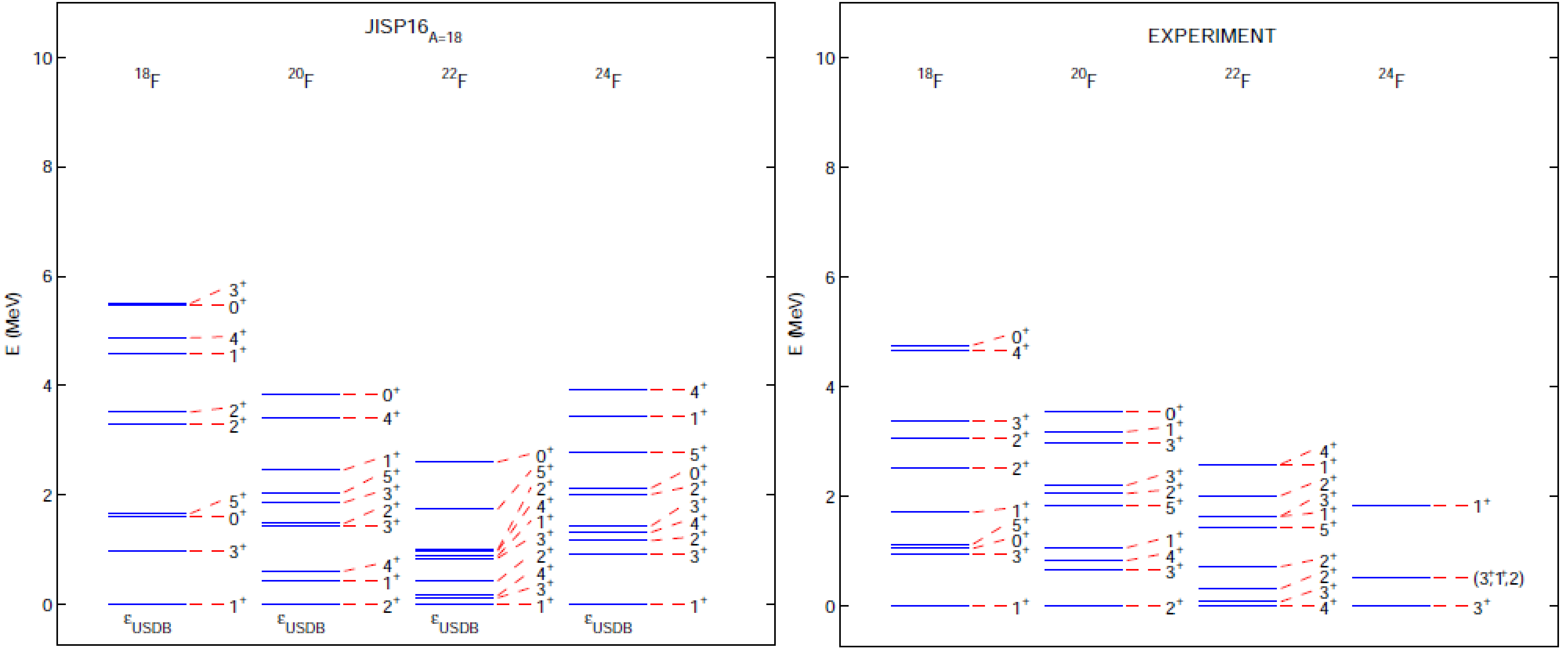
Preliminary Results



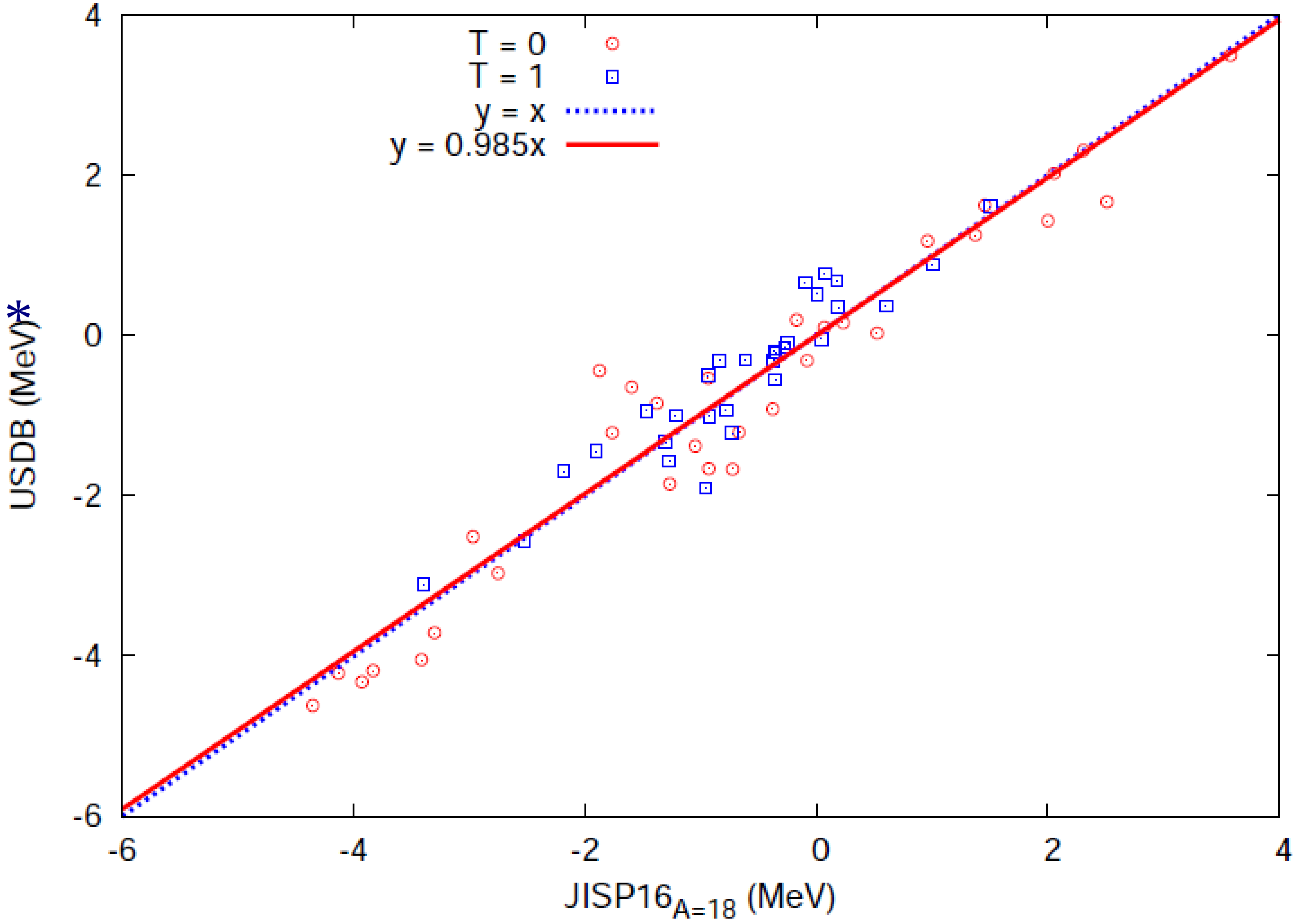


* S.R. Stroberg, et al., arXiv Nucl-th 1511.02802

Preliminary Results



Preliminary Results



RMS deviation of 471 keV

* B.A. Brown & W.A. Richter, PRC 74, 034315 (2006).

Towards a unified description of the nucleus

The goal of nuclear structure theory:

exact treatment of nuclei based on NN, NNN,... interactions

⇨ need to build a bridge between:

ab initio few-body & light nuclei calculations: $A \lesssim 24$

$0\hbar\Omega$ Shell Model calculations: $16 \leq A \leq 60$

Density Functional Theory calculations: $A \geq 60$

From few-body to many-body

Ab initio
No Core Shell Model

Flow chart for a standard NCSM calculation

Realistic NN & NNN forces

↓

Effective interactions in cluster approximation

↓

Diagonalization of many- body Hamiltonian

↓

Many-body experimental data

No Core Shell Model

“*Ab Initio*” approach to microscopic nuclear structure calculations, in which all A nucleons are treated as being active.

Want to solve the A-body Schrödinger equation

$$H_A \Psi^A = E_A \Psi^A$$

R P. Navrátil, J.P. Vary, B.R.B., PRC 62, 054311 (2000)
BRB, P. Navratil, J.P. Vary, Prog.Part.Nucl.Phys. 69, 131 (2013).
P. Navratil, et al., J. Phys. G: Nucl. Part. Phys. 36, 083101 (2009)

No-Core Shell-Model Approach

- Start with the purely intrinsic Hamiltonian

$$H_A = T_{rel} + \mathcal{V} = \frac{1}{A}\sum_{i<j=1}^{A}\frac{(\vec{p}_i - \vec{p}_j)^2}{2m} + \sum_{i<j=1}^{A} V_{NN} \left(+ \sum_{i<j<k}^{A} V_{ijk}^{3b} \right)$$

Note: There are no phenomenological s.p. energies**!**

Can use any NN potentials

Coordinate space: Argonne V8', AV18, Nijmegen I, II

Momentum space: CD Bonn, EFT Idaho

No-Core Shell-Model Approach

- Next, add CM harmonic-oscillator Hamiltonian

$$H_{CM}^{HO} = \frac{\vec{P}^{\,2}}{2Am} + \frac{1}{2}Am\Omega^2\vec{R}^{\,2}\,; \quad \vec{R} = \frac{1}{A}\sum_{i=1}^{A}\vec{r}_i\,, \quad \vec{P} = Am\dot{\vec{R}}$$

To H_A, yielding

$$H_A^{\Omega} = \sum_{i=1}^{A}\left[\frac{\vec{p}_i^{\,2}}{2m} + \frac{1}{2}m\Omega^2\vec{r}_i^{\,2}\right] + \underbrace{\sum_{i<j=1}^{A}\left[V_{NN}(\vec{r}_i - \vec{r}_j) - \frac{m\Omega^2}{2A}(\vec{r}_i - \vec{r}_j)^2\right]}_{V_{ij}}$$

Defines a basis (*i.e.* HO) for evaluating V_{ij}

Effective Interaction

- Must truncate to a finite model space $\quad V_{ij} \dashrightarrow V_{ij}^{effective}$

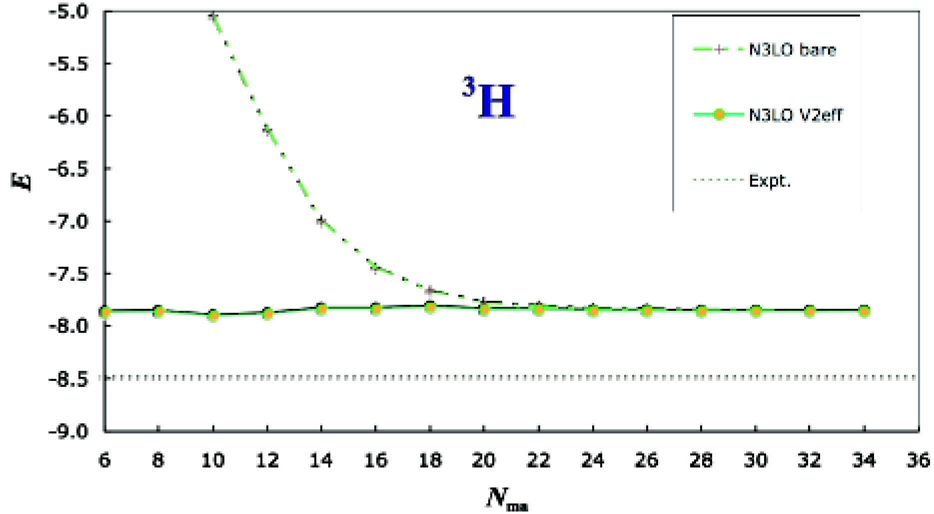
- In general, V_{ij}^{eff} is an A-body interaction

- We want to make an a-body cluster approximation

$$\mathcal{H} = \mathcal{H}^{(I)} + \mathcal{H}^{(A)} \quad \gtrapprox \quad \mathcal{H}^{(I)} + \mathcal{H}^{(a)}$$

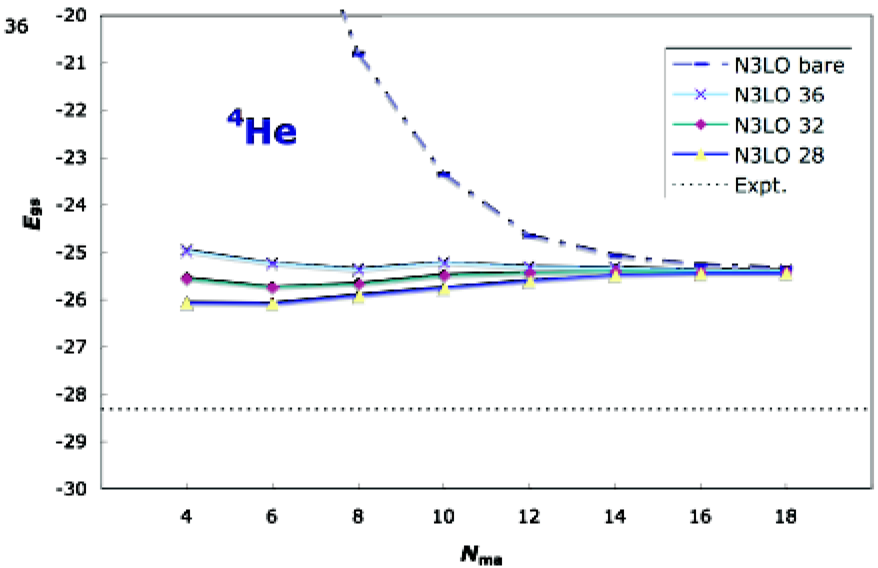
$$a < A$$

- NCSM convergence test
  - Comparison to other methods

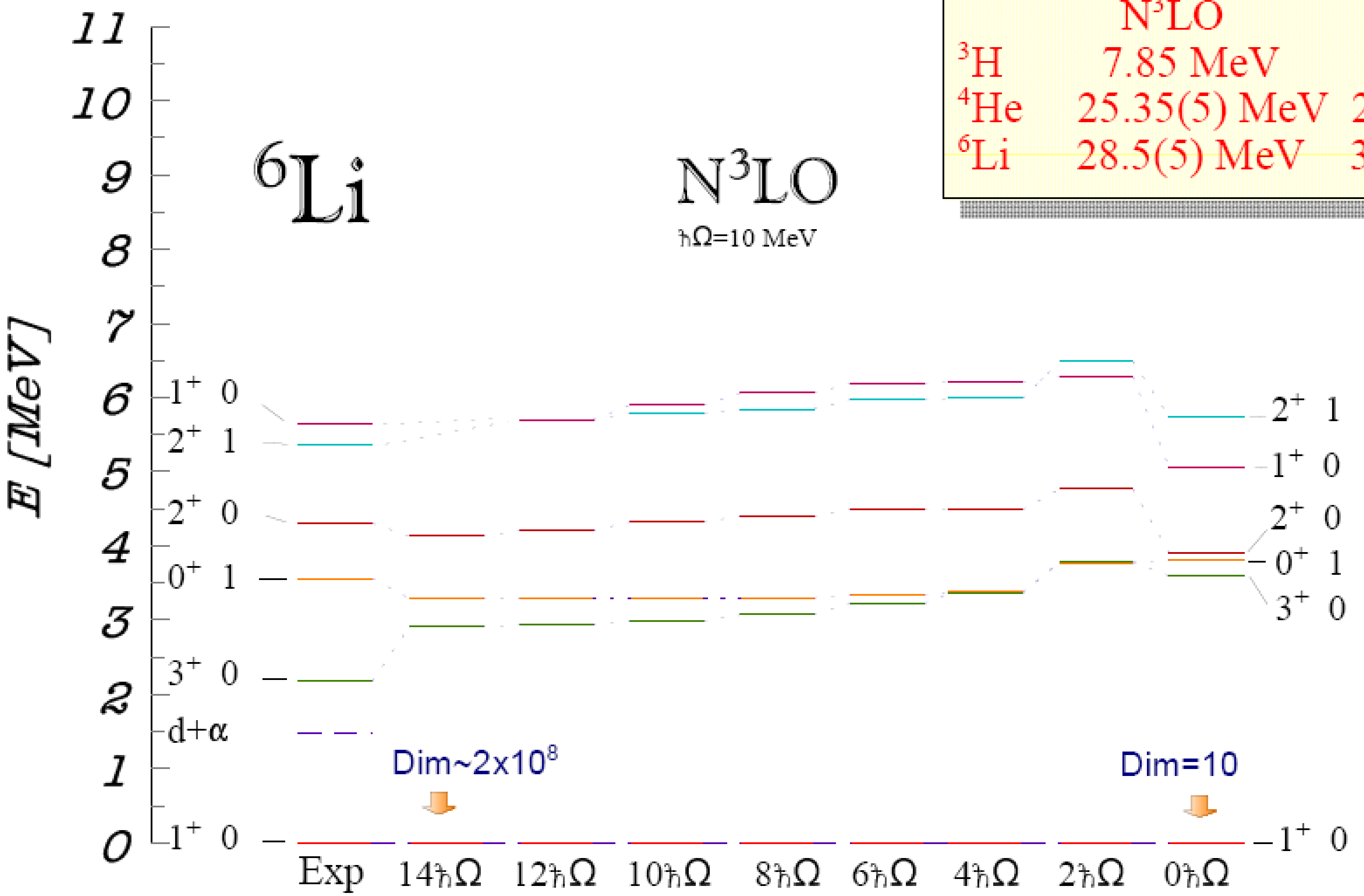


N³LO NN	NCSM	FY	HH
³H	7.852(5)	7.854	7.854
⁴He	25.39(1)	25.37	25.38

- Short-range correlations ⇒ effective interaction
- Medium-range correlations ⇒ multi-$h\Omega$ model space
- Dependence on
  - size of the model space (N_{max})
  - HO frequency ($h\Omega$)
- Not a variational calculation
- Convergence OK
- NN interaction insufficient to reproduce experiment

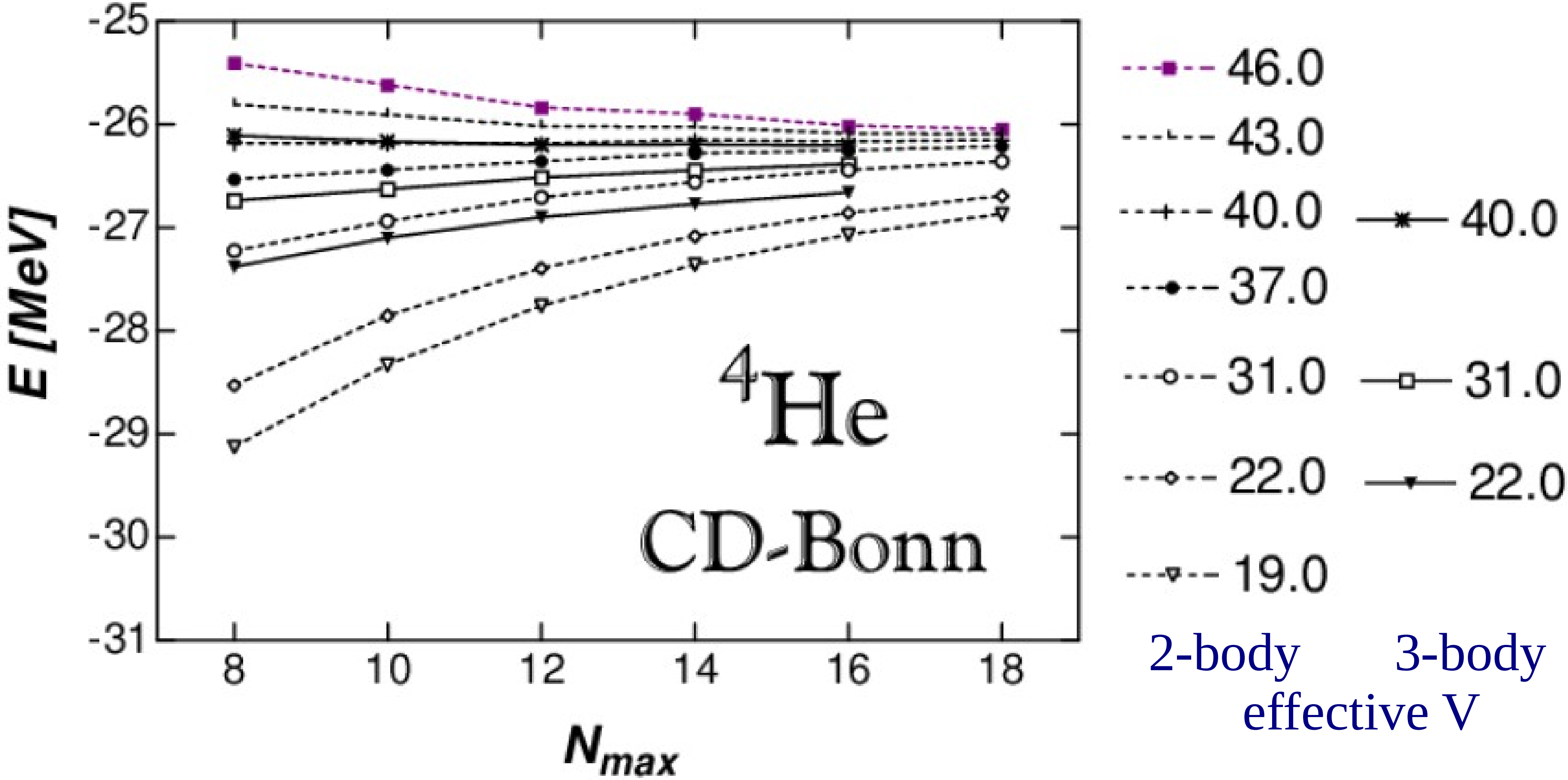


P. Navratil, INT Seminar, November 13, 2007, online



	N^3LO	Exp
^3H	7.85 MeV	8.48 MeV
^4He	25.35(5) MeV	28.30 MeV
^6Li	28.5(5) MeV	31.99 MeV

P. Navrátil and E. Caurier, Phys. Rev. C **69**, 014311 (2004)

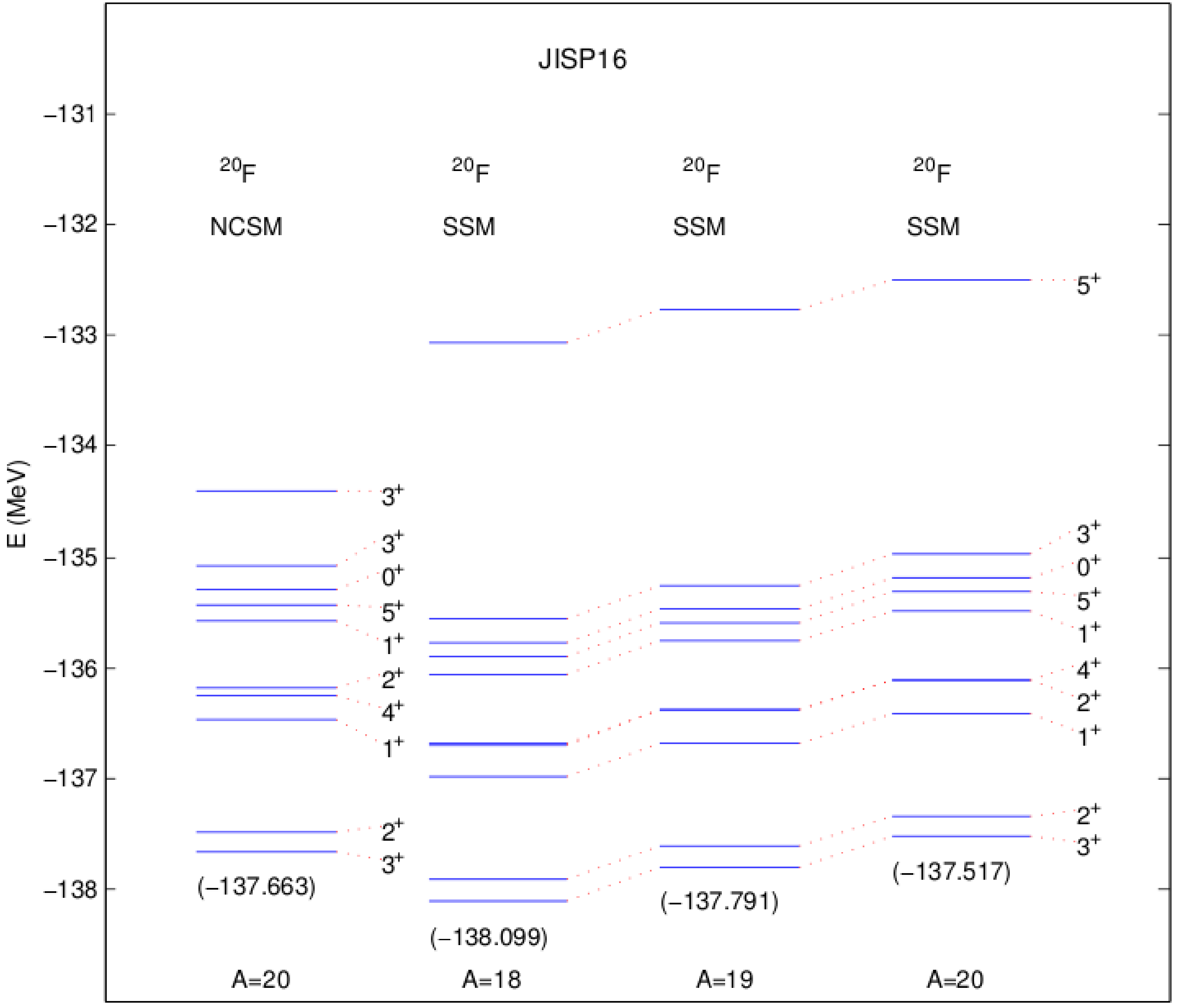


-25
-26
-27
-28
-29
-30
-31
E [MeV]
8
10
12
14
16
18
N_{max}
^{4}He
CD-Bonn
46.0
43.0
40.0
40.0
37.0
31.0
31.0
22.0
22.0
19.0
2-body
3-body
effective V

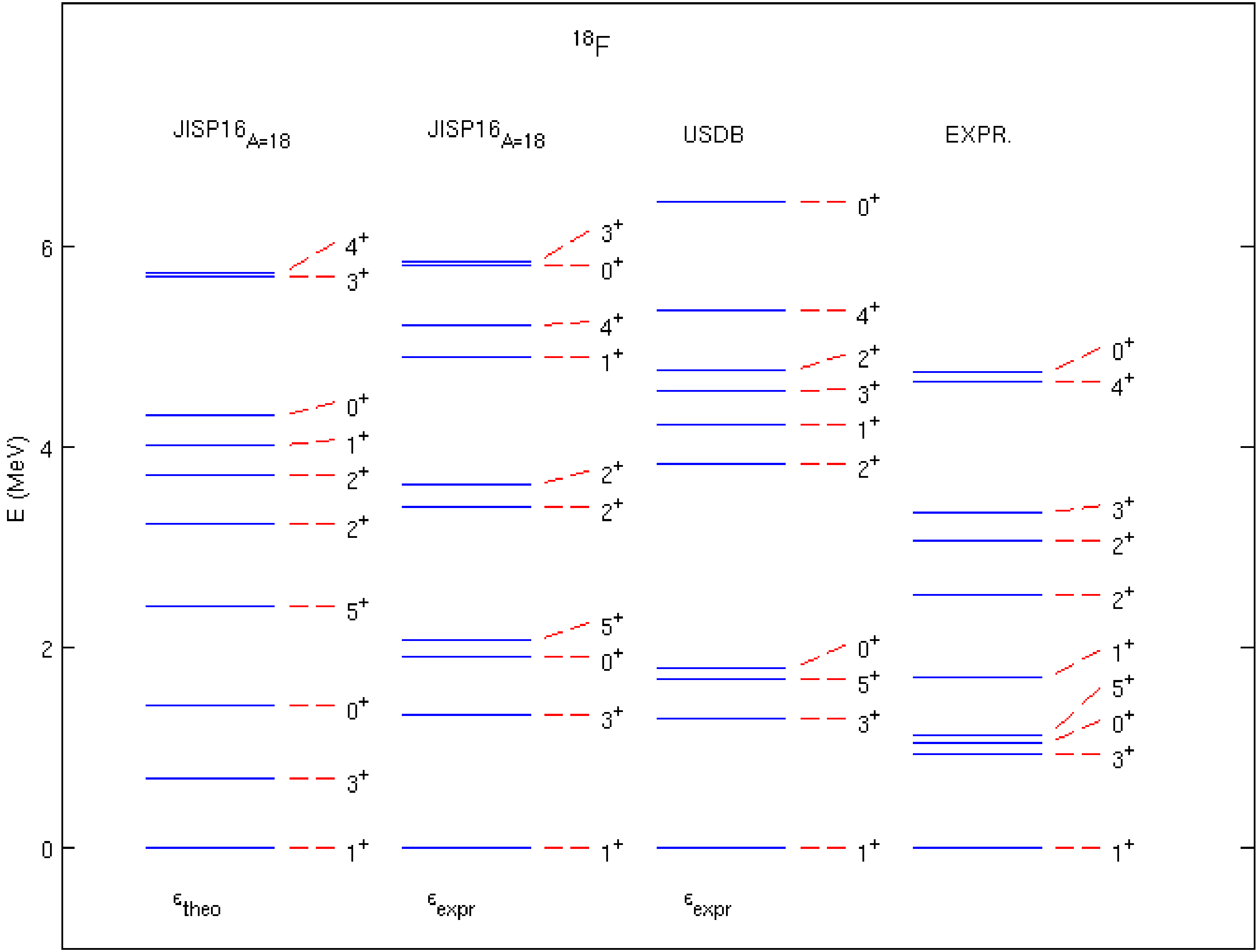
TABLE III: The NCSM energies (in MeV) of the lowest 28 states J_i^π of ^{18}F calculated in $4\hbar\Omega$ model space using JISP16 and chiral N3LO NN interactions with $\hbar\Omega = 14$ MeV.

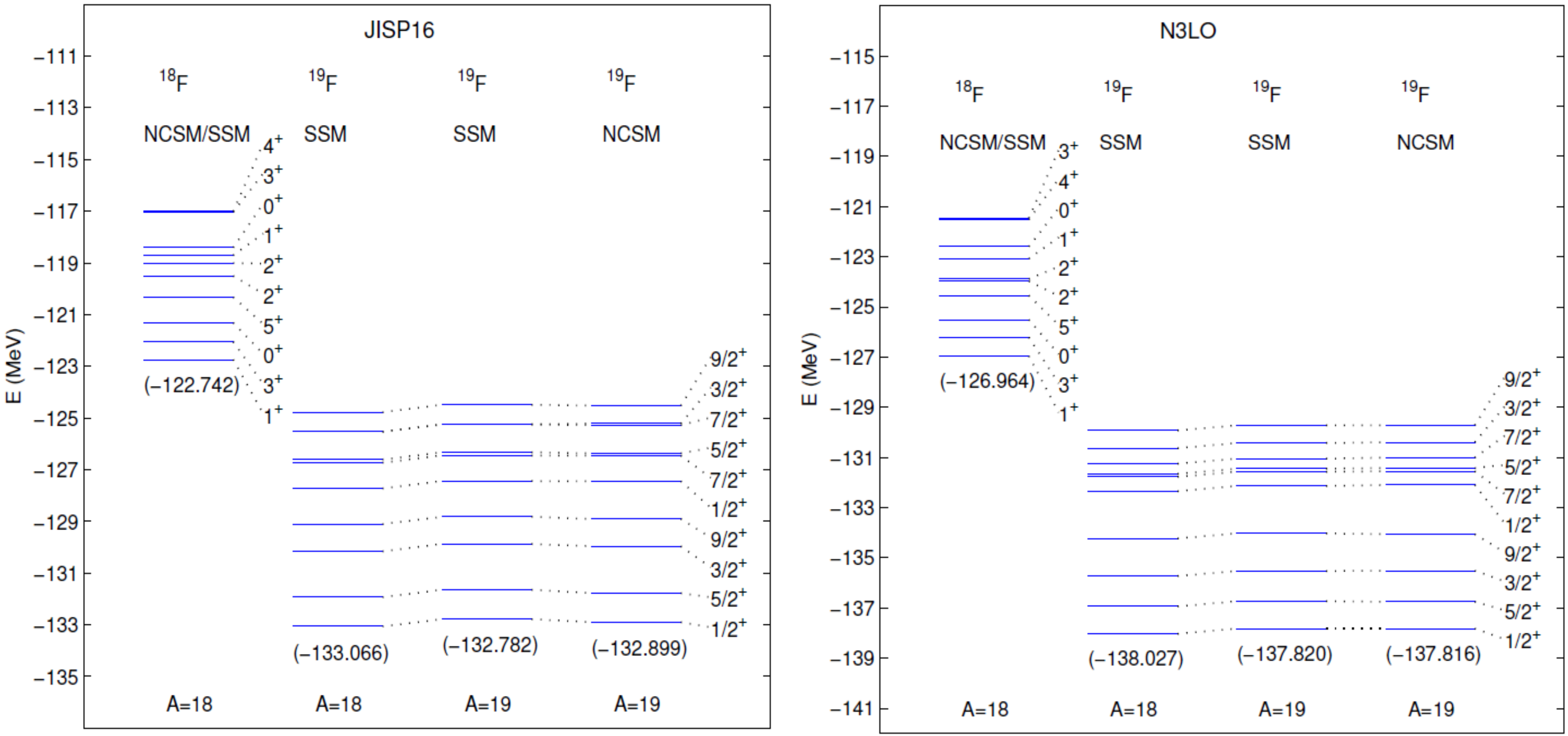
J_i^π	T	JISP16	J_i^π	T	N3LO
1_1^+	0	-122.742	1_1^+	0	-126.964
3_1^+	0	-122.055	3_1^+	0	-126.214
0_1^+	1	-121.320	0_1^+	1	-125.510
5_1^+	0	-120.329	5_1^+	0	-124.545
2_1^+	1	-119.505	2_1^+	1	-123.974
2_2^+	0	-119.011	2_2^+	0	-123.890
1_2^+	0	-118.709	1_2^+	0	-123.077
0_2^+	1	-118.410	0_2^+	1	-122.586
2_3^+	1	-117.211	2_3^+	1	-121.588
3_2^+	1	-117.035	4_1^+	1	-121.512
4_1^+	1	-117.004	3_2^+	1	-121.450
3_3^+	0	-116.765	3_3^+	0	-121.376
1_3^+	0	-113.565	1_3^+	0	-119.658
4_2^+	0	-112.314	4_2^+	0	-118.656
2_4^+	0	-111.899	2_4^+	0	-117.950
1_4^+	0	-110.357	1_4^+	0	-116.106
4_3^+	1	-109.625	4_3^+	1	-115.785
2_5^+	1	-109.292	2_5^+	1	-115.407
1_5^+	1	-108.752	3_4^+	0	-115.309
3_4^+	0	-108.706	1_5^+	1	-114.870
2_6^+	0	-108.485	2_6^+	0	-114.787
1_6^+	1	-108.055	1_6^+	1	-114.392
2_7^+	1	-108.041	3_5^+	1	-114.258
3_5^+	1	-107.874	2_7^+	1	-114.176
3_6^+	0	-101.528	3_6^+	0	-109.316
1_7^+	0	-99.946	1_7^+	0	-107.798
0_3^+	1	-99.848	2_8^+	1	-107.473
2_8^+	1	-99.607	0_3^+	1	-107.436

PRELIMINARY RESULTS



Preliminary Results




JISP16
N3LO
E (MeV)
−111
−113
−115
−117
−119
−121
−123
−125
−127
−129
−131
−133
−135
−139
−141
^{18}F
^{19}F
NCSM/SSM
SSM
NCSM
(−122.742)
(−133.066)
(−132.782)
(−132.899)
(−126.964)
(−138.027)
(−137.820)
(−137.816)
A=18
A=19
4^+
3^+
0^+
1^+
2^+
5^+
$9/2^+$
$3/2^+$
$7/2^+$
$5/2^+$
$1/2^+$

Two-body VCE for ^{6}Li

$$\mathcal{H}^{0,N_{\max}}_{A=6,a_1=6} = V_0^{6,4} + V_1^{6,5} + V_2^{6,6}$$

Need NCSM results in N_{max} space for

^{4}He

^{5}He ^{5}Li

^{6}He ^{6}Li ^{6}Be

With effective interaction for A=6 !!!

$$H^{N_{\max},\Omega,\mathrm{eff}}_{A=6,2}$$

3-body Valence Cluster approximation for A>6

$$\mathcal{H}_{A,a_1=7}^{0,N_{\max}} = V_0^{A,4} + V_1^{A,5} + V_2^{A,6} + V_3^{A,7}$$

Need NCSM results in N_{max} space for

^{4}He | **^{5}He ^{5}Li** | **^{6}He ^{6}Li ^{6}Be** | **^{7}He ^{7}Li ^{7}B ^{7}Be**

With effective interaction for A !!!

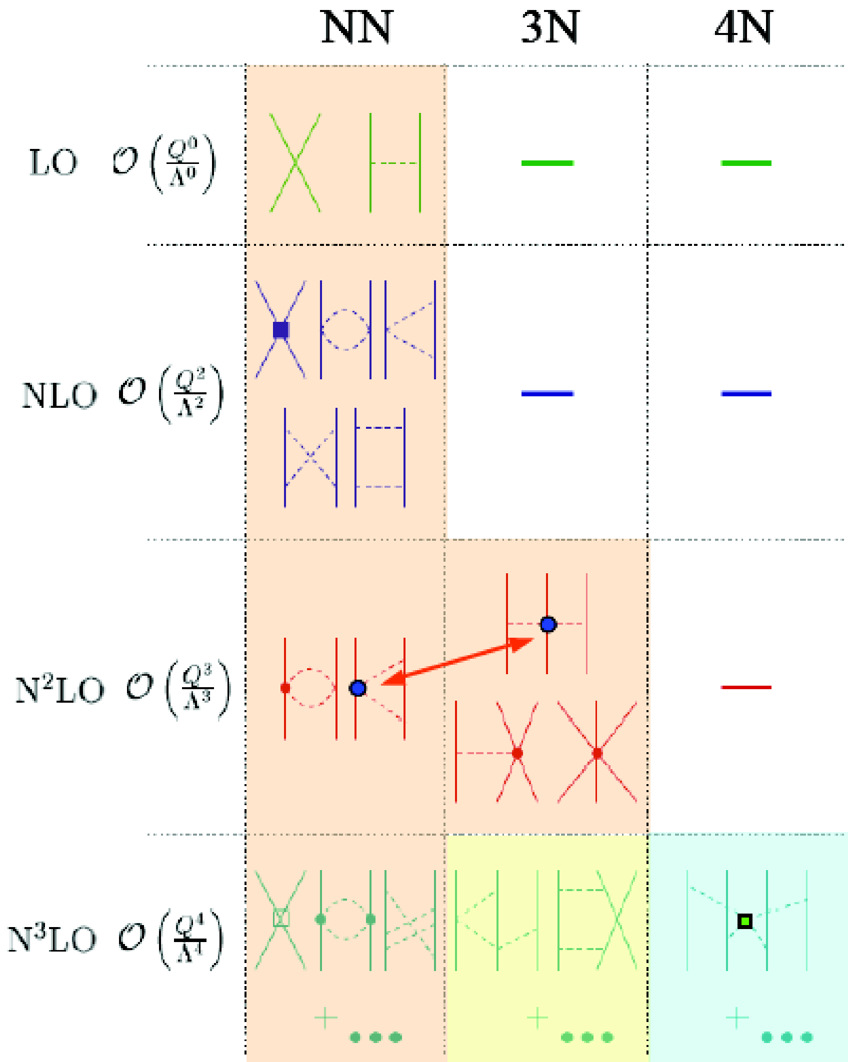
$$H_{A\;\;\;\;,2}^{N_{\max},\Omega,\text{eff}}$$

Construct 3-body interaction in terms of 3-body matrix elements: Yes

$$V_3^{A,7} = \mathcal{H}_{A,7}^{0,N_{\max}} - \mathcal{H}_{A,6}^{0,N_{\max}}$$

Chiral effective field theory (EFT) for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale Λ_b

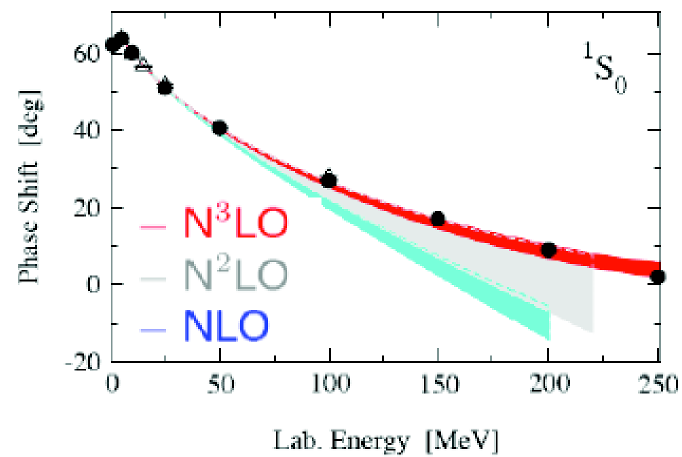


explains pheno hierarchy:
NN > 3N > 4N > …

NN-3N, πN, ππ, electro-weak,…
consistency

3N,4N: 2 new couplings to N^{3}LO!

theoretical error estimates



A. Schwenk

Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Meissner, Nogga, Machleidt,…