First γ-Ray Spectroscopy of an *sd*-shell Hypernucleus, $^{19}_{\Lambda}\mathrm{F}$

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for J-PARC E13 Collaboration

Department of Physics

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Gamma-ray Spectroscopy of Λ-Hypernuclei at J-PARC

■ There was a J-PARC beam time for $^{19}_{\Lambda}\mathrm{F}$ in June 2015.

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First Determination of the Level Structure of an *sd*-Shell Hypernucleus, $^{19}_{\Lambda}\mathrm{F}$

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We report on the first observation of γ rays emitted from an *sd*-shell hypernucleus, $^{19}_{\Lambda}\mathrm{F}$. The energy spacing between the ground state doublet, $1/2^+$ and $3/2^+$ states, of $^{19}_{\Lambda}\mathrm{F}$ is determined to be $315.5 \pm 0.4(\mathrm{stat})^{+0.6}_{-0.5}(\mathrm{syst})$ keV by measuring the γ-ray energy of the $M1(3/2^+ \to 1/2^+)$ transition. In addition, three γ-ray peaks are observed and assigned as $E2(5/2^+ \to 1/2^+)$, $E1(1/2^- \to 1/2^+)$, and $E1(1/2^- \to 3/2^+)$ transitions. The excitation energies of the $5/2^+$ and $1/2^-$ states are determined to be $895.2 \pm 0.3(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ and $1265.6 \pm 1.2(\mathrm{stat})^{+0.7}_{-0.5}(\mathrm{syst})$ keV, respectively. It is found that the ground state doublet spacing is well described by theoretical models based on existing *s*- and *p*-shell hypernuclear data.

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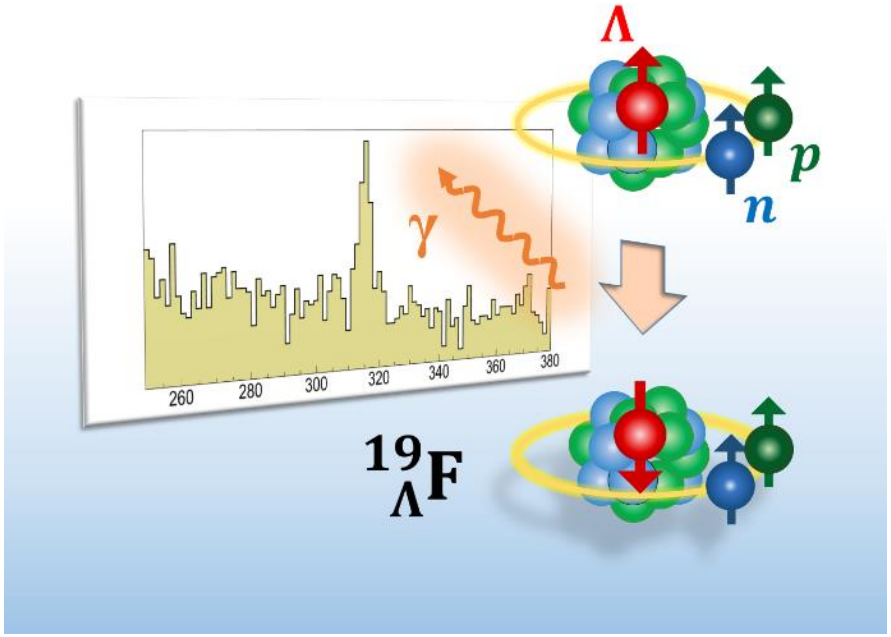
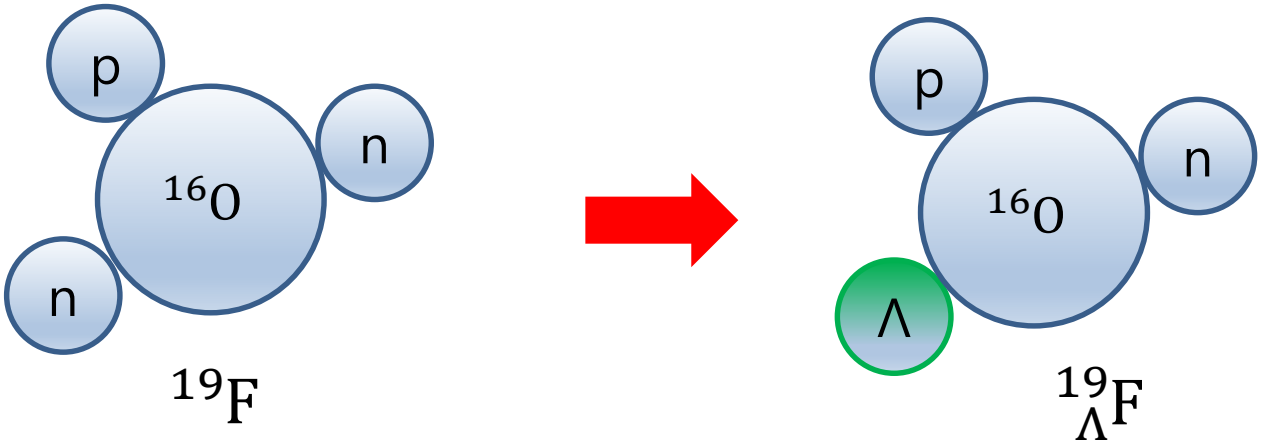


*@PRL **120**, 132505 (2018).*

ΛN Interaction and Λ-Hypernucleus

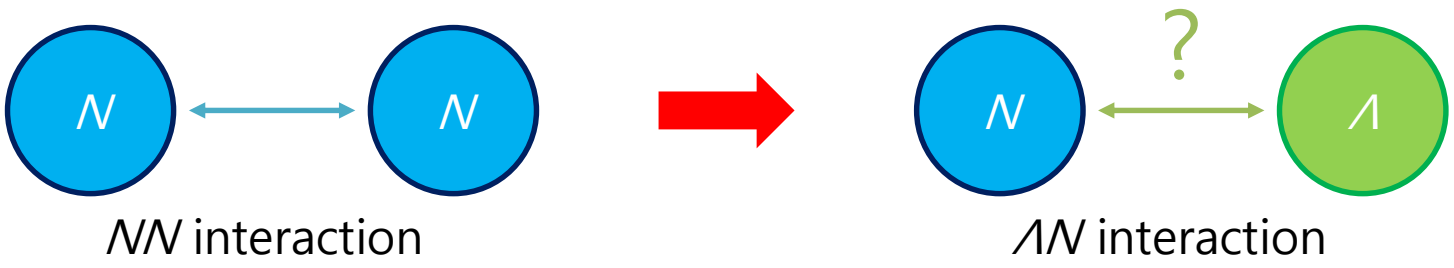
■ Λ-hypernucleus

Due to the short life time of Λ, a scattering experiment is impossible for the *ΛN* interaction. In this case, a spectroscopy of Λ-hypernucleus is the most powerful tool.



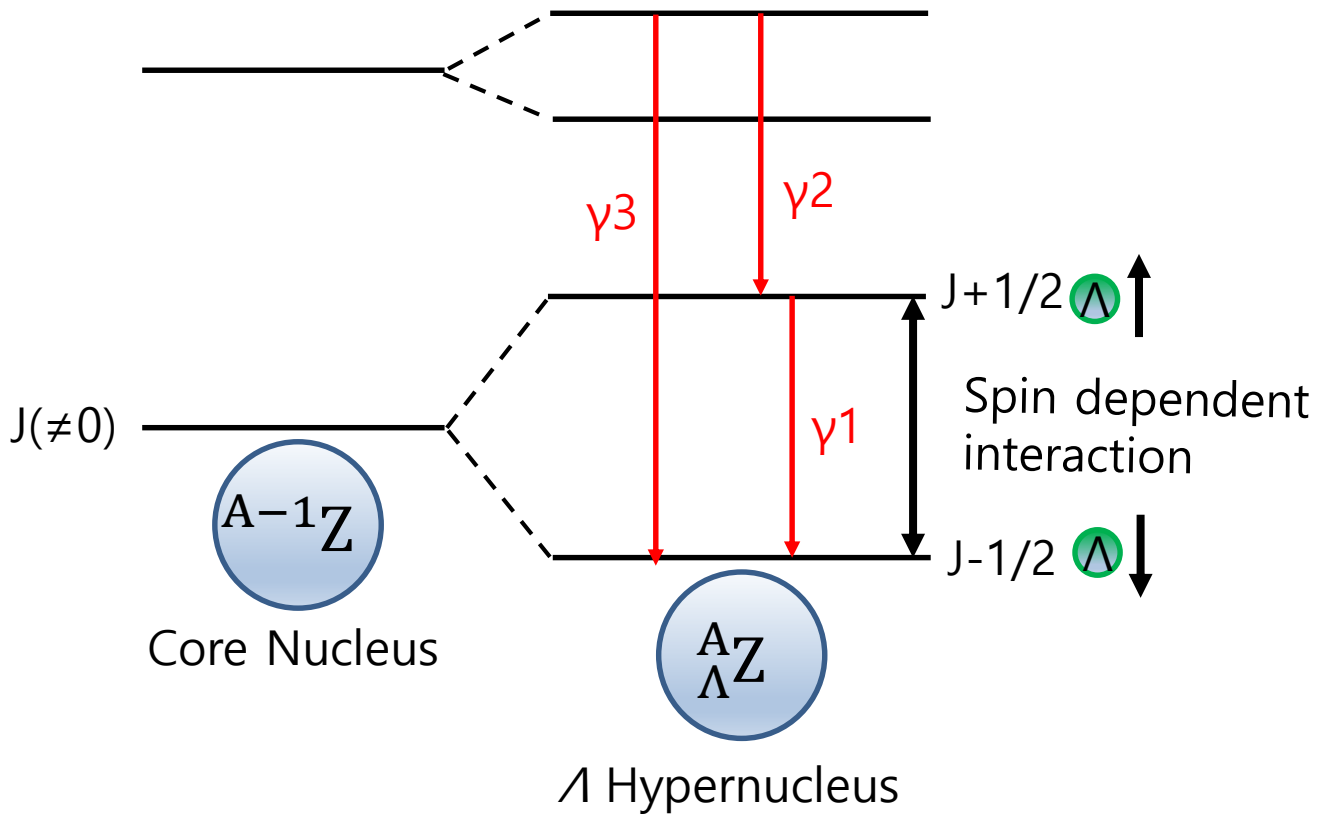
■ *ΛN* interaction

It is the first step to understand the general baryon-baryon interaction.



Gamma-Ray Spectroscopy of Λ Hypernuclei

■ Gamma-ray spectroscopy of Λ-hypernuclei

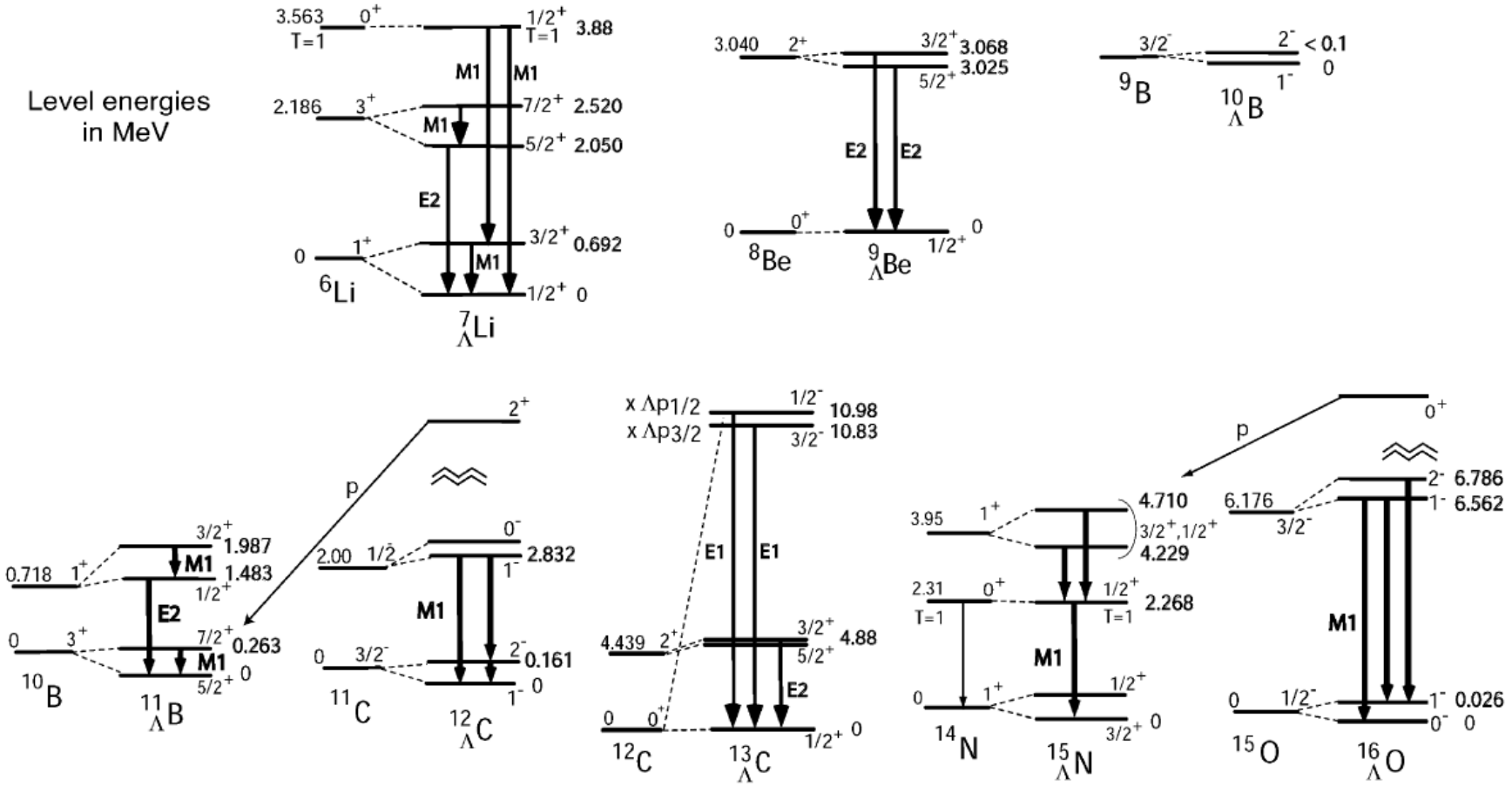


→ By measuring energies of the γ rays, the split energy spacing is precisely estimated and we can know a fine structure of the hypernucleus.

■ Previous gamma-ray spectroscopy of Λ hypernuclei

From 1998, several *s*- and *p*-shell hypernuclei were well studied through the method.

*@NPA **835**, 3 (2010)*



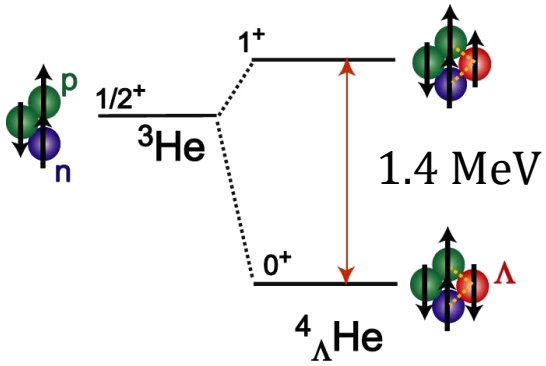
→ We continue this experiment at J-PARC.

Gamma-ray Spectroscopy of $^{19}_{\Lambda}$F

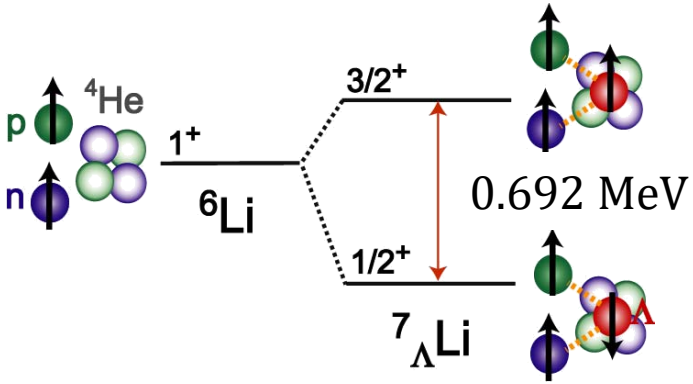
■ Precise level data for *s*- and *p*-shell hypernuclei have revealed strengths of the spin-dependent ΛN interaction and the ΛNN interaction ($\Lambda\Sigma$ coupling effect).

■ It is the first measurement of fine structure of an *sd*-shell hypernuclei, beyond *s*- and *p*-shell hypernuclei.

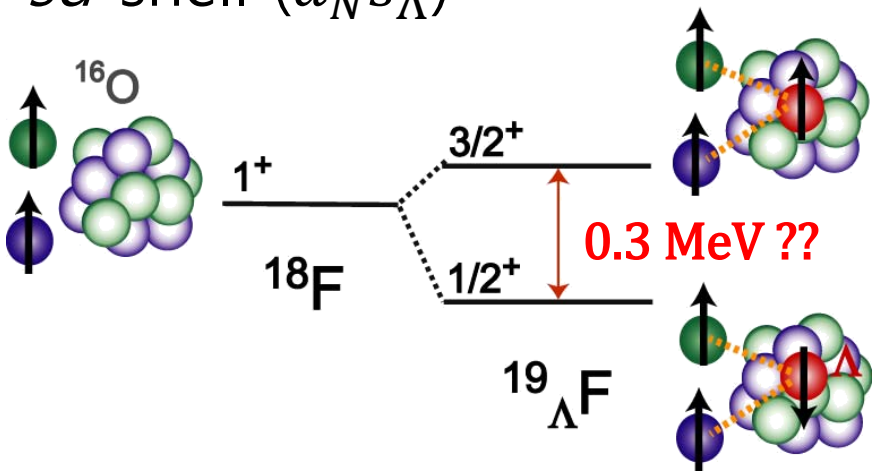
s-shell ($s_N s_\Lambda$)



p-shell ($p_N s_\Lambda$)



sd-shell ($d_N s_\Lambda$)

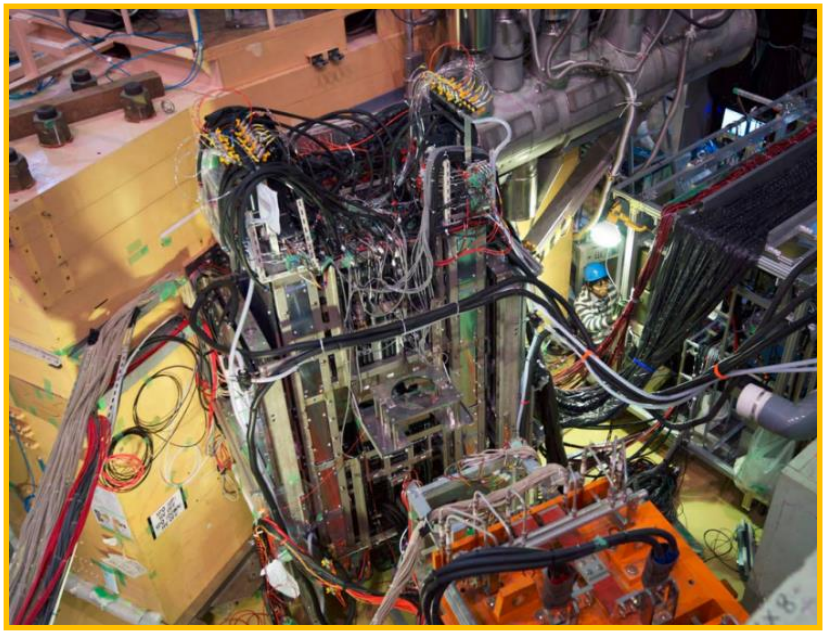


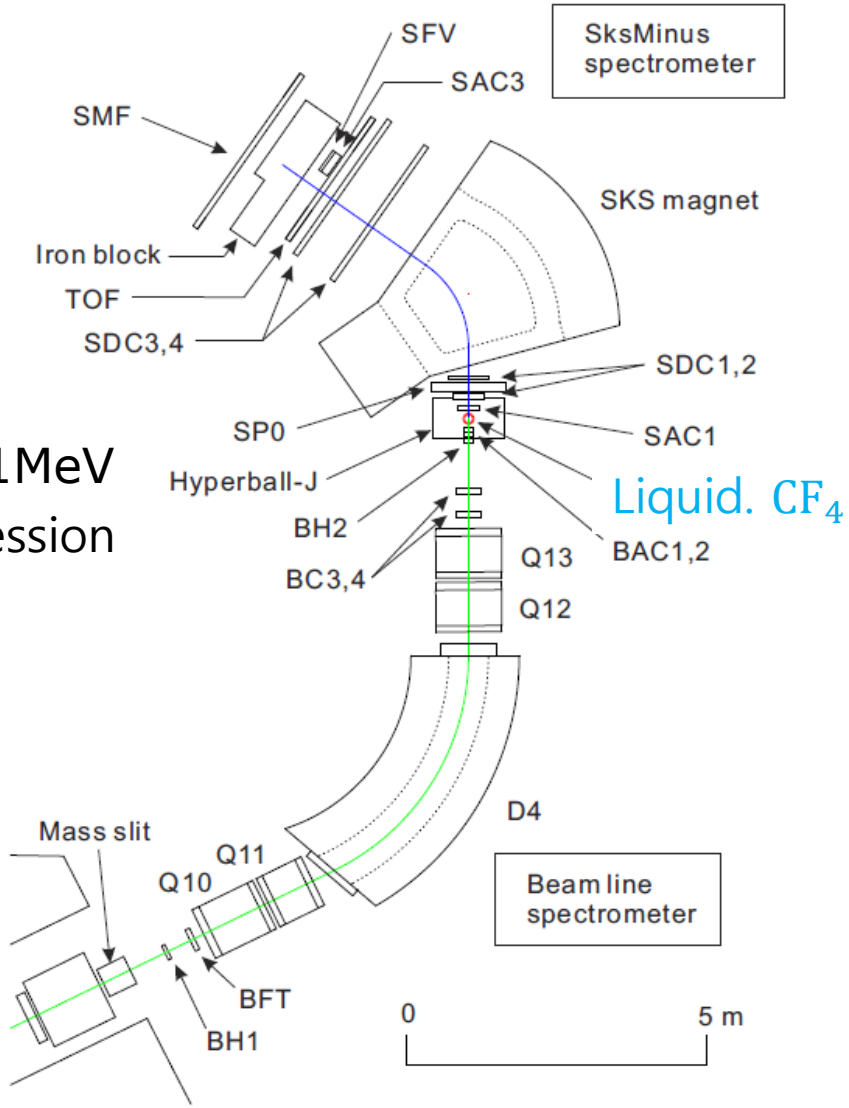
They have $\bar{r}(d_N{-}s_\Lambda) > \bar{r}(p_N{-}s_\Lambda) > \bar{r}(s_N{-}s_\Lambda)$ and different wave functions. Can we apply the ΛN interaction to heavier hypernuclei?

Experimental Setup for J-PARC E13

■ SKS & K1.8 Beamline Spectrometers
→ High resolution of missing mass
→ Large acceptance for (K^-, π^-)
→ good beam decay suppressor (SP0, SMF)

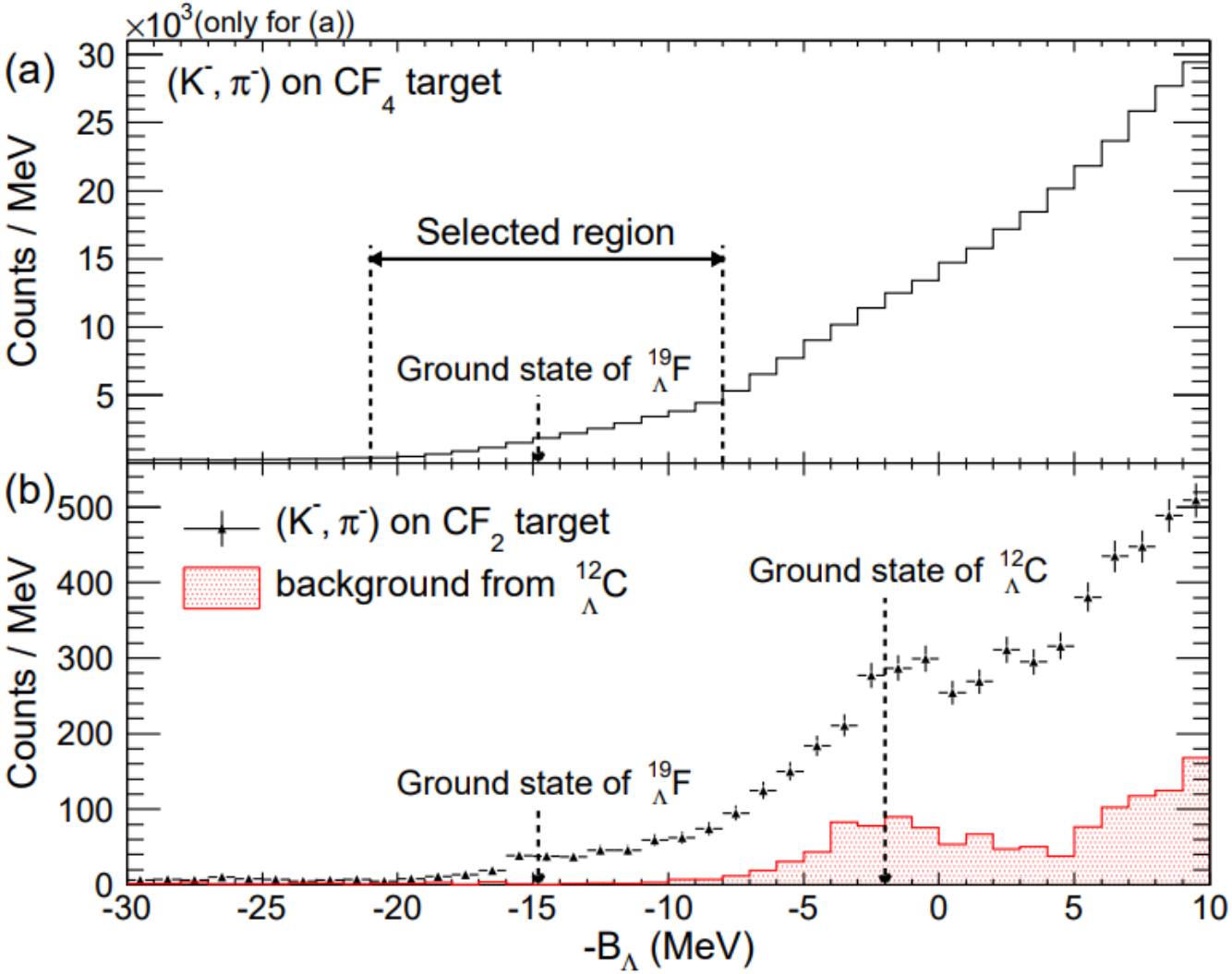
■ Hyperball-J
→ ~25 HPGe detectors - ΔE ~4.5 keV @ 1MeV
→ PWO counters - Fast background suppression



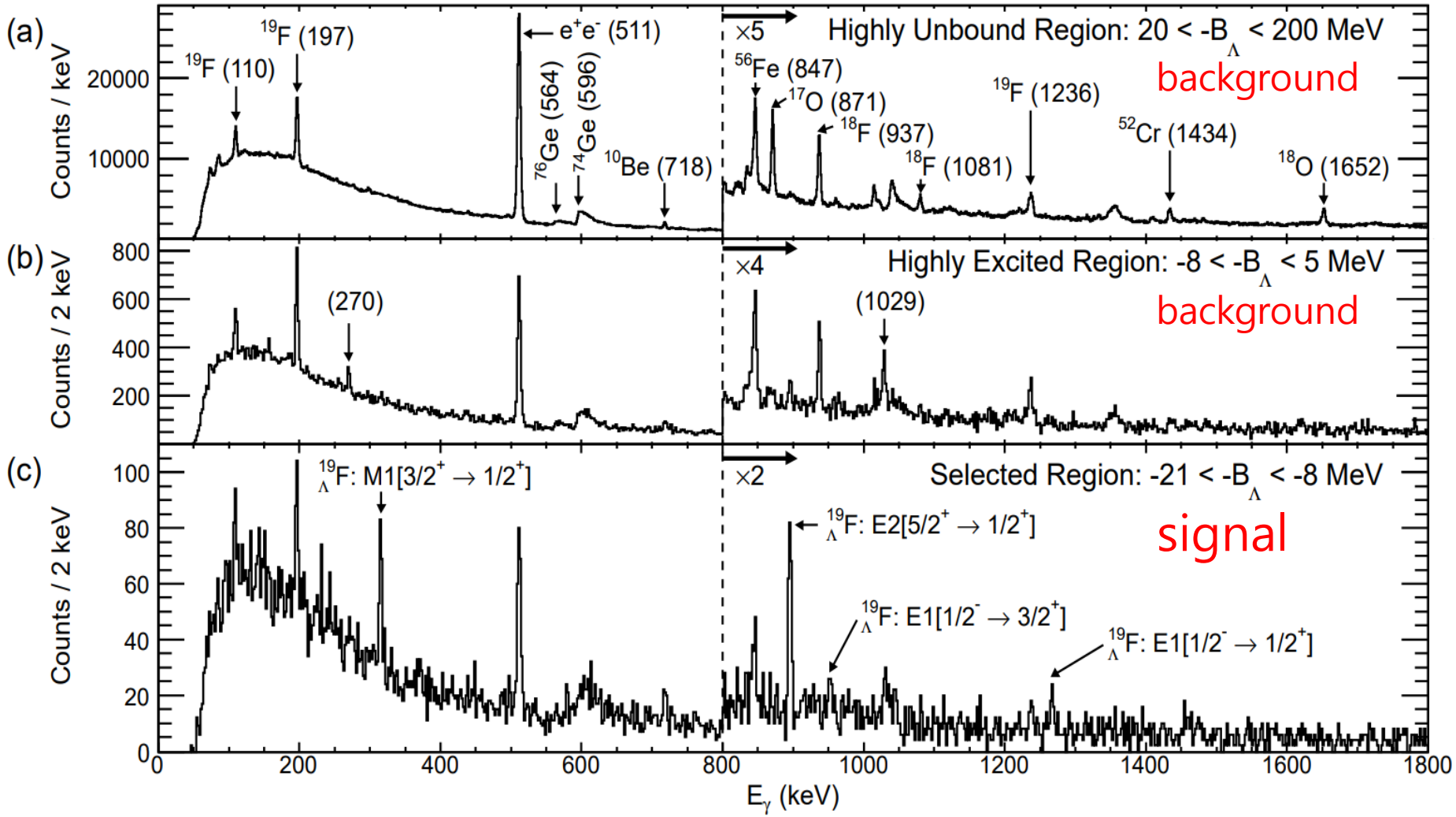


Results of J-PARC E13

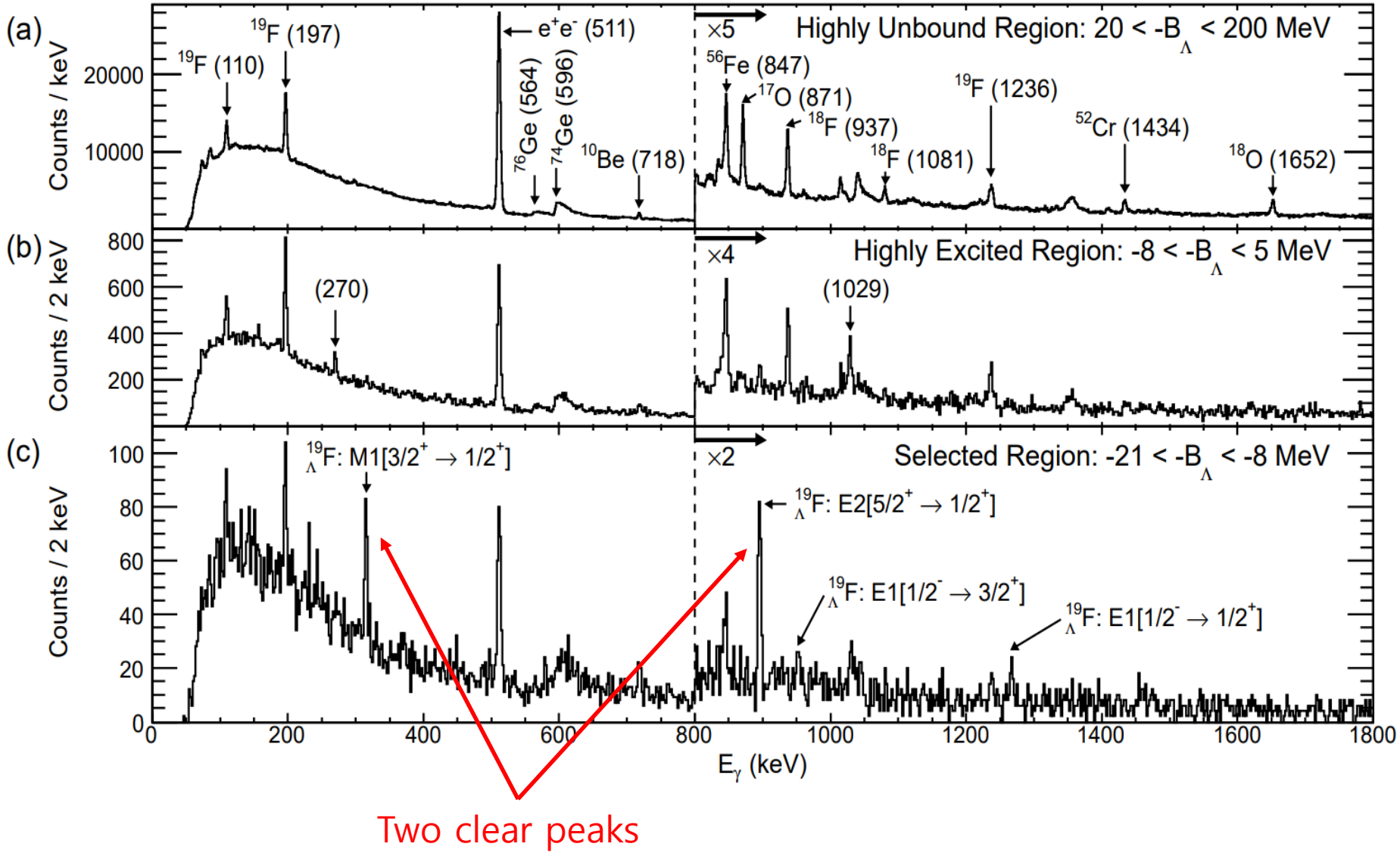
■ Λ binding energy spectra of ${}^{19}_{\Lambda}\mathrm{F}$. We selected the B_Λ range, $-21 < -B_\Lambda < -8$ MeV, to observe gamma rays emitted from the ${}^{19}_{\Lambda}\mathrm{F}$ low-lying states.

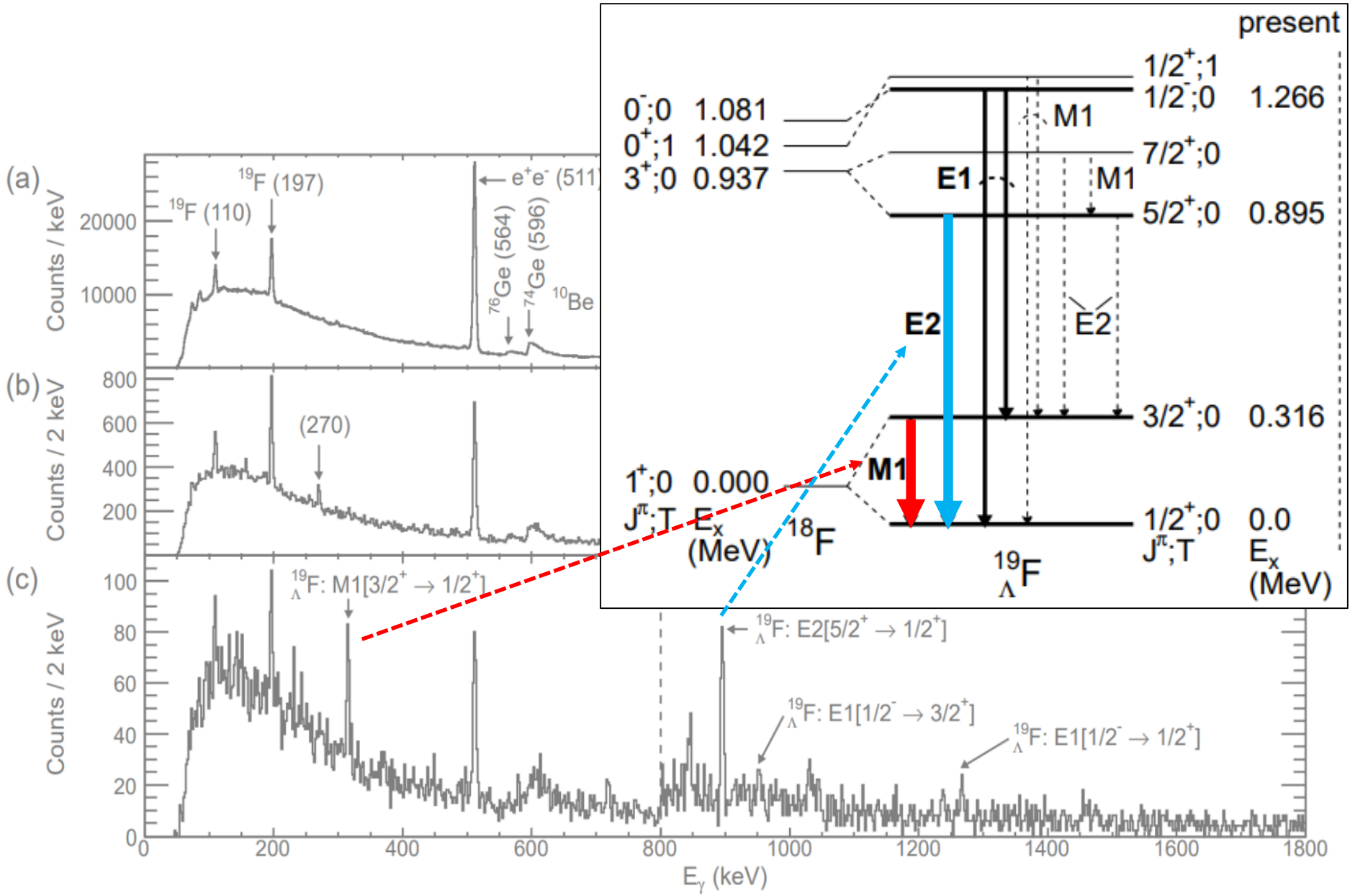


■ γ-ray spectra with three Λ binding energy conditions.

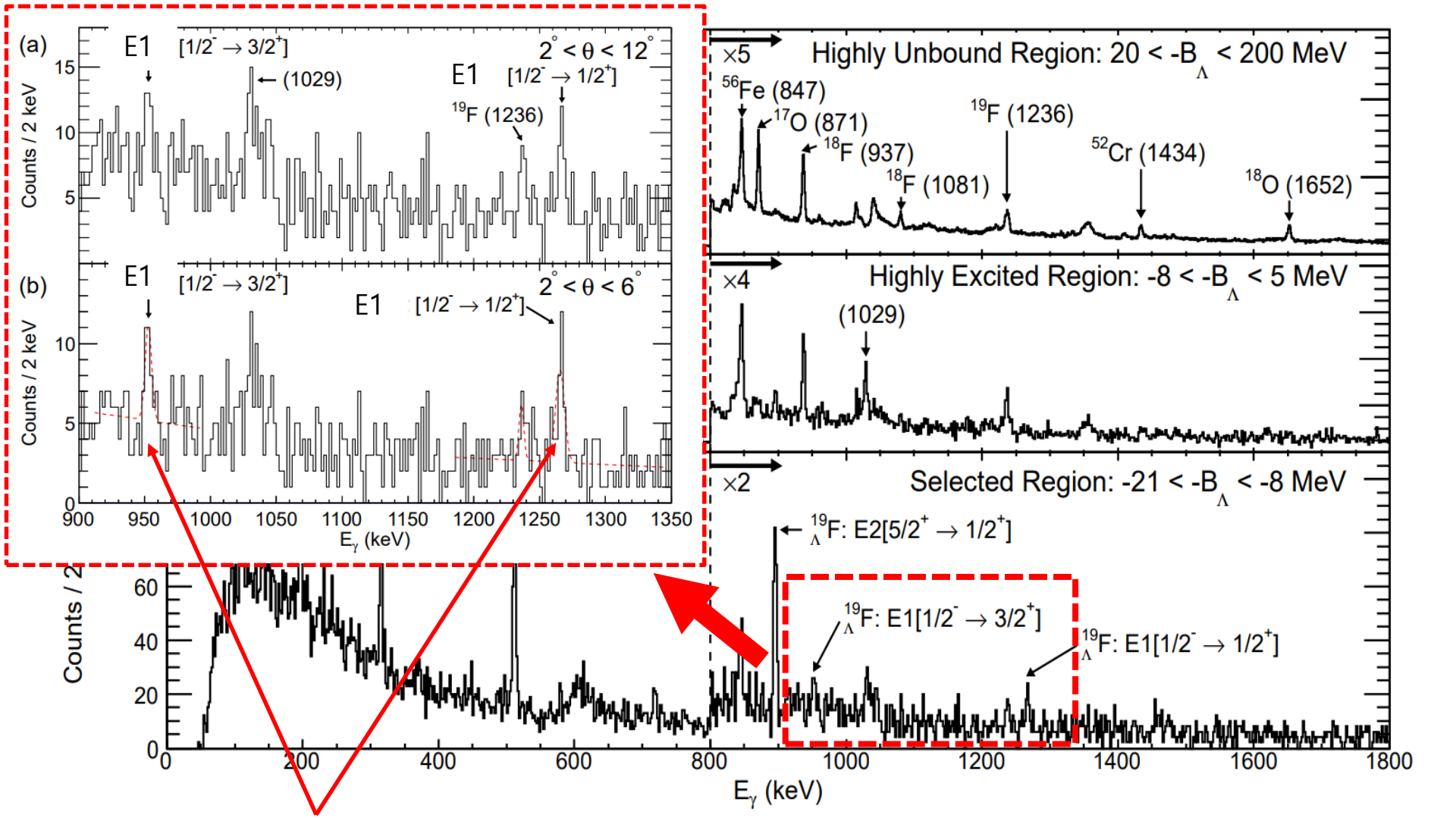


→ There are four gamma rays from low-lying states of $^{19}_{\Lambda}\mathrm{F}$.

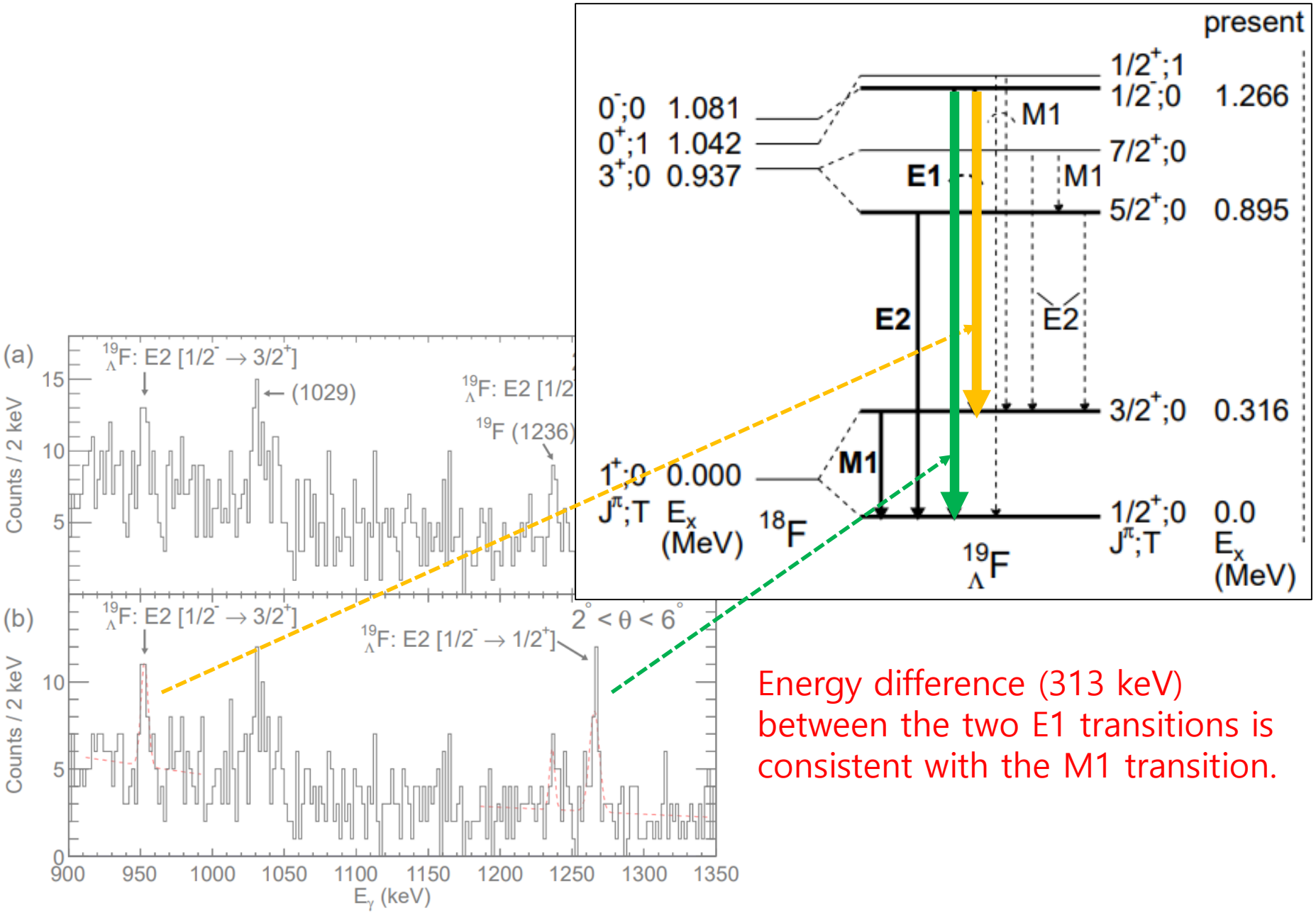

(a)
Counts / keV
^{19}F (110)
^{19}F (197)
e$^+$e$^-$ (511)
^{76}Ge (564)
^{74}Ge (596)
^{10}Be (718)
×5
Highly Unbound Region: 20 < -B$_\Lambda$ < 200 MeV
^{56}Fe (847)
^{17}O (871)
^{18}F (937)
^{18}F (1081)
^{19}F (1236)
^{52}Cr (1434)
^{18}O (1652)
(b)
Counts / 2 keV
(270)
×4
Highly Excited Region: -8 < -B$_\Lambda$ < 5 MeV
(1029)
(c)
Counts / 2 keV
$^{19}_\Lambda$F: M1[3/2$^+$ → 1/2$^+$]
×2
Selected Region: -21 < -B$_\Lambda$ < -8 MeV
$^{19}_\Lambda$F: E2[5/2$^+$ → 1/2$^+$]
$^{19}_\Lambda$F: E1[1/2$^-$ → 3/2$^+$]
$^{19}_\Lambda$F: E1[1/2$^-$ → 1/2$^+$]
E$_\gamma$ (keV)
Two clear peaks



Compared to the theoretical calculation [A. Umeya and T. Motoba, NPA 954, (2016) 242]

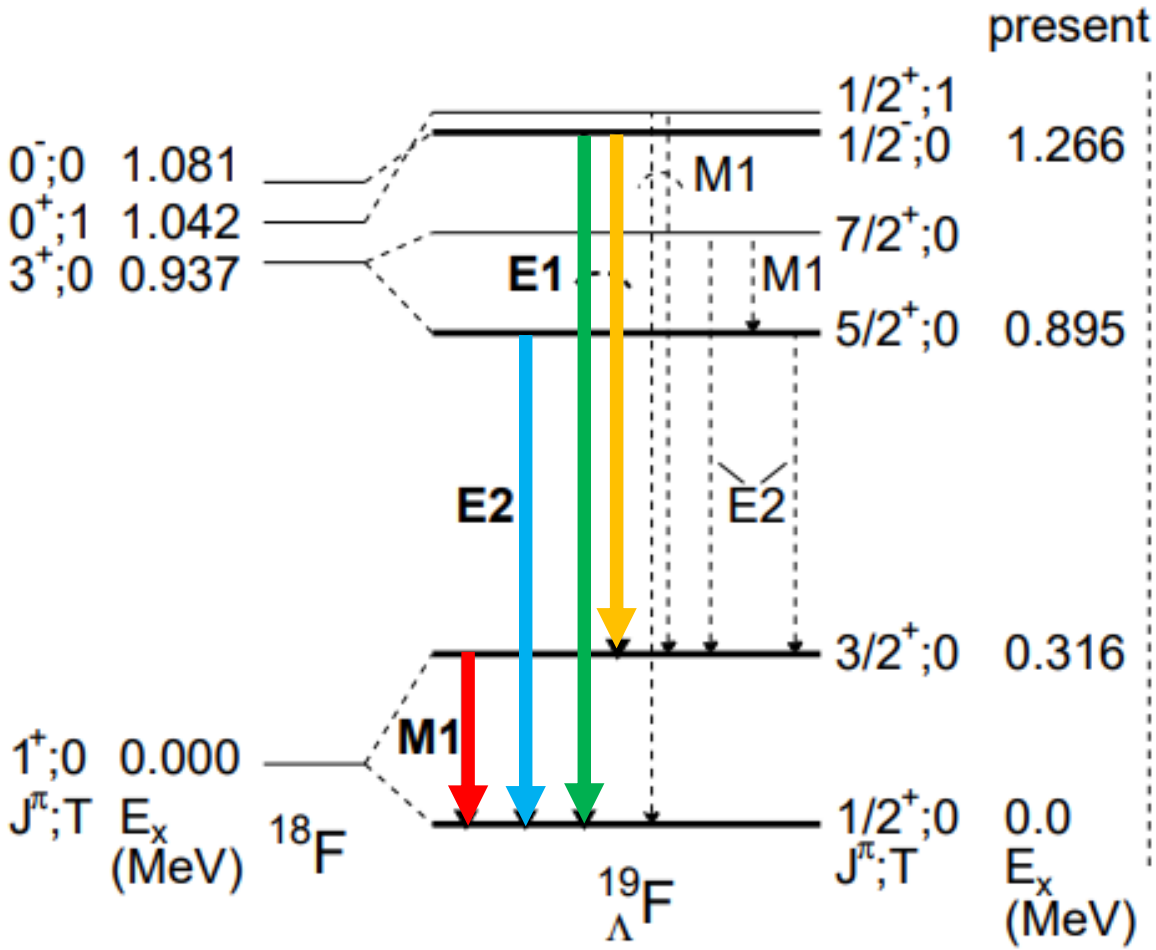


Two more clear peaks at forward reaction angle



Energy difference (313 keV) between the two E1 transitions is consistent with the M1 transition.

■ Low-lying energy scheme of $^{19}_{\Lambda}\mathrm{F}$



→ We clearly observed four γ rays from low-lying states of $^{19}_{\Lambda}\mathrm{F}$ and successfully assigned them to their gamma transitions.

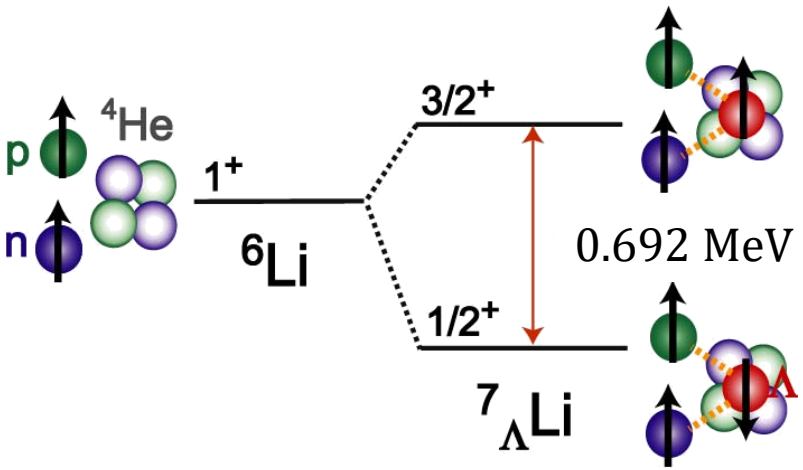
■ Effective ΛN interaction from Nijmegen SC97 models

Theoretical Calculation	(Experiment)	NSC97f	NSC97e
$\Delta E(3/2^+, 1/2^+)$ [keV]	$315.5 \pm 0.4^{+0.3}_{-0.2}$	419*	245*

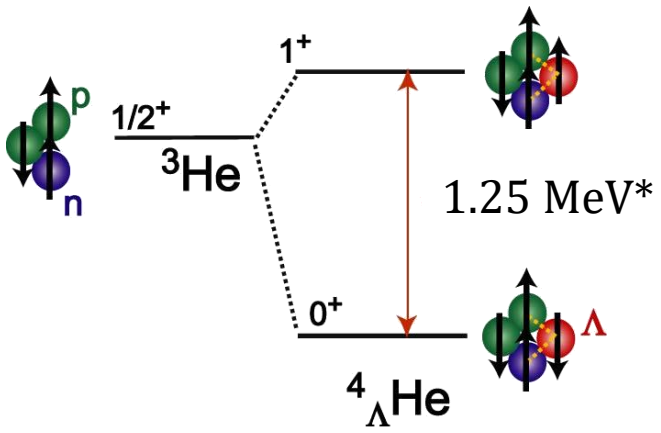
*by A. Motoba and T. Umeya

$419 \times 0.6(\mathrm{NSC97f}) + 245 \times 0.4(\mathrm{NSC97e}) = 315$ keV ?

*Similar to the case of s- and p-shell hypernuclei



→ 704 keV



→ 1.24 MeV

*${}^{4}_{\Lambda}\mathrm{He}$ and ${}^{4}_{\Lambda}\mathrm{H}(1^+, 0^+;$ 1.25 MeV in average)

■ Phenomenological calculation

Theoretical Calculation	(Experiment)	*ΛN* spin-dependent interaction at *p*-shell hypernuclei
$\Delta E(3/2^+, 1/2^+)$ [keV]	$315.5 \pm 0.4^{+0.3}_{-0.2}$	305*

*by D. J. Millener

→ The energy spacing, $3/2^+ \rightarrow 1/2^+$, is well represented by the spin-dependent interactions obtained from *s*- and *p*-shell hypernuclei. It indicates that the present theoretical frameworks work quite successfully in describing structure of not only light *s*- and *p*-shell hypernuclei but also a heavier one beyond p-shell hypernuclei.

→ ΛΣ coupling effect is negligibly small in the sd-shell hypernuclei?

Summary

- Gamma-ray spectroscopy of ${}^{19}_{\Lambda}\mathrm{F}$ J-PARC E13 was successfully performed in June, 2015.
- We clearly observed four γ rays from low-lying states of ${}^{19}_{\Lambda}\mathrm{F}$ and successfully assigned them to their gamma transitions.
- The energy spacing between the ground state doublet is determined to be 316 keV. It is well represented by the spin-dependent *ΛN* Interaction in *p*-shell hypernuclei.
- The experiment will be continued at the new constructed beam line (K1.1 beam line), and next targets are ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{7}_{\Lambda}\mathrm{Li}$.

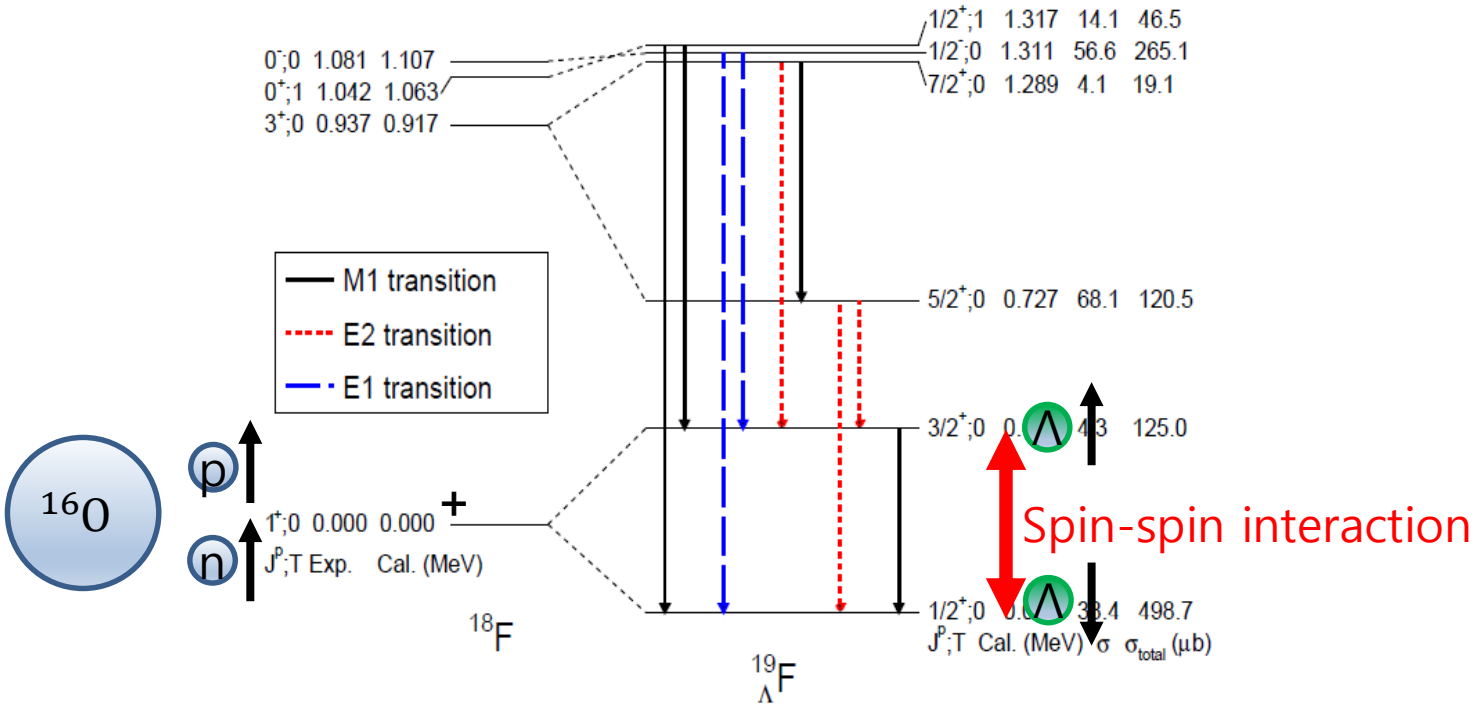
*Backup Slides

Gamma-ray Spectroscopy of $^{19}_{\Lambda}$F (J-PARC E13 1st Phase)

- It is the first γ-ray spectroscopy for *sd*-shell hypernuclei.
- Energy spacing between ground state doublet ($1/2^+$, $3/2^+$)

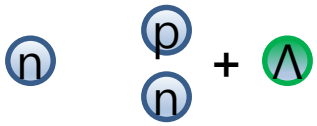
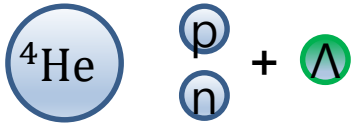
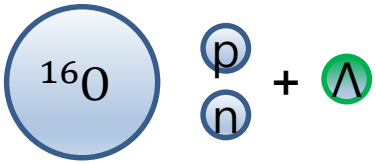
→ Radial dependency of the *ΛN* spin-spin interaction?

→ *ΛN* spin-dependent interaction with different wave-function?



low-lying energy levels of $^{19}_{\Lambda}$F

A. Umeya and T. Motoba, NPA **116, 122501 (2016)*

	${}^{4}_{\Lambda}\mathrm{H}$	${}^{7}_{\Lambda}\mathrm{Li}$	${}^{19}_{\Lambda}\mathrm{F}$
Four-body Cluster model			
Wave-function	$s_N s_\Lambda$	$p_N s_\Lambda$	$(sd)_N s_\Lambda$
N, RMS radius [fm] *@by Millener, private communication*	2.5 $(0s)$	3.0 $(0p_{1/2})$ 2.9 $(0p_{3/2})$	3.4 $(1s_{1/2})$ 3.5 $(0p_{1/2})$ 3.3 $(0d_{5/2})$
Λ, RMS radius [fm] *@by Millener, private communication*	3.5 $(0s)$	2.6 $(0s)$	2.3 $(0s)$
ΔE_x (ground state doublet)	1.1 MeV	0.695 MeV ($\Delta_{p_N s_\Lambda}$=0.43 MeV)	?

γ-ray Detector (Hyperball-J)

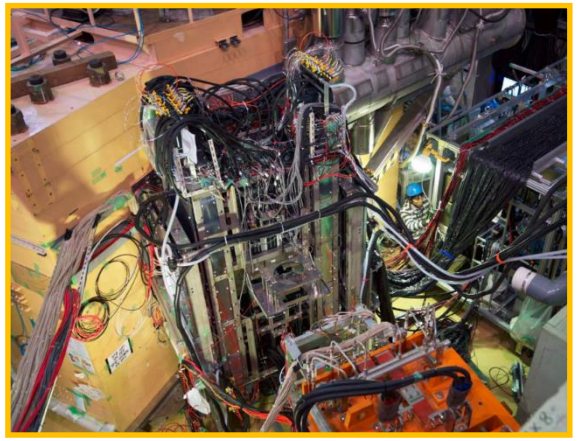
- $^{19}\mathrm{F}(K^-,\ \pi^-)^{19}_{\Lambda}\mathrm{F}^*,\ ^{19}_{\Lambda}\mathrm{F}^* \rightarrow \gamma + {}^{19}_{\Lambda}\mathrm{F}$
- Hyperball-J

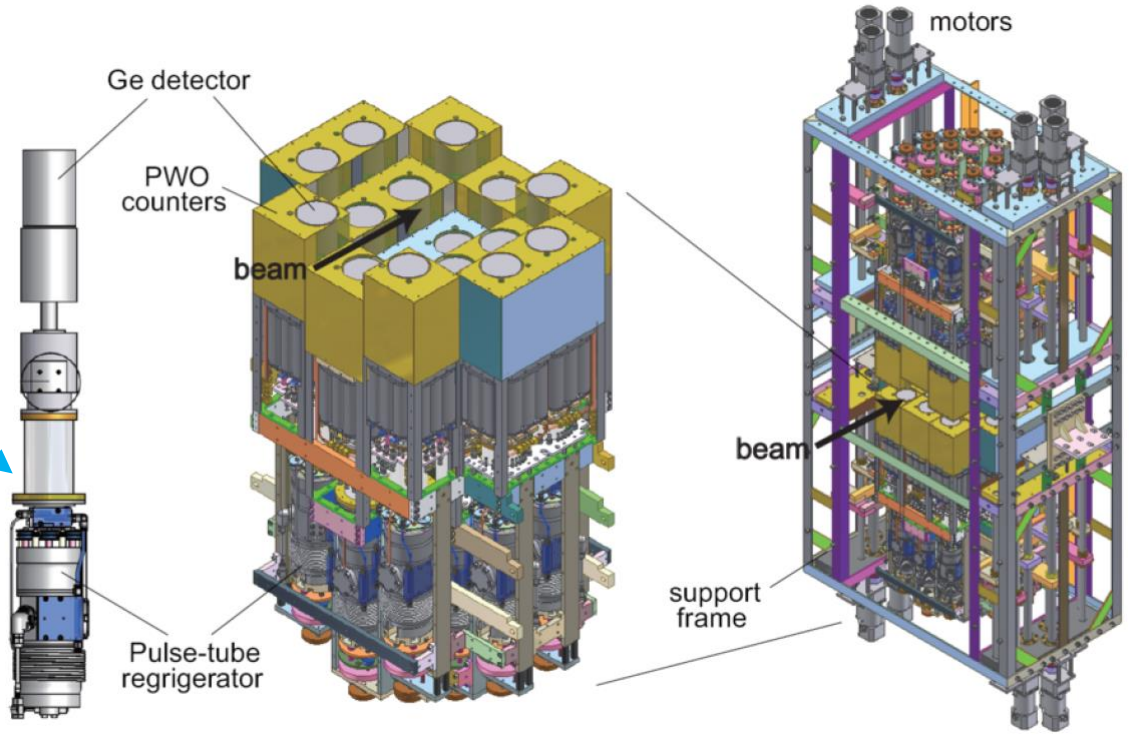
→ 25 HPGe detectors - ΔE ~4.5 keV @ 1MeV

→ PWO counters - Fast background suppression

Mechanical cooling system
Crystal temp. ~70 K

*a view of K1.8 experimental hall





@NPA, 835, 3 (2012)