Higher spin resonances in photoproduction processes

Yongseok Oh

Kyungpook National University

JLAB Theory Seminar

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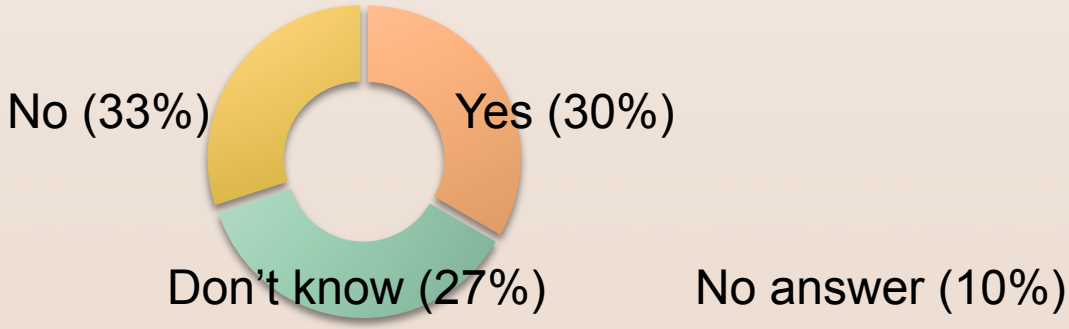
0

BASIC SCIENCE INSTITUTE & KORIA

Basic Science Institute (tentative name)

- Motivation
  - Brain drain
    - Foreign students in the US universities (as of 2008)
      - India: ~ 103,000 students
      - China: ~ 98,000 students
      - Korea: ~ 75,000 students (still increasing)
    - Return to Korea after getting Ph.D degree
      - 2003: ~ 2,100
      - 2006: ~ 1,300 (decreasing)
    - A survey of 100 young Korean scientists in the US (Are you willing to return to Korea?)



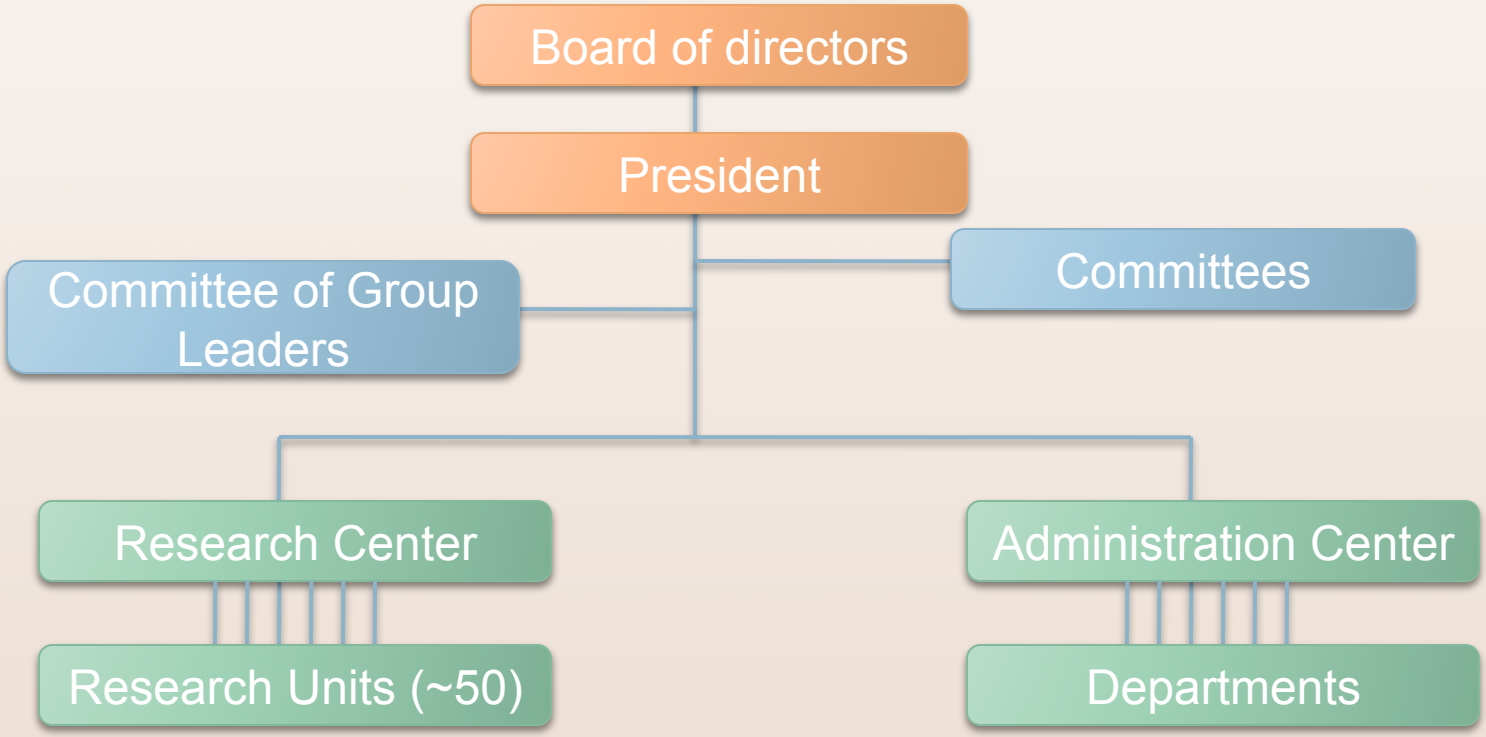
- Crisis of science & technology in Korea
  - High school student's preference in S&T
    - Medical doctor (e.g. plastic surgeons)
    - Average score of entrance exam of Seoul National Univ.
      - Before 2000: physics ~ medical school >> math education
      - Now: medical school >> math education > physics
- National labs in Korea
  - Crucial role in the development of Korean economy
  - Korea research council for fundamental sciences and technology
    - Supported by the Ministry of Education, Science and Technology
    - 13 institutions: atomic energy, standards & science, nuclear fusion, BT, NT, etc
  - Korea research council for industrial sciences and technology
    - Supported by the Ministry of Knowledge-based Economics
    - 13 institutions: IT, materials, foods, electricity, train, NT, etc
  - However, no national lab for pure sciences (cf. KIAS)
    → lack of large scale research facilities

New Science City

- Science Business Belt project
  - Construction of a science city
    - (Inter-)national labs. (BSI): ~2,000 researchers
    - Large scale research facilities
    - Knowledge-based business center
    - Budget: ~3.2 billion US $ for the first 7 yrs (assumed US $1 = 1,100 KRW)
  - New environment for R&D in pure sciences
    - Good payroll
    - Enough research fund
    - Freedom in research topics (but with responsibility for the output)
  - Large scale research facilities
    - E.g.: Accelerators
      - At present, only one accelerator in Korea – a photon source at Pohang
    - Plan: Rare Isotope Accelerator
      KoRIA: Korea Rare Isotope Accelerator
  - The law for SBB has passed the parliament at Dec. 2010.
    (But the details are yet to be discussed.)

BSI

- Science Business Belt: construction of a new city
  - The core should be Basic Science Institute.
- Organization of BSI (tentative)



BSI

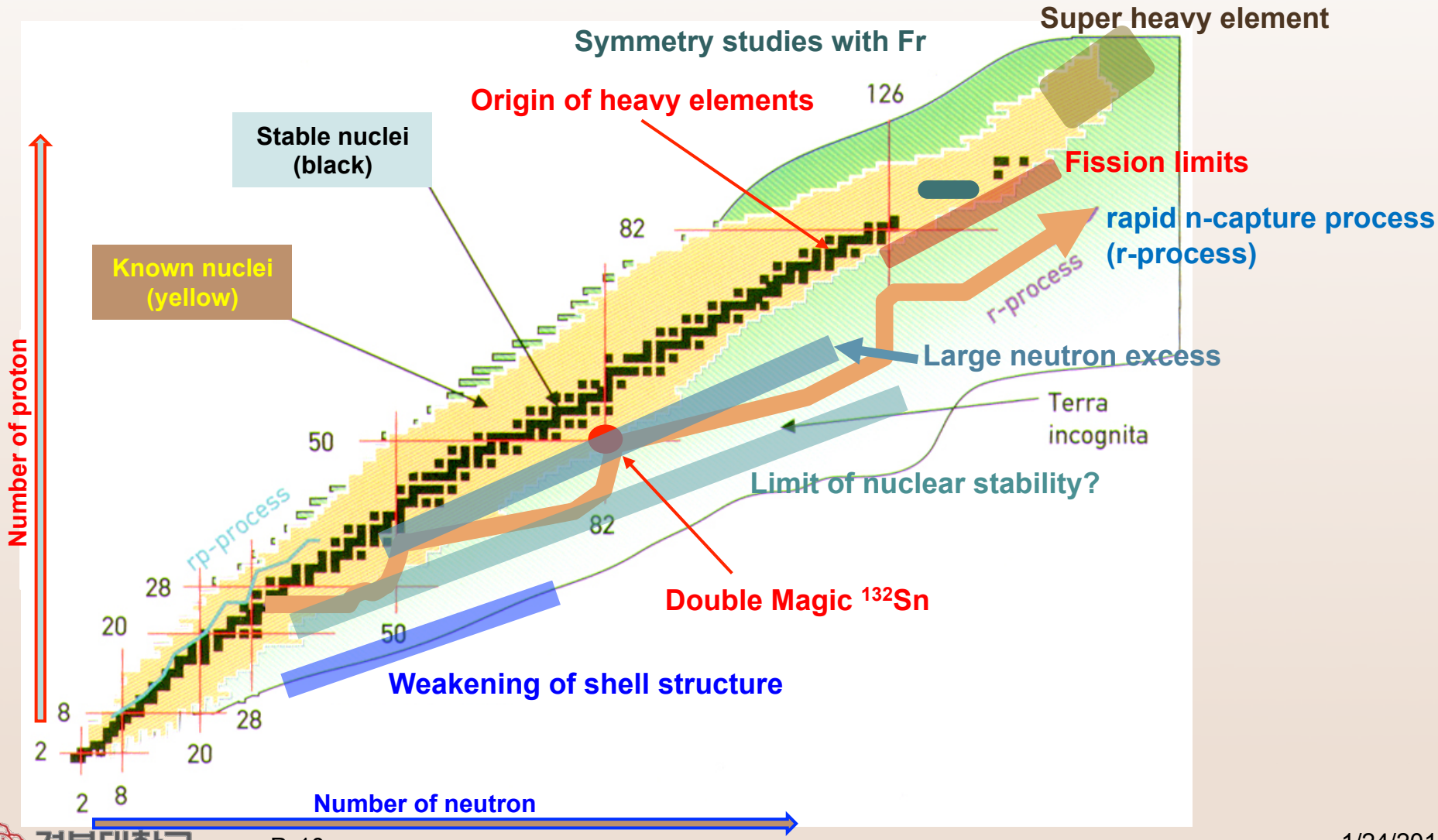
- Scale
  - Eventually ~50 research units
    - ~ 2,000 Ph.Ds and ~ 2,000 Graduate Students
- Research Units
  - Research fields: the WHOLE area in pure sciences
  - Locate in the BSI campus or in other universities
  - International manpower
    - open to ALL nationalities (researchers and Group Leaders)
    - Group leaders: selected by international committees
    - Non-Korean researchers: > 30% (required)
  - The budget of each unit: 5M ~ 10M / year in the US $
    (in principle, no overhead)
    - Execution of the budget (including the payroll): by the group leader
  - Sunset system
    - E.g. 5 yrs + 5 yrs
    - Will be closed for the next research topics

KoRIA

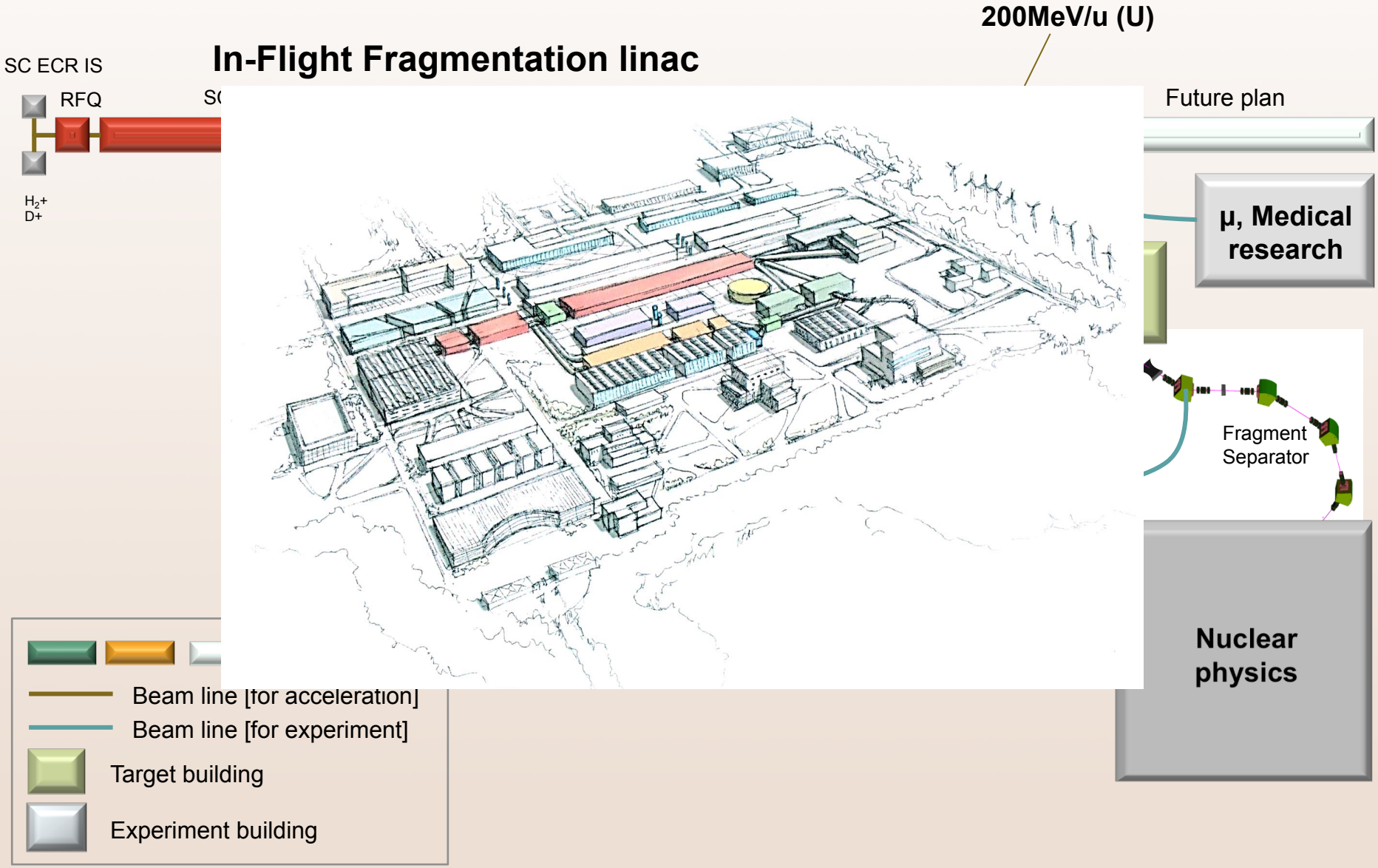
- ***Ko***rea ***R***are ***I***sotope ***A***ccelerator
- Multipurpose, heavy-ion accelerator for basic science research
  - Nuclear physics & nuclear astrophysics & atomic physics
  - Material science
  - Bio and medical science
  - Nuclear data production
  - Nuclear fusion
- The first large scale research facility for pure science in Korea
- Proposed construction budget : 460 B Won (~ $450M)
  - ~$90M for experimental instruments + ~ $360M for accelerator
  - Site purchasing & payroll from a separate budget
- Schedule (plan)
  - Design and R&D: 2009 ~ 2012
  - Construction: 2012 ~ 2016
  - No sunset system

Why Rare Isotopes (RIs)?

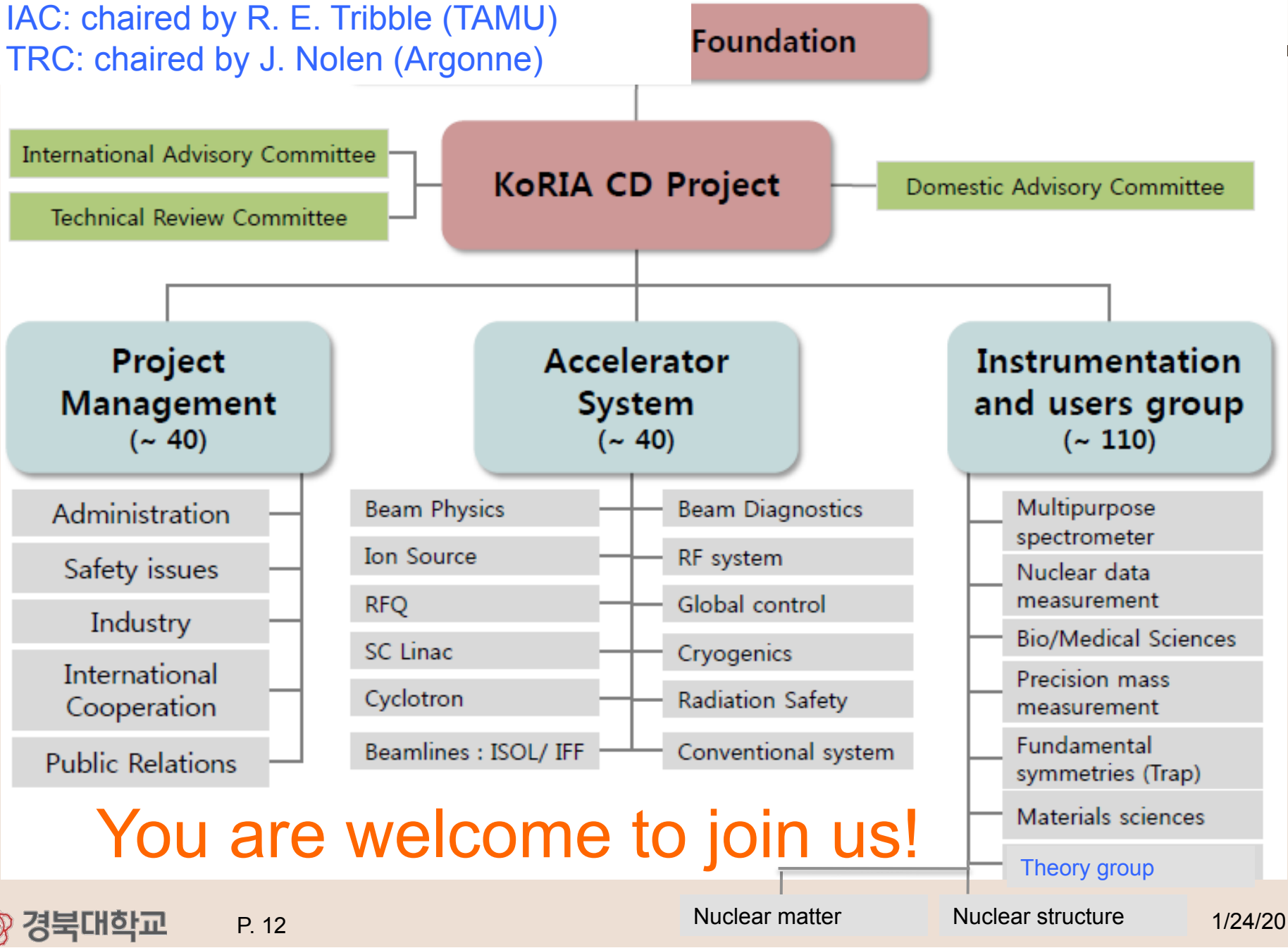
"Nuclear science is entering a new era of discovery in understanding how nature works at the most basic level and in applying that knowledge in useful ways". - National Academy 2007 RISAC Report -



KoRIA layout



IAC: chaired by R. E. Tribble (TAMU)
TRC: chaired by J. Nolen (Argonne)



You are welcome to join us!

Higher spin resonances in photoproduction processes

I

INTRODUCTION

With T.-S.H. Lee and K. Nakayama

Introduction

- Missing resonance puzzle
- At a mass region > 1.8 GeV → many high spin states $j \geq 5/2$
  - N and Δresonances as well as hyperons

Particle	$L_{2I\cdot 2J}$	Overall status
$N(939)$	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1\,11}$	***
$N(2700)$	$K_{1\,13}$	**

$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3\,11}$	****
$\Delta(2750)$	$I_{3\,13}$	**
$\Delta(2950)$	$K_{3\,15}$	**

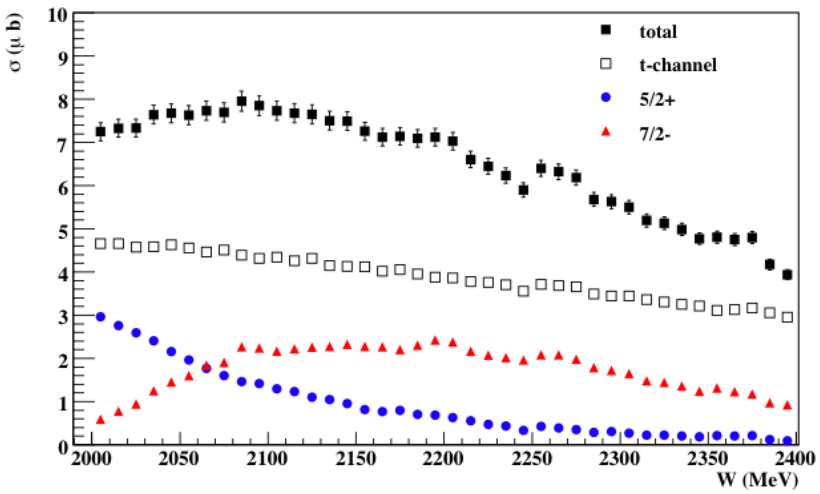
Λ states					Σ states				
State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Lambda K}\rvert$	State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Sigma K}\rvert$
$\Lambda(1116)$	$1/2^+$		****		$\Sigma(1193)$	$1/2^+$		****	
$\Lambda(1405)$	$1/2^-$	≈ 50	****		$\Sigma(1385)$	$3/2^+$	≈ 37	****	
$\Lambda(1520)$	$3/2^-$	≈ 16	****						
$\Lambda(1600)$	$1/2^+$	≈ 150	***	4.2	$\Sigma(1660)$	$1/2^+$	≈ 100	***	2.5
$\Lambda(1670)$	$1/2^-$	≈ 35	****	0.3	$\Sigma(1670)$	$3/2^-$	≈ 60	****	2.8
$\Lambda(1690)$	$3/2^-$	≈ 60	****	4.0	$\Sigma(1750)$	$1/2^-$	≈ 90	***	0.5
$\Lambda(1800)$	$1/2^-$	≈ 300	***	1.0	$\Sigma(1775)$	$5/2^-$	≈ 120	****	
$\Lambda(1810)$	$1/2^+$	≈ 150	***	2.8	$\Sigma(1915)$	$5/2^+$	≈ 120	****	
$\Lambda(1820)$	$5/2^+$	≈ 80	****		$\Sigma(1940)$	$3/2^-$	≈ 220	***	< 2.8
$\Lambda(1830)$	$5/2^-$	≈ 95	****		$\Sigma(2030)$	$7/2^+$	≈ 180	****	
$\Lambda(1890)$	$3/2^+$	≈ 100	****	0.8	$\Sigma(2250)$	$?^?$	≈ 100	***	
$\Lambda(2100)$	$7/2^-$	≈ 200	****						
$\Lambda(2110)$	$5/2^+$	≈ 200	***						
$\Lambda(2350)$	$9/2^+$	≈ 150	***						

Fit: 2 GeV $< \sqrt{s} <$ 2.4 GeV

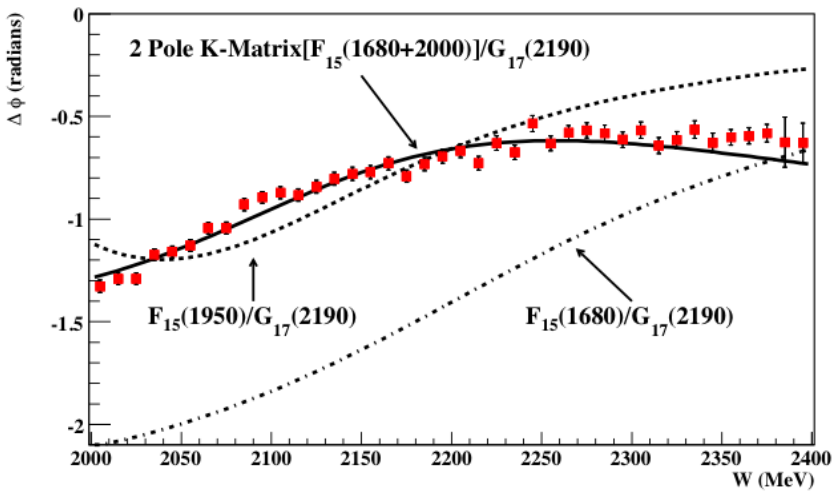
From V. Burkert
CLAS @ JLab

Free $5/2^+$,$7/2^-$ with Locked Oh, Titov, Lee t-channel

Yields vs $\sqrt{s}$



Phase Difference vs $\sqrt{s}$



Is this the **** $G_{17}(2190)$? Yes (most likely).
Suggestive (but not conclusive) evidence for a *missing* $F_{15}(2000)$ state.

Introduction

- Testing hadron models (such as quark models)
  - Data analyses: coupled-channels method
    → extract coupling constants of interaction Lagrangian
  - Quark models give predictions on the decay (amplitudes)
  - Decay widths cannot fix the sign of the coupling constant (sign ambiguity)
    → work with decay amplitudes
    → need for the relationship between coupling constants and the predicted decay amplitudes

II

FORMALISM FOR HIGHER SPIN RESONANCES

Propagators

- Propagators for bosons and fermions of arbitrary spin

$$S(p) = \frac{i}{p^2 - M^2}\Delta \quad \text{for a boson}$$

$$S(p) = \frac{i}{p^2 - M^2}(p \cdot \gamma + M)\Delta \quad \text{for a fermion}$$

- Rarita-Schwinger Formalism (wavefunctions)
  - Boson of spin s: tensor of rank s

$$\left(p^2 + m^2\right)\Phi_{\alpha_1\alpha_2\ldots\alpha_s} = 0$$

with subsidiary conditions

$$\Phi_{\ldots\alpha_i\ldots\alpha_j\ldots} = \Phi_{\ldots\alpha_j\ldots\alpha_i\ldots}, \quad p^{\alpha_1}\Phi_{\alpha_1\ldots\alpha_s} = 0, \quad g^{\alpha_1\alpha_2}\Phi_{\alpha_1\alpha_2\ldots\alpha_s} = 0$$

  - Fermion of spin $s = n - \frac{1}{2}$: tensor of rank $n - 1$

$$\left(\gamma \cdot \partial + m\right)\Phi_{\alpha_1\alpha_2\ldots\alpha_{n-1}} = 0$$

with subsidiary conditions

$$\Phi_{\ldots\alpha_i\ldots\alpha_j\ldots} = \Phi_{\ldots\alpha_j\ldots\alpha_i\ldots}, \quad \gamma^{\alpha_1}\Phi_{\alpha_1\ldots\alpha_{n-1}} = 0, \quad g^{\alpha_1\alpha_2}\Phi_{\alpha_1\alpha_2\ldots\alpha_s} = 0,$$

$$\partial^{\alpha_1}\Phi_{\alpha_1\ldots\alpha_{n-1}} = 0$$

Propagators

- The form of Δ

$$\sum_{\text{spin}} \Phi_{\alpha_1\alpha_2\ldots}\bar{\Phi}^{\beta_1\beta_2\ldots} = \Lambda_{\pm}\Delta^{\beta_1\ldots}_{\alpha_1\ldots}$$

$\Lambda_{\pm}$: spin projection operator of spin-1/2 (for fermion)

$= 1$ (for boson)

Rushbrooke, PR 143 (66')
Behrends and Fronsdal, PR 106 (57')
Chang, PR 161 (67')

$$\theta^{\beta}_{\alpha} = -\left(g^{\beta}_{\alpha} - \frac{1}{M^2}p_{\alpha}p^{\beta}\right)$$

$$\Gamma^{\alpha} = i\left(\gamma^{\alpha} - \frac{1}{M^2}p\cdot\gamma\, p^{\alpha}\right)$$

- The general expressions

For integer spin n

$$\Delta^{\beta_1\cdots\beta_n}_{\alpha_1\cdots\alpha_n}(n,p) = \left(\frac{1}{n!}\right)^2 \sum_{P(\alpha),P(\beta)}\left[\prod_{i=1}^{n}\theta^{\beta_i}_{\alpha_i} + a_1\theta_{\alpha_1\alpha_2}\theta^{\beta_1\beta_2}\prod_{i=3}^{n}\theta^{\beta_i}_{\alpha_i} + \cdots\right]$$

for even n

with

$$a^{(n)}_r = \left(-\frac{1}{2}\right)^r \frac{n!}{r!(n-2r)!}\frac{1}{(2n-1)(2n-3)\cdots(2n-2r+1)}$$

  - Similar expressions for odd n and for half-integer spin

Propagators

- Explicit expressions for several cases
  - Spin-1

$$\Delta_{\alpha}^{\beta}(1) = \theta_{\alpha}^{\beta}$$

  - Spin-1/2

$$\Delta\left(\frac{1}{2}\right) = \frac{1}{3}\gamma_{\alpha}\gamma_{\beta}\Delta_{\alpha}^{\beta}(1) = 1$$

  - Spin-2

$$\Delta_{\alpha_1\alpha_2}^{\beta_1\beta_2}(2) = \frac{1}{2}\left(\theta_{\alpha_1}^{\beta_1}\theta_{\alpha_2}^{\beta_2} + \theta_{\alpha_1}^{\beta_2}\theta_{\alpha_2}^{\beta_1} - \frac{2}{3}\theta_{\alpha_1\alpha_2}\theta^{\beta_1\beta_2}\right)$$

  - Spin-3/2

$$\Delta\left(\frac{3}{2}\right) = -g_{\alpha}^{\beta} + \frac{1}{3}\gamma_{\alpha}\gamma^{\beta} + \frac{1}{3M}\left(\gamma_{\alpha}p^{\beta} - p_{\alpha}\gamma^{\beta}\right) + \frac{2}{3M^2}p_{\alpha}p^{\beta}$$

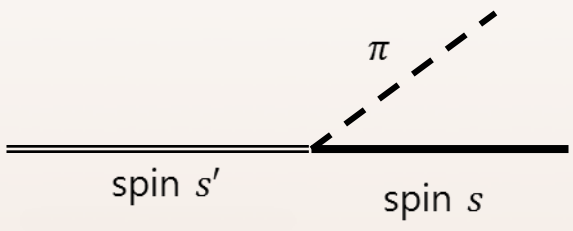
  - Straightforward to get the expressions for higher spin propagators

III

EFFECTIVE LAGRANGIAN & COUPLING CONSTANTS

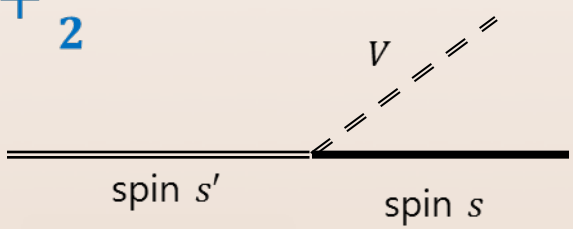
Interactions

- Number of independent couplings
  - Angular momentum conservation
  - P and T invariance



- Pion ($J^P = 0^-$) vertex: $\boldsymbol{J^\pm \to 0^- + \frac{1}{2}^+}$
  - $RN\pi$ vertex where N: nucleon ($1/2^+$)
    R: nucleon resonance of J^P
    ⇨ only ***one*** interaction term

- Vector meson ($J^P = 1^-$) vertex: $\boldsymbol{J^\pm \to 1^- + \frac{1}{2}^+}$
  - RNV vertex
    ⇨ ***two*** interaction terms for R with $\frac{1}{2}^\pm$
    ⇨ ***three*** interaction terms for R with $J^\pm$ ($J \geq \frac{3}{2}$)
  - If V is the photon, the numbers are reduced by one. ($\because q^2 = 0$)



$RN\pi$ Lagrangian

- $J^P = \frac{1}{2}^{\pm}$ case

$$\mathcal{L}_{1/2} = g_{\pi NR}\overline{N}\left[i\lambda\Gamma^{(\pm)}\pi \mp \frac{1-\lambda}{M_R \pm M_N}\Gamma_\mu^{(\pm)}\partial^\mu\pi\right]R + \text{H.c.}$$

$$\Gamma^{(\pm)} = \begin{pmatrix}\gamma_5 \\ 1\end{pmatrix}, \quad \Gamma_\mu^{(\pm)} = \begin{pmatrix}\gamma_\mu\gamma_5 \\ \gamma_\mu\end{pmatrix}$$

- $J^P = \frac{3}{2}^{\pm}$ case

$$\mathcal{L}_{3/2} = \frac{g_{\pi NR}}{M_\pi}\overline{N}\Gamma^{(\mp)}\partial^\mu\pi R_\mu + \text{H.c.}$$

- $J^P = \frac{5}{2}^{\pm}$ case

$$\mathcal{L}_{5/2} = i\frac{g_{\pi NR}}{M_\pi^2}\overline{N}\Gamma^{(\pm)}\partial^\mu\partial^\nu\pi R_{\mu\nu} + \text{H.c.}$$

- $J^P = \frac{7}{2}^{\pm}$ case

$$\mathcal{L}_{7/2} = \frac{g_{\pi NR}}{M_\pi^3}\overline{N}\Gamma^{(\mp)}\partial^\mu\partial^\nu\partial^\alpha\pi R_{\mu\nu\alpha} + \text{H.c.}$$

Pion interaction Lagrangian

- The general expression for the decay widths

$$\Gamma(R \to N\pi) = \frac{3g_{\pi NR}^2}{4\pi}\frac{2^n (n!)^2}{n(2n)!}\frac{k_\pi^{2n-1}}{M_R M_\pi^{2(n-1)}}\left(E_N \pm M_N\right)$$

for $(-1)^n P_s = \pm 1$ with P_s being the parity of the spin - s resonance R

- Examples

$$\Gamma\left(\frac{1}{2}^{\pm} \to N\pi\right) = \frac{3g_{\pi NR}^2}{4\pi}\frac{k_\pi}{M_R}\left(E_N \mp M_N\right)$$

$$\Gamma\left(\frac{3}{2}^{\pm} \to N\pi\right) = \frac{g_{\pi NR}^2}{4\pi}\frac{k_\pi^3}{M_R M_\pi^2}\left(E_N \pm M_N\right)$$

$$\Gamma\left(\frac{5}{2}^{\pm} \to N\pi\right) = \frac{g_{\pi NR}^2}{4\pi}\frac{2}{5}\frac{k_\pi^5}{M_R M_\pi^4}\left(E_N \mp M_N\right)$$

$$\Gamma\left(\frac{7}{2}^{\pm} \to N\pi\right) = \frac{g_{\pi NR}^2}{4\pi}\frac{6}{35}\frac{k_\pi^7}{M_R M_\pi^6}\left(E_N \pm M_N\right)$$

Isospin factor 3 is included.

RNV Lagrangian

- $J^P = \frac{1}{2}^{\pm}$ case

$$\mathcal{L}_{1/2} = -\frac{1}{2M_N}\overline{N}\left[g_3\left(\pm\frac{\Gamma_\mu^{(\pm)}\partial^2}{M_R \mp M_N} - i\Gamma^{(\pm)}\partial_\mu\right)V^\mu - g_1\Gamma^{(\pm)}\sigma_{\mu\nu}\partial^\nu V^\mu\right]R + \text{H.c.}$$

- $J^P = \frac{3}{2}^{\pm}$ case

$$\mathcal{L}_{3/2} = -i\frac{g_1}{2M_N}\overline{N}\Gamma_\nu^{(\pm)}V^{\mu\nu}R_\mu - \frac{g_2}{(2M_N)^2}\partial_\nu\overline{N}\Gamma^{(\pm)}V^{\mu\nu}R_\mu + \frac{g_3}{(2M_N)^2}\overline{N}\Gamma^{(\pm)}\partial_\nu V^{\mu\nu}R_\mu + \text{H.c.}$$

- $J^P = \frac{5}{2}^{\pm}$ case

$$\mathcal{L}_{5/2} = \frac{g_1}{(2M_N)^2}\overline{N}\Gamma_\nu^{(\mp)}\partial^\alpha V^{\mu\nu}R_{\mu\alpha} - \frac{ig_2}{(2M_N)^3}\partial_\nu\overline{N}\Gamma^{(\mp)}\partial^\alpha V^{\mu\nu}R_{\mu\alpha} + \frac{ig_3}{(2M_N)^3}\overline{N}\Gamma^{(\mp)}\partial^\alpha\partial_\nu V^{\mu\nu}R_{\mu\alpha} + \text{H.c.}$$

- $J^P = \frac{7}{2}^{\pm}$ case

$$\mathcal{L}_{7/2} = \frac{ig_1}{(2M_N)^3}\overline{N}\Gamma_\nu^{(\pm)}\partial^\alpha\partial^\beta V^{\mu\nu}R_{\mu\alpha\beta} + \frac{g_2}{(2M_N)^4}\partial_\nu\overline{N}\Gamma^{(\pm)}\partial^\alpha\partial^\beta V^{\mu\nu}R_{\mu\alpha\beta}$$

$$- \frac{g_3}{(2M_N)^4}\overline{N}\Gamma^{(\pm)}\partial^\alpha\partial^\beta\partial_\nu V^{\mu\nu}R_{\mu\alpha\beta} + \text{H.c.}$$

$RN\gamma$ interaction

- Similar to RNV interaction
  - But with $g_3 = 0$

$$\mathcal{L}_{RN\gamma}\left(\tfrac{1}{2}^{\pm}\right) = \frac{ef_1}{2M_N}\bar{N}\Gamma^{(\mp)}\sigma_{\mu\nu}\partial^{\nu}A^{\mu}R + \text{H.c.},$$

$$\mathcal{L}_{RN\gamma}\left(\tfrac{3}{2}^{\pm}\right) = -\frac{ief_1}{2M_N}\overline{N}\Gamma_{\nu}^{(\pm)}F^{\mu\nu}R_{\mu} - \frac{ef_2}{(2M_N)^2}\partial_{\nu}\bar{N}\Gamma^{(\pm)}F^{\mu\nu}R_{\mu} + \text{H.c.},$$

$$\mathcal{L}_{RN\gamma}\left(\tfrac{5}{2}^{\pm}\right) = \frac{ef_1}{(2M_N)^2}\bar{N}\Gamma_{\nu}^{(\mp)}\partial^{\alpha}F^{\mu\nu}R_{\mu\alpha} - \frac{ief_2}{(2M_N)^3}\partial_{\nu}\bar{N}\Gamma^{(\mp)}\partial^{\alpha}F^{\mu\nu}R_{\mu\alpha} + \text{H.c.},$$

Helicity amplitudes

$$\Gamma(R \to N\gamma) = \frac{k_{\gamma}^2}{\pi}\frac{2M_N}{(2j+1)M_R}[|A_{1/2}|^2 + |A_{3/2}|^2],$$

$$A_{1/2}\left(\tfrac{1}{2}^{\pm}\right) = \mp\frac{ef_1}{2M_N}\sqrt{\frac{k_{\gamma}M_R}{M_N}},$$

$$A_{1/2}\left(\tfrac{3}{2}^{\pm}\right) = \mp\frac{e\sqrt{6}}{12}\sqrt{\frac{k_{\gamma}}{M_N M_R}}\left[f_1 + \frac{f_2}{4M_N^2}M_R(M_R \mp M_N)\right],$$

$$A_{3/2}\left(\tfrac{3}{2}^{\pm}\right) = \mp\frac{e\sqrt{2}}{4M_N}\sqrt{\frac{k_{\gamma}M_R}{M_N}}\left[f_1 \mp \frac{f_2}{4M_N}(M_R \mp M_N)\right],$$

$$A_{1/2}\left(\tfrac{5}{2}^{\pm}\right) = \pm\frac{e}{4\sqrt{10}}\frac{k_{\gamma}}{M_N}\sqrt{\frac{k_{\gamma}}{M_N M_R}} \times\left[f_1 + \frac{f_2}{4M_N^2}M_R(M_R \pm M_N)\right],$$

$$A_{3/2}\left(\tfrac{5}{2}^{\pm}\right) = \pm\frac{e}{4\sqrt{5}}\frac{k_{\gamma}}{M_N^2}\sqrt{\frac{k_{\gamma}M_R}{M_N}}\left[f_1 \pm \frac{f_2}{4M_N}(M_R \pm M_N)\right],$$

Interactions of R with spin-3/2 baryons

- $J^{\pm} \to 0^{-} + \frac{3}{2}^{+}$

Lagrangian

$$\mathcal{L}_{RK\Sigma^*}\left(\tfrac{1}{2}^{\pm}\right) = \frac{h_1}{M_K}\partial_\mu K \bar{\Sigma}^{*\mu}\Gamma^{(\mp)}R + \text{H.c.},$$

$$\mathcal{L}_{RK\Sigma^*}\left(\tfrac{3}{2}^{\pm}\right) = \frac{h_1}{M_K}\partial^\alpha K \bar{\Sigma}^{*\mu}\Gamma^{(\pm)}_\alpha R_\mu + \frac{ih_2}{M_K^2}\partial^\mu\partial^\alpha K \bar{\Sigma}^*_\alpha \Gamma^{(\pm)} R_\mu + \text{H.c.},$$

$$\mathcal{L}_{RK\Sigma^*}\left(\tfrac{5}{2}^{\pm}\right) = \frac{ih_1}{M_K^2}\partial^\mu\partial^\beta K \bar{\Sigma}^{*\alpha}\Gamma^{(\mp)}_\mu R_{\alpha\beta} - \frac{h_2}{M_K^3}\partial^\mu\partial^\alpha\partial^\beta K \bar{\Sigma}^*_\mu \Gamma^{(\mp)} R_{\alpha\beta} + \text{H.c.}.$$

Decay widths

$$\Gamma\left(\tfrac{1}{2}^{\pm} \to K\Sigma^*\right) = \frac{h_1^2}{2\pi}\frac{q^3 M_R}{M_K^2 M_{\Sigma^*}^2}(E_{\Sigma^*} \pm M_{\Sigma^*}),$$

$$\Gamma\left(\tfrac{3}{2}^{\pm} \to K\Sigma^*\right) = \frac{1}{24\pi}\frac{q}{M_R M_{\Sigma^*}^2}(E_{\Sigma^*} \mp M_{\Sigma^*}) \times \left\{ \frac{h_1^2}{M_K^2}(M_R \pm M_{\Sigma^*})^2 \times \left(2E_{\Sigma^*}^2 \mp 2E_{\Sigma^*}M_{\Sigma^*} + 5M_{\Sigma^*}^2\right) \mp 2\frac{h_1 h_2}{M_K^3}M_R q^2 (M_R \pm M_{\Sigma^*})(2E_{\Sigma^*} \mp M_{\Sigma^*}) + 2\frac{h_2^2}{M_K^4}M_R^2 q^4 \right\},$$

$$\Gamma\left(\tfrac{5}{2}^{\pm} \to K\Sigma^*\right) = \frac{1}{60\pi}\frac{q^3}{M_R M_{\Sigma^*}^2}(E_{\Sigma^*} \pm M_{\Sigma^*}) \times \left\{ \frac{h_1^2}{M_K^4}(M_R \mp M_{\Sigma^*})^2 \times \left(4E_{\Sigma^*}^2 \pm 4E_{\Sigma^*}M_{\Sigma^*} + 7M_{\Sigma^*}^2\right) \mp 4\frac{h_1 h_2}{M_K^5}M_R q^2 (M_R \mp M_{\Sigma^*})(2E_{\Sigma^*} \pm M_{\Sigma^*}) + 4\frac{h_2^2}{M_K^6}M_R^2 q^4 \right\},$$

Matching with quark model predictions

- Decay amplitude

$$\langle K(q)\Sigma^*(-q, m_f)| - i\mathcal{H}_{\rm int}|R(0, m_j)\rangle = 2\pi M_R\sqrt{\frac{2}{q}}\sum_{\ell, m_\ell}\langle \ell m_\ell \tfrac{3}{2} m_f | j m_j\rangle Y_{\ell m_\ell}(\hat{q})G(\ell),$$

$$\Gamma(R \to K\Sigma^*) = \sum_\ell |G(\ell)|^2,$$

Quark model predictions on G(l)

For $\frac{1}{2}^+$ $$G(1) = -\frac{1}{\sqrt{2\pi}}\frac{q}{M_{\Sigma^*}}\sqrt{qM_R}\sqrt{E_{\Sigma^*} + M_{\Sigma^*}}\frac{h_1}{M_K},$$

For $\frac{1}{2}^-$ $$G(2) = -\frac{1}{\sqrt{2\pi}}\frac{q}{M_{\Sigma^*}}\sqrt{qM_R}\sqrt{E_{\Sigma^*} - M_{\Sigma^*}}\frac{h_1}{M_K},$$

G's can be related to cc

For $\frac{3}{2}^+$ $$G(1) = G_{11}^{(3/2)}\frac{h_1}{M_K} + G_{12}^{(3/2)}\frac{h_2}{M_K^2},$$ $$G(3) = G_{31}^{(3/2)}\frac{h_1}{M_K} + G_{32}^{(3/2)}\frac{h_2}{M_K^2},$$

$$G_{11}^{(3/2)} = \frac{\sqrt{30}}{60\sqrt{\pi}}\frac{1}{M_{\Sigma^*}}\sqrt{\frac{q}{M_R}}\sqrt{E_{\Sigma^*} - M_{\Sigma^*}}(M_R + M_{\Sigma^*}) \times (E_{\Sigma^*} + 4M_{\Sigma^*}),$$

$$G_{12}^{(3/2)} = -\frac{\sqrt{30}}{60\sqrt{\pi}}\frac{q^2\sqrt{qM_R}}{M_{\Sigma^*}}\sqrt{E_{\Sigma^*} - M_{\Sigma^*}},$$

$$G_{31}^{(3/2)} = -\frac{\sqrt{30}}{20\sqrt{\pi}}\frac{1}{M_{\Sigma^*}}\sqrt{\frac{q}{M_R}}\sqrt{E_{\Sigma^*} - M_{\Sigma^*}} \times (M_R + M_{\Sigma^*})(E_{\Sigma^*} - M_{\Sigma^*}),$$

$$G_{32}^{(3/2)} = \frac{\sqrt{30}}{20\sqrt{\pi}}\frac{q^2\sqrt{qM_R}}{M_{\Sigma^*}}\sqrt{E_{\Sigma^*} - M_{\Sigma^*}},$$

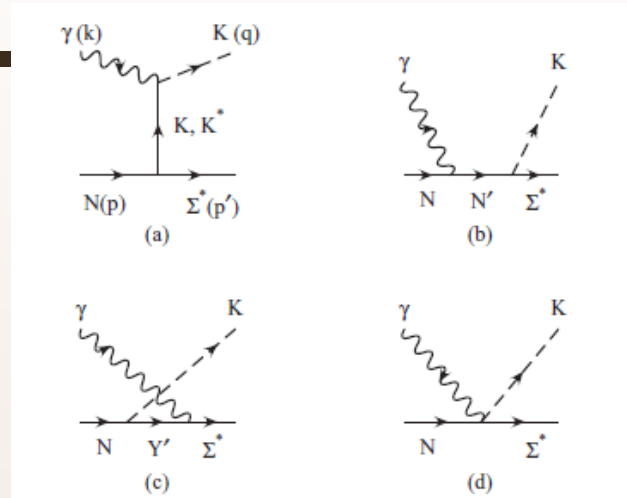
and so on …

IV

APPLICATION

Σ* photoproduction

- The reaction of $\gamma N \rightarrow K\Sigma^*$

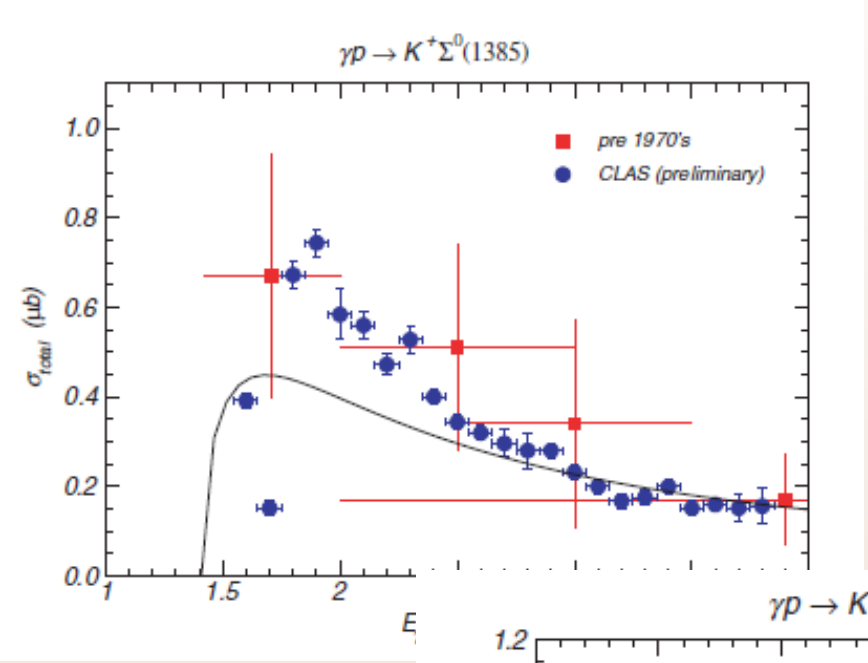


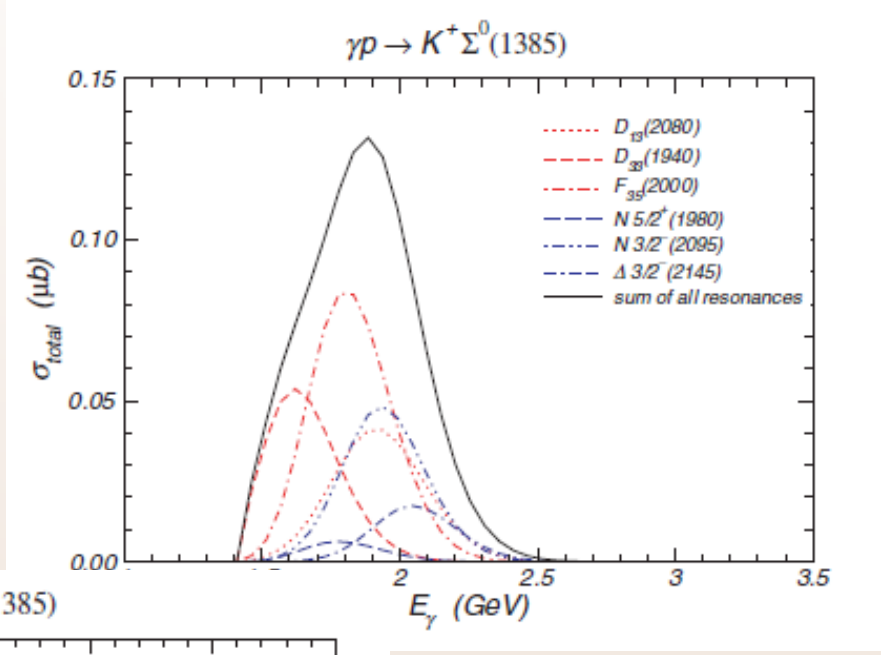
Considered resonances

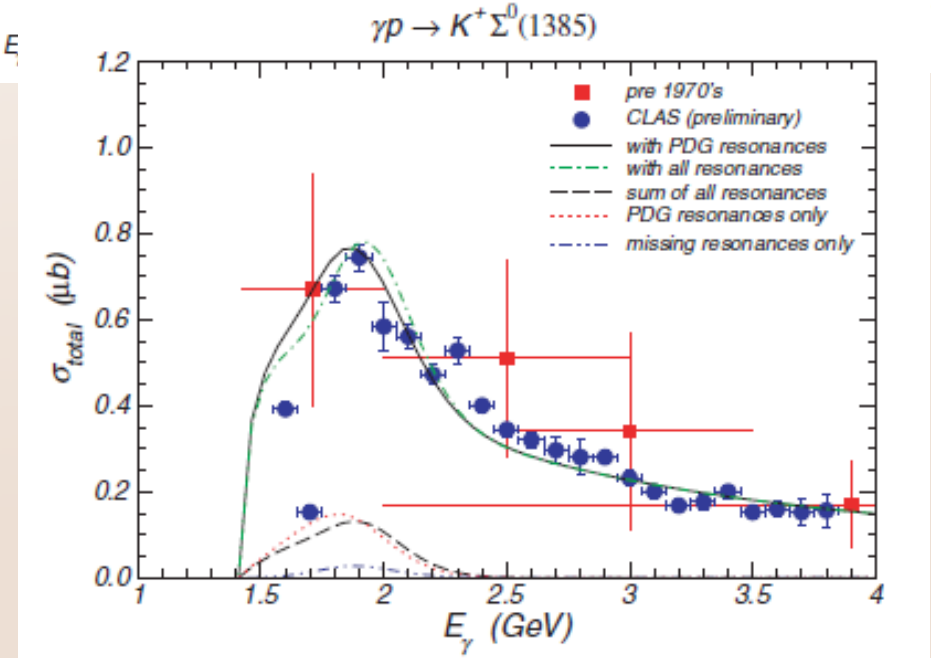
Resonance	PDG [29]	Amplitudes of $R \rightarrow K\Sigma(1385)$[a]		h_1	h_2	Amplitudes of $R \rightarrow N\gamma$[b]		f_1	f_2
		$G(\ell_1)$	$G(\ell_2)$			$A^p_{1/2}$	$A^p_{3/2}$		
$N\frac{1}{2}^-(1945)$	$S^*_{11}(2090)$	$G(2) = +1.7$	–	−9.8	–	+12	–	−0.055	–
$N\frac{3}{2}^-(1960)$	$D^{**}_{13}(2080)$	$G(0) = +1.3$	$G(2) = +1.4$	0.24	−0.54	+36	−43	−1.25	1.21
$N\frac{5}{2}^-(2095)$	$D^{**}_{15}(2200)$	$G(2) = -2.0$	$G(4) = 0.0$	0.29	−0.08	−9	−14	0.37	−0.57
$\Delta\frac{3}{2}^-(2080)$	$D^*_{33}(1940)$	$G(0) = -4.1$	$G(3) = -0.5$	−0.68	1.00	−20	−6	0.39	−0.57
$\Delta\frac{5}{2}^+(1990)$	$F^{**}_{35}(2000)$	$G(1) = +4.0$	$G(3) = -0.1$	−0.87	0.11	−10	−28	−0.68	−0.062

Resonance	Amplitudes of $R \rightarrow K\Sigma(1385)$[a]		h_1	h_2	Amplitudes of $R \rightarrow N\gamma$[b]		f_1	f_2
	$G(\ell_1)$	$G(\ell_2)$			$A^p_{1/2}$	$A^p_{3/2}$		
$N\frac{3}{2}^-(2095)$	$G(0) = +7.7$	$G(2) = -0.8$	0.99	0.27	−9	−14	0.49	−0.83
$N\frac{5}{2}^+(1980)$	$G(1) = -3.6$	$G(3) = -0.1$	0.59	0.24	−11	−6	0.019	−0.13
$\Delta\frac{3}{2}^-(2145)$	$G(0) = +5.2$	$G(2) = -1.9$	0.25	0.46	0	+10	0.11	−0.059

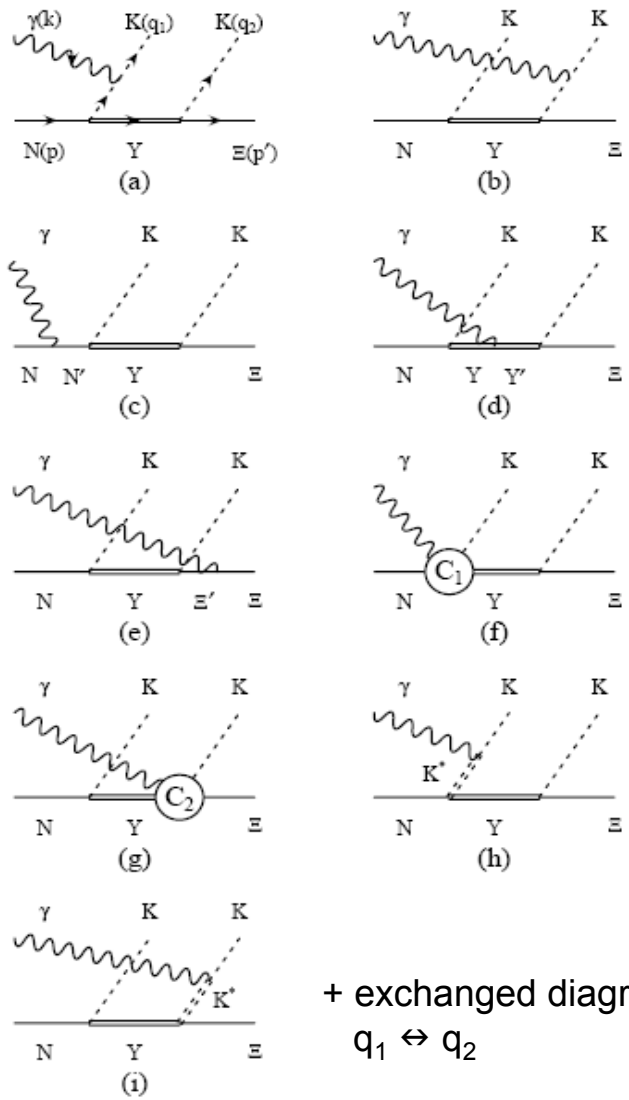
Results (cross section)







Ξ photoproduction $\gamma N \to KK\Xi$



+ exchanged diagrams
$q_1 \leftrightarrow q_2$

Λ states					Σ states				
State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Lambda K}\rvert$	State	J^P	Γ (MeV)	Rating	$\lvert g_{N\Sigma K}\rvert$
Λ(1116)	$1/2^+$		****		Σ(1193)	$1/2^+$		****	
Λ(1405)	$1/2^-$	≈ 50	****		Σ(1385)	$3/2^+$	≈ 37	****	
Λ(1520)	$3/2^-$	≈ 16	****						
Λ(1600)	$1/2^+$	≈ 150	***	4.2	Σ(1660)	$1/2^+$	≈ 100	***	2.5
Λ(1670)	$1/2^-$	≈ 35	****	0.3	Σ(1670)	$3/2^-$	≈ 60	****	2.8
Λ(1690)	$3/2^-$	≈ 60	****	4.0	Σ(1750)	$1/2^-$	≈ 90	***	0.5
Λ(1800)	$1/2^-$	≈ 300	***	1.0	Σ(1775)	$5/2^-$	≈ 120	****	
Λ(1810)	$1/2^+$	≈ 150	***	2.8	Σ(1915)	$5/2^+$	≈ 120	****	
Λ(1820)	$5/2^+$	≈ 80	****		Σ(1940)	$3/2^-$	≈ 220	***	< 2.8
Λ(1830)	$5/2^-$	≈ 95	****		Σ(2030)	$7/2^+$	≈ 180	****	
Λ(1890)	$3/2^+$	≈ 100	****	0.8	Σ(2250)	$?^?$	≈ 100	***	
Λ(2100)	$7/2^-$	≈ 200	****						
Λ(2110)	$5/2^+$	≈ 200	***						
Λ(2350)	$9/2^+$	≈ 150	***						

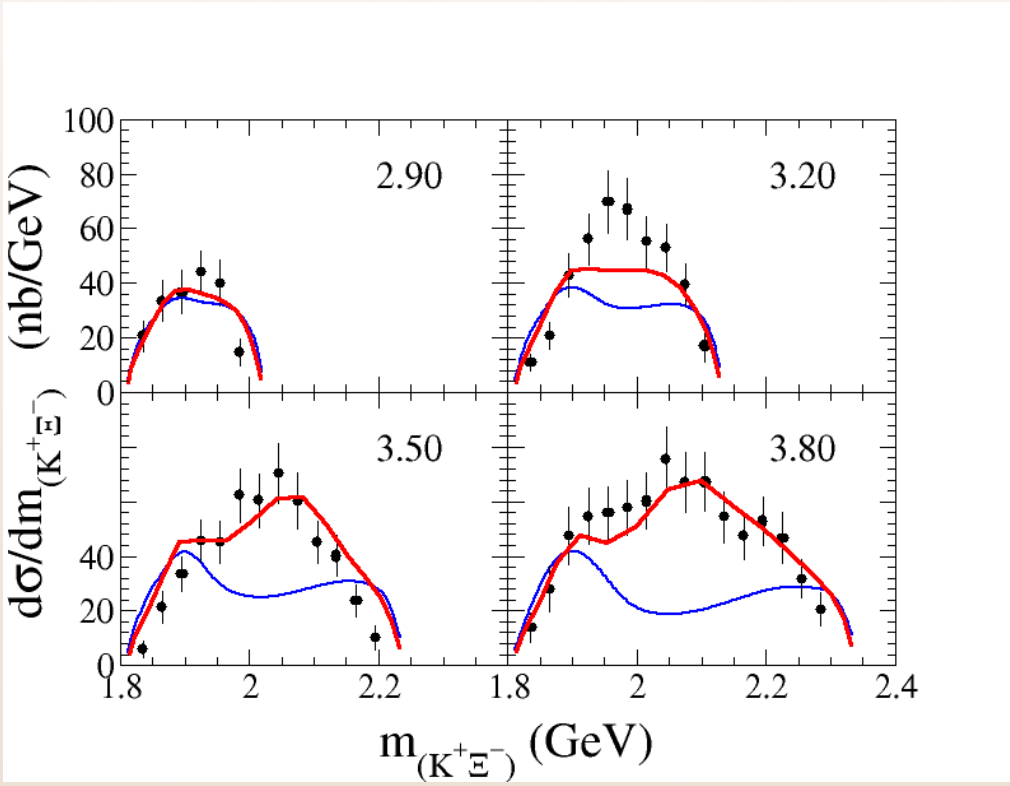
$$\left|M_{1/2^\pm}\right|^2,\ \left|M_{5/2^\pm}\right|^2 \propto \left(E_N \mp M_N\right)\left(E_\Xi \mp M_\Xi\right)$$

$$\left|M_{3/2^\pm}\right|^2,\ \left|M_{7/2^\pm}\right|^2 \propto \left(E_N \pm M_N\right)\left(E_\Xi \pm M_\Xi\right)$$

Nakayama, YO, Haberzettl, PRC 74

This work

$\gamma p \rightarrow K^+K^+\Xi^-$ (new result)



CLAS, PRC 76 (2007)

Nakayama, YO, Haberzettl, PRC 74

This work

V

SUMMARY

Summary

- Inclusion of higher spin resonances
  - To understand the mechanism of photoproduction processes
  - To search for the missing resonances
  - To test various hadron models in the market
- To-do
  - Matching the coupling constants to models for hadron structure
    - A complete list for the relationship between the CC and the decay amplitudes (of hadron models)
  - Off-shell parameters
  - Etc

THANK YOU!