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* Production of neutron-rich Λ hypernuclei in the (π^-, K^+) reaction
  - Production of $^{12}_{\Lambda}Be$ and $^{10}_{\Lambda}Li$: meson charge exchange and Σ admixture
  - Mechanism of production on Δ baryon admixture
* Production of Θ^+ (pentaquark) nuclei
  - Recoilless kinematics for Θ production on a nucleon pair
  - Rough estimations of the cross sections

Partly in collaboration with
T. Tretyakova (Dubna)

in the (π^-, K^+) reaction

The first experimental evidence: KEK E521, 2002-2003

$^{10}B(\pi^-, K^+)^{10}_{\Lambda}Li$

$^{12}C(\pi^-, K^+)^{12}_{\Lambda}Be$

Theoretically, two mechanisms of the reaction were considered

1. Two-step mechanism with meson charge exchange

$$\pi^- p \rightarrow \pi^0 n \;, \; \pi^0 p \rightarrow K^+ \Lambda$$
$$\pi^- p \rightarrow K^0 \Lambda \;, \; K^0 p \rightarrow K^+ n$$

2. One-step mechanism via Σ^- doorway state

mixing $\Lambda n \leftrightarrow \Sigma^- p$ in the final (hypernuclear) state

$$\pi^- p \rightarrow K^+ \Sigma^-$$

$$|^A_\Lambda Z\rangle = \alpha\, |\Lambda \otimes {}^{A-1}Z\rangle + \beta\, |\Sigma^- \otimes {}^{A-1}(Z+1)\rangle$$

$$P_\Sigma = |\beta|^2 \ll |\alpha|^2$$

$$F = \beta \langle \Sigma^- \otimes {}^{A-1}(Z+1) | \hat{F} | {}^A Z \rangle$$

The first mechanism is suppressed because of its two-step nature, the second one - since P_Σ is small are by about three orders of magnitude smaller than the cross sections of the "usual" (π^+, K^+) reaction

- The two-step mechanism is dominated (The mechanisms give comparable contributions for the (K^-_{st}, π^+) production)
- Kaon and pion charge exchange contribute comparably
- Cross sections of $^{10}_{\Lambda}Li$ production are higher than that for $^{12}_{\Lambda}Be$

	p_π, GeV/c	$\frac{d\sigma}{d\Omega}\left(\frac{nb}{sr}\right)$ Sum over neutron bound states	$\frac{d\sigma}{d\Omega}\left(\frac{nb}{sr}\right)$, E521 Sum over $0 < B_\Lambda < 15$ Me
$^{10}B(\pi^-, K^+)^{10}_{\Lambda}Li$	1.05	38	
	1.2	22	12 ± 2
$^{12}C(\pi^-, K^+)^{12}_{\Lambda}Be$	1.05	5	
	1.2	2.5	(7)

The main disagreement

$$\frac{d\sigma}{d\Omega}(1.2\,GeV/c) > \frac{d\sigma}{d\Omega}(1.05\,GeV/c) \quad \text{experiment}$$
$$< \quad \text{theory}$$

One-step mechanism of the ${}^{A}Z(\pi^-,K^+){}^{A}_{\Lambda}(Z-2)$ reaction using Δ baryonic admixture in the initial (nuclear) states

$$\pi^-\Delta^{++}\rightarrow K^+\Lambda$$

$$\frac{d\sigma}{d\Omega}(\pi^-\ {}^{A}Z\rightarrow K^+\ {}^{A}_{\Lambda}(Z-2))=\frac{d\sigma}{d\Omega}(\pi^-\Delta^{++}\rightarrow K^+\Lambda)\,p_\Delta\cdot N_{eff}$$

Numbers of Δ per nucleon in ${}^{12}C$ from experiments

Morris et al., PL B419(1998)25 ${}^{12}C(\pi^+,\pi^-p)$

$$N_{\Delta^{++}}/A=(0.37\pm0.07)\%$$
$$(0.73\pm0.14)\%$$

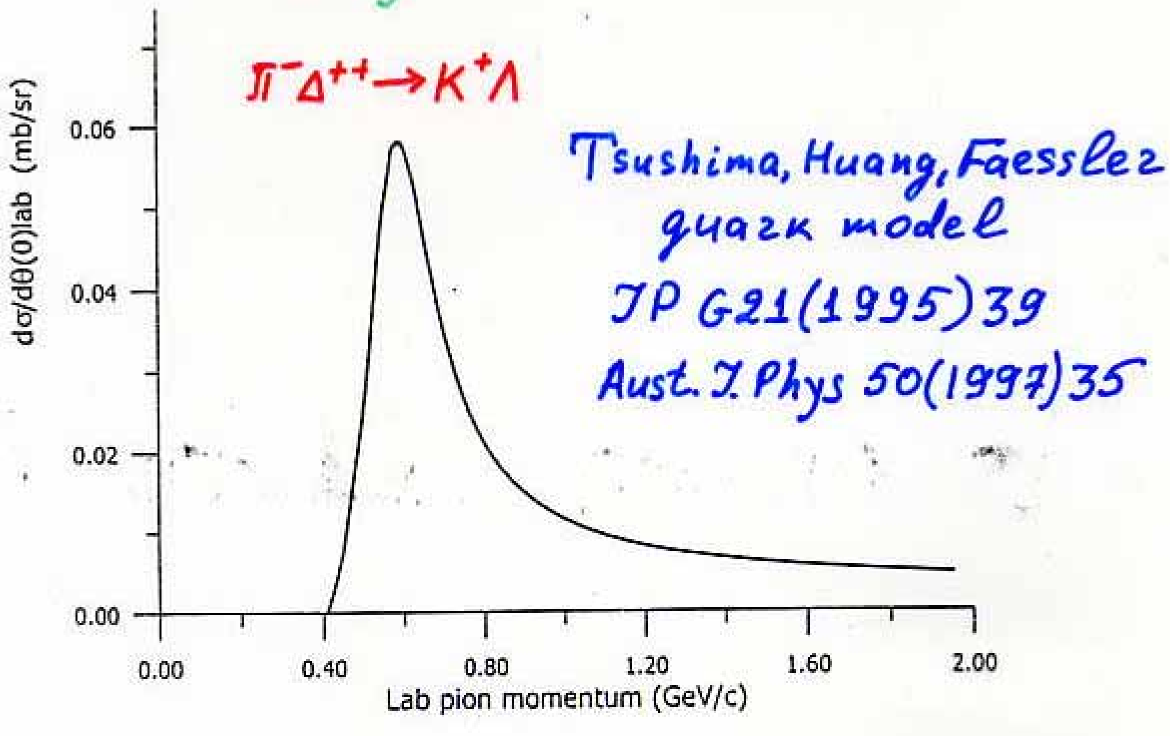
Bystritsky et al., NP A705(2002)55 ${}^{12}C(\gamma,\pi^+p)$

$$N_{\Delta^{++}}/A=(0.40\pm0.16)\%$$

We take $N_{\Delta^{++}}=0.4\%\cdot A$ $p_\Delta<N_\Delta$!

Total $N_{\Delta^{++}}$ is not related to a certain ${}^{A}Be$ state and give an upper limit only

Elementary cross section



One-step mechanism $\pi\,\Delta \rightarrow K\,\Lambda$

$$^{12}C(\pi^-, K^+)\,^{12}_{\Lambda}Be\ ,\quad p_\pi = 1.05\ GeV/c$$

$$\frac{d\sigma}{d\Omega}(0^\circ) \approx 500 \cdot N_{eff}\ \frac{nb}{sr}$$

For typical $N_{eff} = (2\text{-}3)\cdot 10^{-2}$, the cross sections are about $(10-15)\,nb/sr$ (upper limit)

not smaller than for the other mechanisms

Discovery of pentaquark 2002–2003

Θ^+, $B=1$, $S=+1$ (PDG04 ***)

$M = 1539.2 \pm 1.6$ MeV

$\Gamma < 9$ MeV (direct measurement)

$\Gamma \lesssim 1$ MeV (from kaon-nucleon scattering)

$J^\pi = ??$ $I = 0$ (?)

Hyperon + nucleus = hypernucleus

Pentaquark + nucleus = pentanucleus (!?)

Is Θ^+ bound by a nucleus?

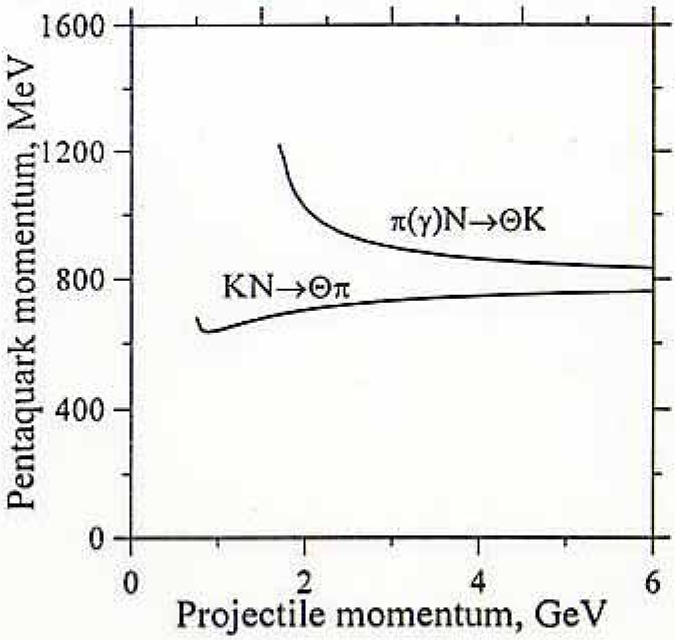
Miller, nucl-th/0402099, collective vibrational model. Θ^+ is very strongly bound (decays weakly in a nucleus)

Kim et al., hep-ph/0402141, self-energy in nuclear matter. A shallow well, not enough to bind Θ^+

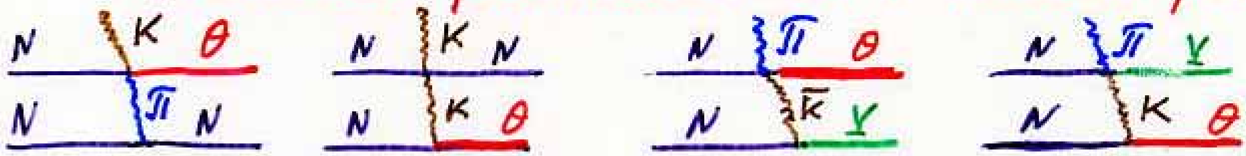
Cabrera et al., nucl-th/0407007, self-energy in nuclear matter with account of $\Theta \leftrightarrow N\pi K$ coupling. A deep well, enough for several bound states, but lying above the threshold of the strong decay (Vicente Vacas, SNP04)

Hypernuclear experience: even in the case of repulsion (Σ^-A interaction, KEK (π^-, K^+) experiment, Noumi et al., PRL89(2002)072301), the spectrum gives certain information about

For Θ production on nucleon, the momentum transfer is high

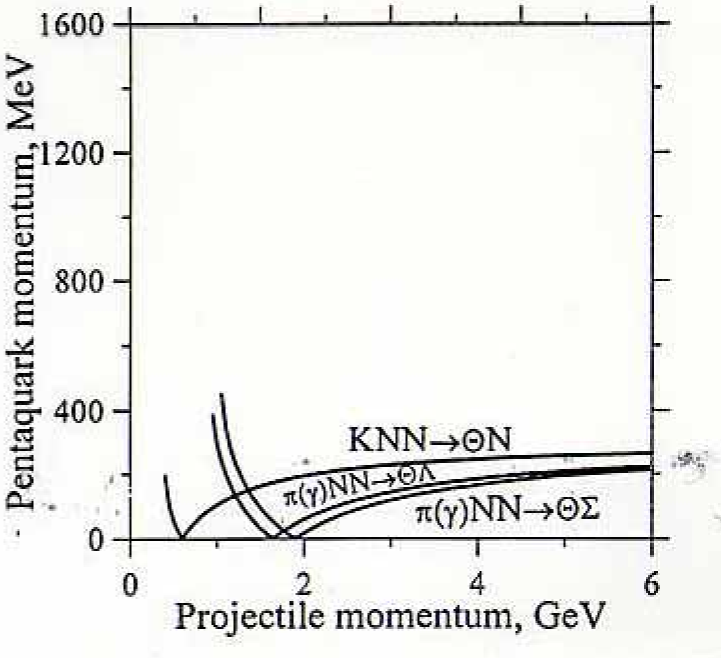


Recoilless production on a nucleon pair!



Magic momenta, GeV/c

NN → ΘΛ	1.67
NN → ΘΣ	1.93
N → ΘΛ	1.64
N → ΘΣ	1.89
N → ΘN	0.60



To avoid uncertainties from unknown Θ-nucleus interaction, we estimate the cross section **summed** over all **final states** within the **closure** approximation (similarly to Dalitz, Gal PLB64(1976)154 for the (K^-,π^-) reaction)

$$\frac{d\sigma_{sum}}{d\Omega}(0^\circ) = \frac{d\sigma}{d\Omega}(ad \to B\Theta)\cdot N_d \cdot S_{dist}$$

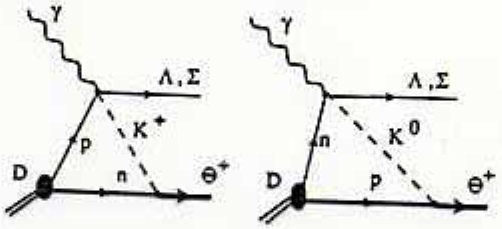
N_d is the number of deuteron clusters

$$S_{dist} = \int d^2b\,dz\,\rho_d(b,z)\left(1-\sigma_a T_N(\vec{b},-\infty,z)-\sigma_B T_N(\vec{b},z,+\infty)\right)^{A-2}$$

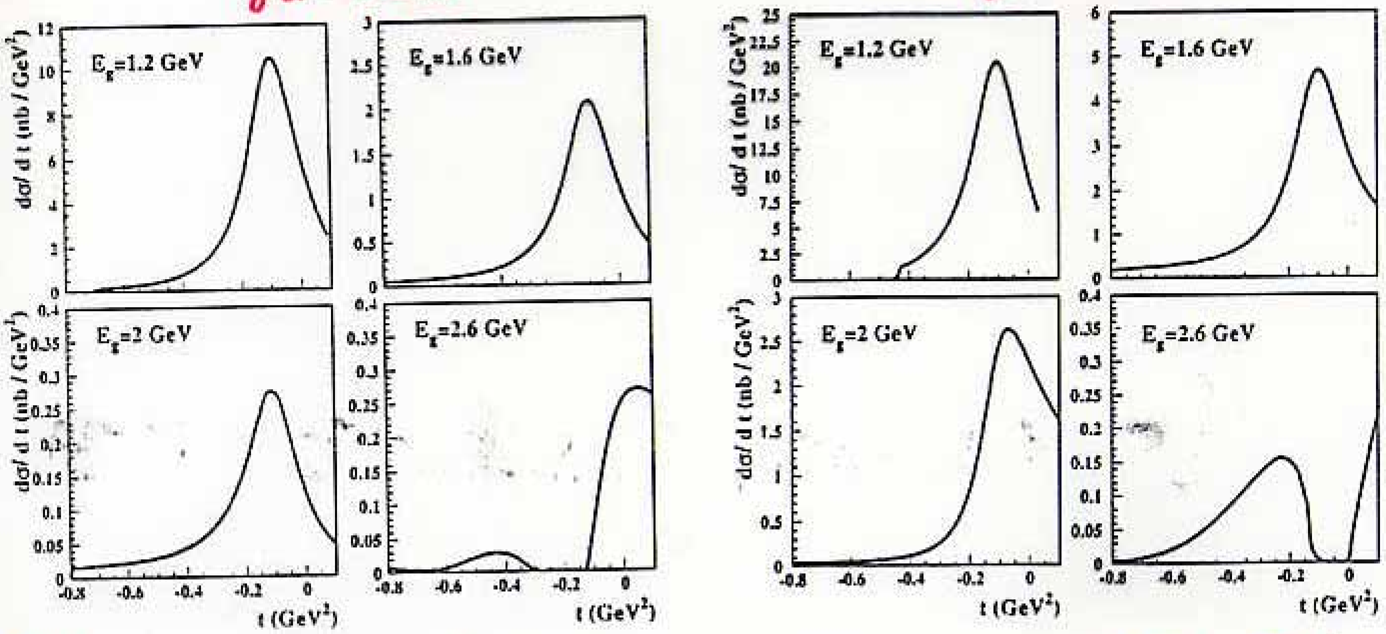
$$T_N(\vec{b},z_1,z_2) = \int_{z_1}^{z_2} dz\,\rho_N(b,z); \quad \int d^3z\,\rho_{d,N}(\vec{z}) = 1$$

"Elementary" cross section $\gamma d \to \Theta Y$

From:
Guzey
PRC69(2004)
065203



$\gamma d \to \Theta\Lambda$ $\gamma d \to \Theta\Sigma^0$



The cross sections are proportional to Γ_Θ!

The curves are obtained at $\Gamma_\Theta = 5$ MeV

E_γ, GeV	$^{12}C(\gamma,\Lambda)^{11}_{\Theta}C$	$^{12}C(\gamma,\Sigma^0)^{11}_{\Theta}C$	$^{40}Ca(\gamma,\Lambda)^{39}_{\Theta}Ca$	$^{40}Ca(\gamma,\Sigma^0)^{39}_{\Theta}Ca$
1.2	29	59	120	240
1.6	10	24	42	98
2.0	2	18	7	71

$\times\ \Gamma_\Theta / 5$ MeV

What part of the $\frac{d\sigma_{sum}}{d\Omega}$ corresponds to low-lying states?

Hypernuclear experience: $^{A}Z(K^-,\pi^-)^{A}_{\Lambda}Z$
recoilless process, Bouyssy NP A290(1977)324
Recoilless (without changing of the quantum numbers) part is 50% for ^{12}C
26% for ^{40}Ca

experiments aimed on the reactions

$$\gamma d \longrightarrow \Theta^+ \Lambda$$
$$\pi^\pm d \longrightarrow \Theta^+ \Sigma^\pm$$
$$K^+ d \longrightarrow \Theta^+ p$$

are highly desirable

Production of pentadeuteron !?

$^3He(a, B)^{2}_{\Theta}He$ or $^{2}_{\Theta}H$

Reactions (γ, Y), (π, Y), and (K, N) are probably the most promising way to produce Θ nuclei (pentanuclei)