Carnegie Mellon
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Doubly-Strange Hypernuclei Production in E885 at AGS

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- Baryon-baryon interaction at low energies
  - One Boson Exchange models
  - Why study hypernuclei?
- Experimental setup
  - Production mechanisms
- Analysis
  - Ξ^- capture on carbon
  - Direct production
- Conclusions

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Baryon-baryon interactions at low energies

- Non-perturbative QCD region

One Boson Exchange Models extended to baryon octet:

$NN \longrightarrow BB, \quad B \equiv N \cup Y$

$Y \equiv \{ \underbrace{\Sigma^-, \Sigma^0, \Sigma^+}_{T=1}, \underbrace{\Lambda}_{T=0}, \underbrace{\Xi^-, \Xi^0}_{T=1/2} \}$

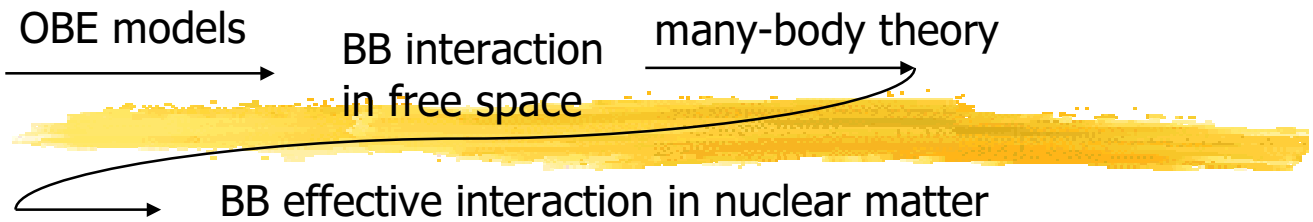
- Interaction described by exchange of nonets of pseudoscalar (π, η, η', K), vector $(\rho, \omega, \phi, K^{*})$ and scalar $(\delta, \varepsilon, S^{*}, \kappa)$ mesons.

- Coupling constants from data and symmetry considerations.

- Short-range repulsion by introducing hard or soft cores.

Nijmegen D and F models, Juelich models

Hypernuclear spectroscopy



BB effective interaction in nuclear matter

hyperon-nucleus potential

binding energies

Test OBE models through measurement of hypernuclear states energy

BB effective interaction in the nuclear matter:

$V(r) = V_c(r) + V_1 \mathbf{l_{12}} \cdot \sigma_1 + V_2 \mathbf{l_{12}} \cdot \sigma_2 +$ spin-spin + tensor

radial spin-orbit

S=-1: Λ and Σ hypernuclei, ΛN and ΣN interaction.

LN: radial established, spin-orbit controversial

ΣN: peak observed in (K^-,π^-), no peak in (K^-,π^+)

attractive for $\Sigma^{0,+}$, repulsive for Σ^-.

S=-2: Ξ and double-Λ hypernuclei, ΞN and $\Lambda\Lambda$ interaction

no firm evidence for S=-2 hypernuclei existence

The E885 collaboration

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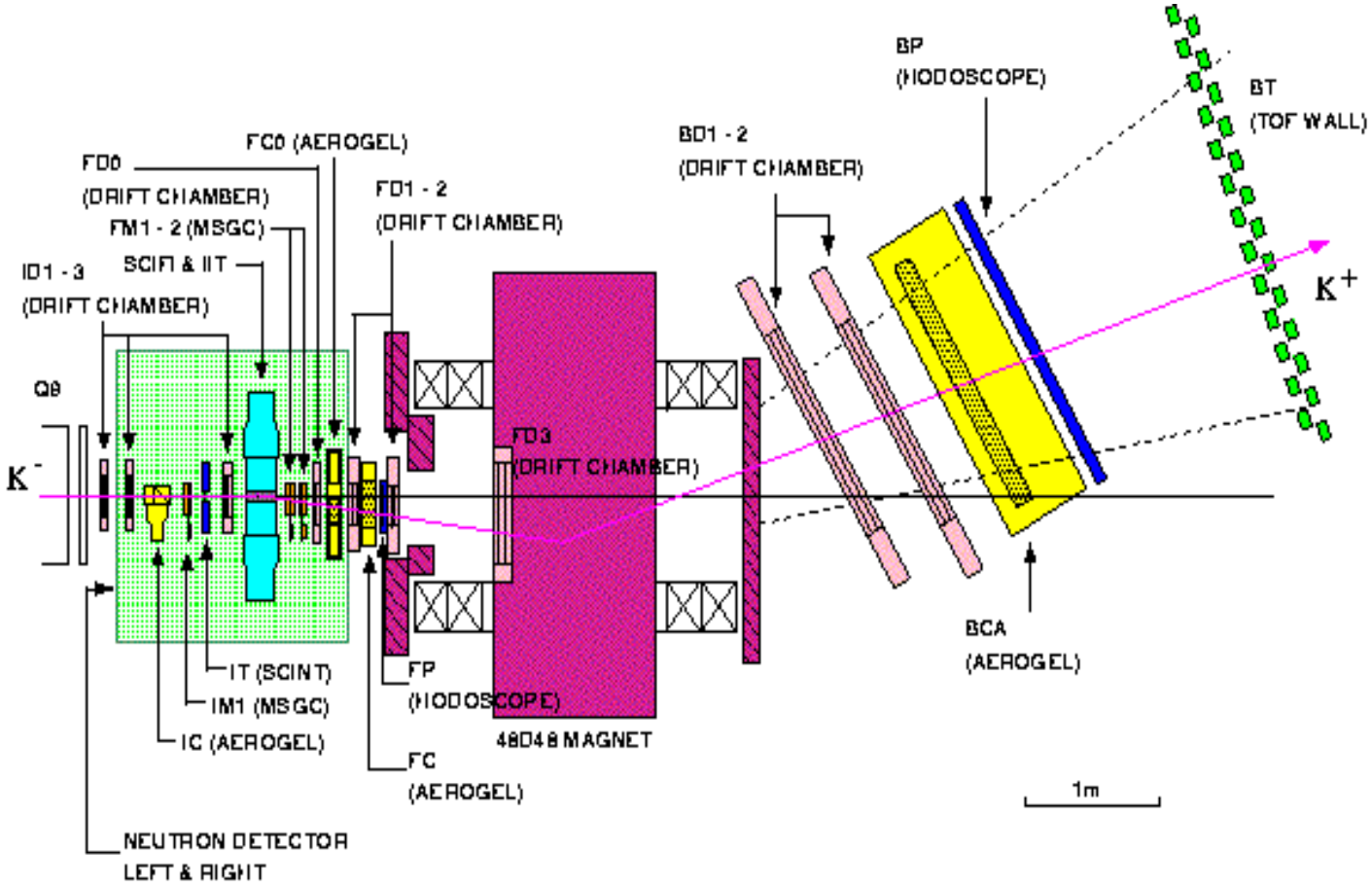
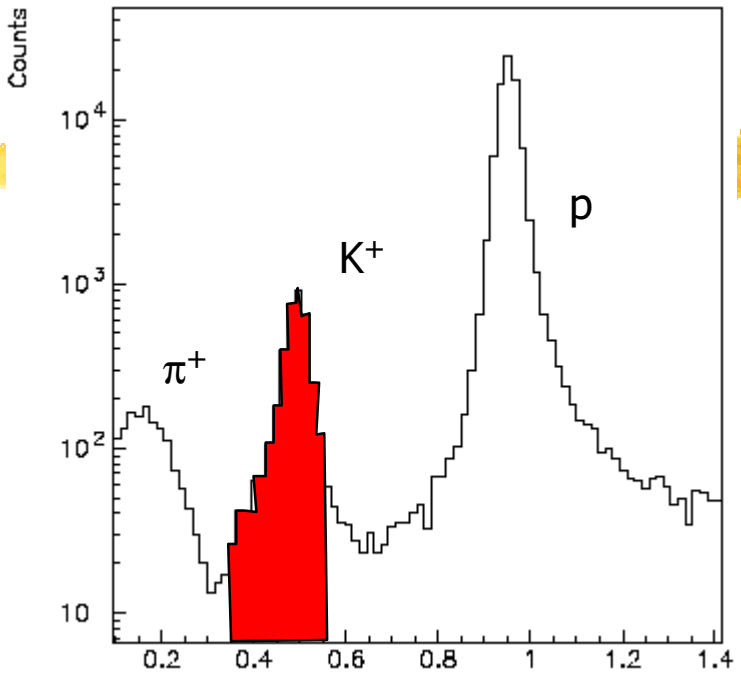
The experimental setup

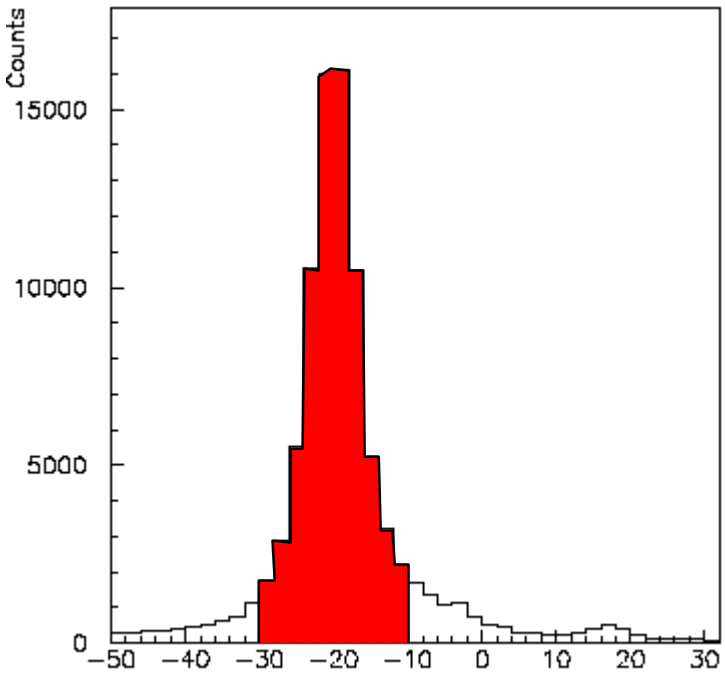


- 1-2 GeV/c D6 beamline, ~10^6 K^-/spill, K/π^- ~ 1/1
- Data taking completed (March - July 96)
- 0.8 x 10^{12} K^- incident on diamond target
- 300, 000 (K^-, K^+) events

Raw data



secondary mass, GeV/c^2



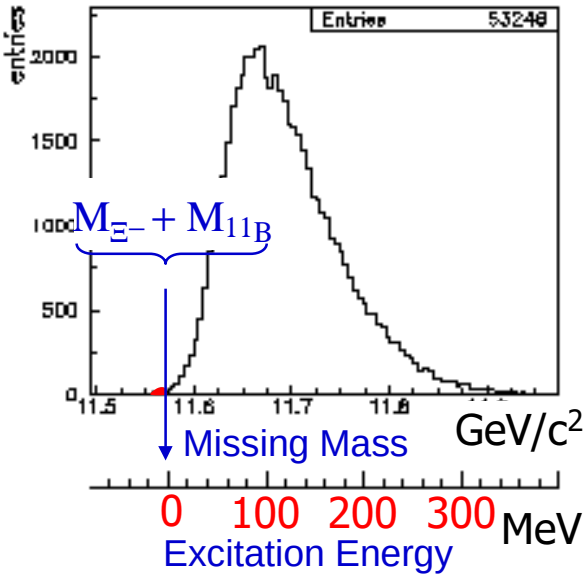
vertex *z*-position, cm

Hypernuclei production in E885

- Direct production in the $^{12}C(K^-,K^+)X$ reaction

$$K^- + {}^{12}C \longrightarrow \left\{ {}^{12}_{\Xi}Be^*,\ {}^{12}_{\Lambda\Lambda}Be^* \right\} + K^+$$

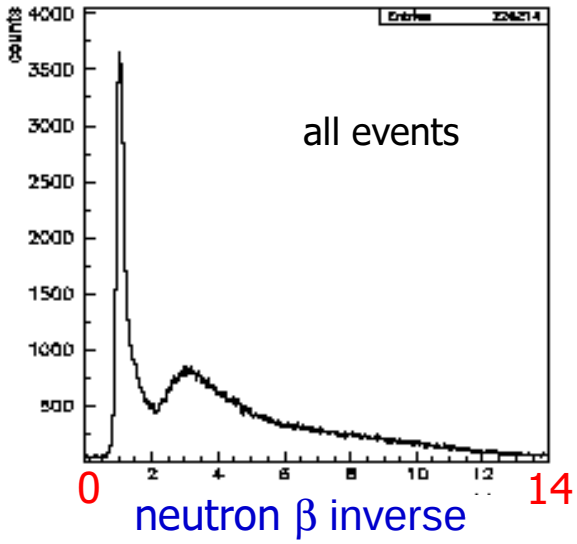
  - background suppression
  - normalization
  - comparison with theory

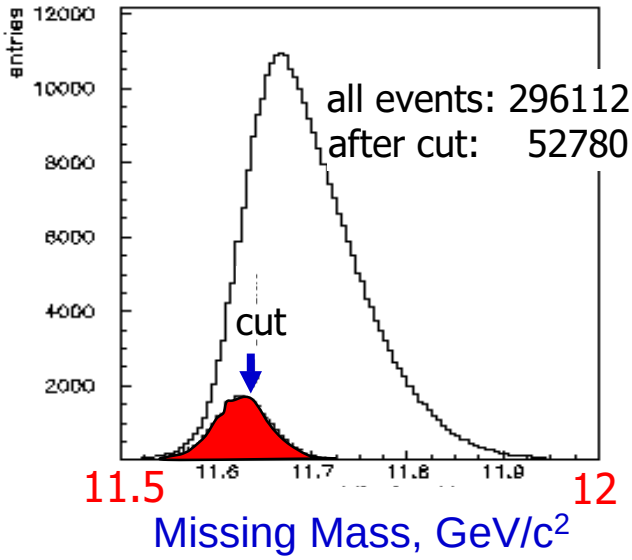


- Double-Λ hypernuclei formation via Ξ^- capture on carbon

$$K^- + {}^{12}C \longrightarrow K^+ + \Xi^- + X\,,\ (\Xi^-,{}^{12}C)_{atom} \longrightarrow {}^{12}_{\Lambda\Lambda}B^* + n$$

  - Ξ^- stopping rate
  - cut optimization
  - neutron detection efficiency, energy resolution





Present knowledge

Branching ratio of neutron-emission decay channel

- $(\Xi^-, {}^6\mathrm{Li})_{\mathrm{atom}} \rightarrow {}^{\ 6}_{\Lambda\Lambda}\mathrm{He} + \mathrm{n}$ – branching ratio $= 5\%$[44],
- ${}^{12}_{\ \Xi}\mathrm{Be} \rightarrow {}^{11}_{\Lambda\Lambda}\mathrm{Be} + \mathrm{n}$ – branching ratio $= 20\%$[46].

Λ-Λ binding energy in relative $^1S_0$ state inside the nucleus

The observed double-Λ hypernuclei and Λ-Λ binding energies are:

- ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$, $\Delta B_{\Lambda\Lambda} = 4.3$ MeV $\pm$ 0.4 MeV [25],
- ${}^{6}_{\Lambda\Lambda}\mathrm{He}$, $\Delta B_{\Lambda\Lambda} = 4.7$ MeV $\pm$ 1.0 MeV [26],
- ${}^{13}_{\Lambda\Lambda}\mathrm{B}$, $\Delta B_{\Lambda\Lambda} = 4.8$ MeV $\pm$ 0.7 MeV [27], or in other interpretation ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$, $\Delta B_{\Lambda\Lambda} = -4.9$ MeV $\pm$ 0.7 MeV .

$V_{0\Xi}$ potential well depth

- ${}^{\ 6}_{\Xi}\mathrm{He}$, $B_\Xi = 5.9$ MeV $\pm$ 1.2 MeV [30],
- ${}^{11}_{\Xi}\mathrm{B}$, $B_\Xi = 9.2$ MeV $\pm$ 2.2 MeV [31],
- ${}^{13}_{\Xi}\mathrm{C}$, $B_\Xi = 18.1$ MeV $\pm$ 3.2 MeV [32],
- ${}^{15}_{\Xi}\mathrm{C}$, $B_\Xi = 16.0$ MeV $\pm$ 4.7 MeV [33],
- ${}^{17}_{\Xi}\mathrm{O}$, $B_\Xi = 16.0$ MeV $\pm$ 5.5 MeV [33],
- ${}^{28}_{\Xi}\mathrm{Al}$, $B_\Xi = 23.2$ MeV $\pm$ 6.8 MeV [33],

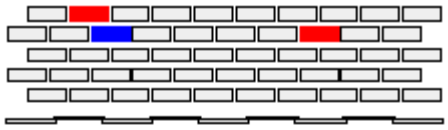
They obtained the value of 21 MeV $\pm$ 4 MeV or 24 MeV $\pm$ 4 MeV

Cross section of double-Λ direct production

A. J. Baltz *et al.* [23] predicted the cross section of direct double-Λ production in the reaction ${}^{16}\mathrm{O}(\mathrm{K}^-, \mathrm{K}+){}^{16}_{\Lambda\Lambda}\mathrm{C}^*$ to be a few nb/sr for $p_{K^-} = 1.1$ GeV/c. C. B. Dover *et al.* [24] pointed out the possibility of Ξ and double-Λ hypernuclear states mixing which would introduce an amplitude for direct one-step double-Λ hypernuclei production

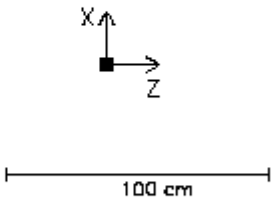
Double-Λ hypernuclei formation via Ξ⁻ capture on carbon

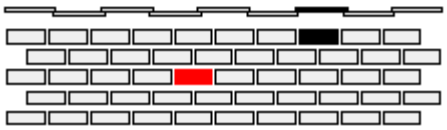
Detect mono-energetic neutrons from $(\Xi^-, {}^{12}C)_{atom} \rightarrow {}^{12}_{\Lambda\Lambda}B^* + n$



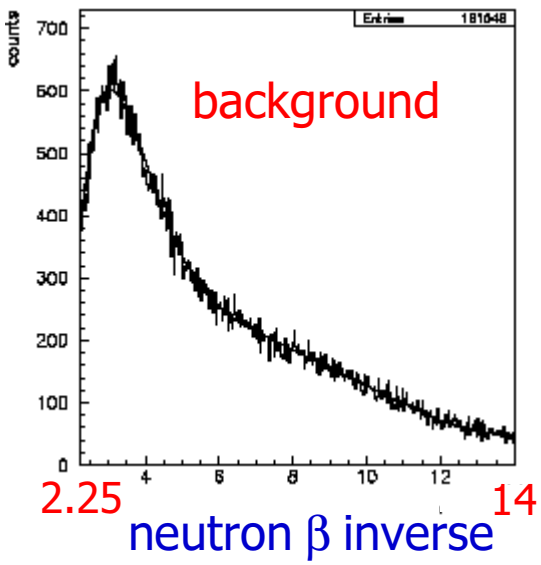
- 100 signal counters

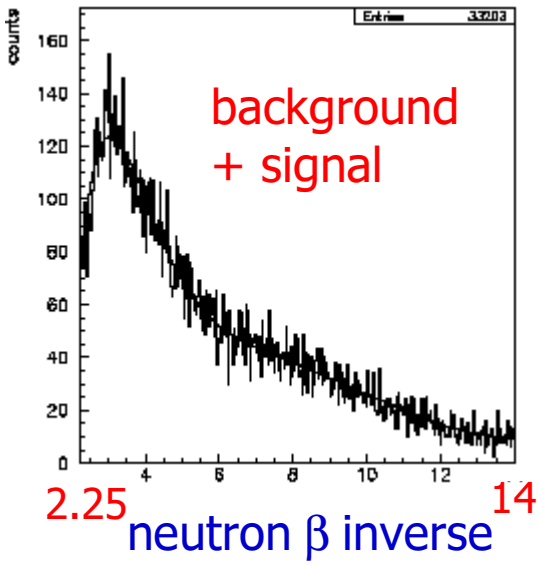
  5 cm x 183 cm x 15 cm
- Neutron energy determined through time-of-flight and path length





Total events: 296112, after missing mass cut: 52780, Ξ⁻ stops: 16750





Double-Λ hypernuclei formation via Ξ^- capture on carbon

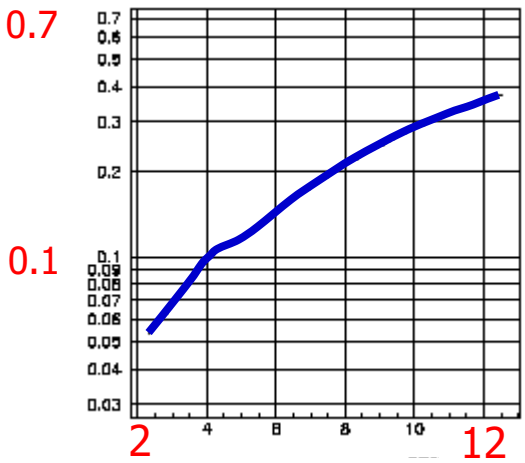
- Observations
  - Background is smooth and can be fit by a polynomial very well.
  - Background shape does not change

- Fit procedure

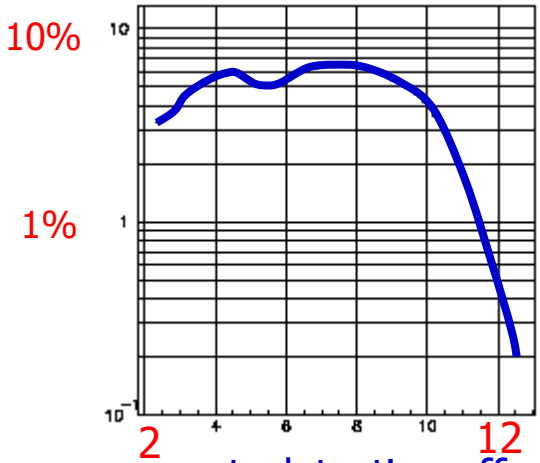
For a particular β inverse

- Fit spectrum with scaled background + gaussian peak of known width → number of mono-energetic neutrons in a peak at a given β inverse.
- Find 90% C.L. interval using new ordering principle
- Convert best fit value and 90% C.L. interval to branching ratio:
  # neutrons / (detection efficiency × # Ξ^- stops)

Repeat for other β inverse values

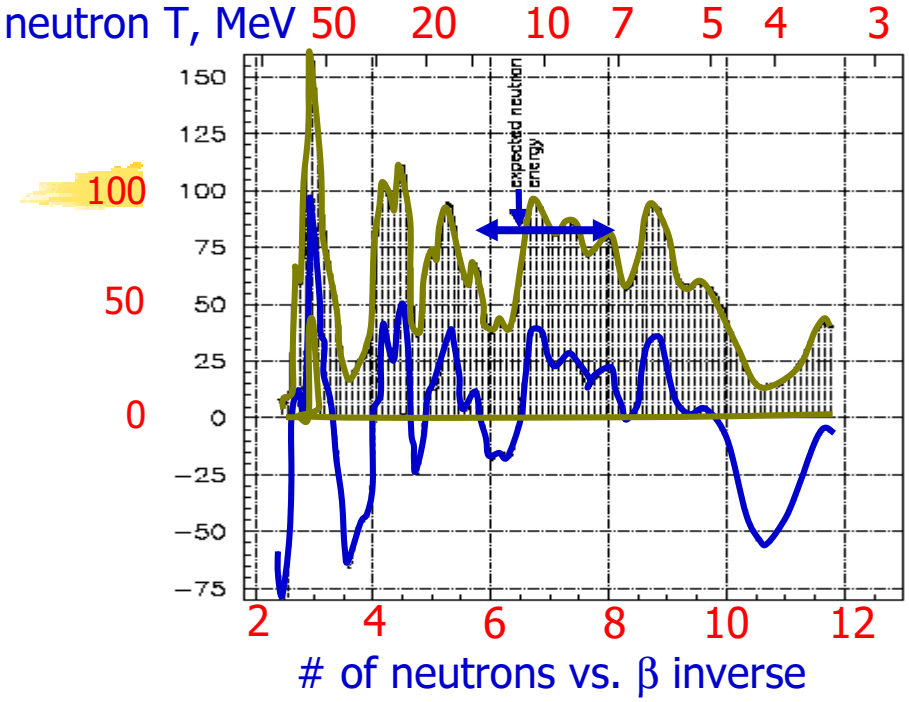


peak width vs. β inverse



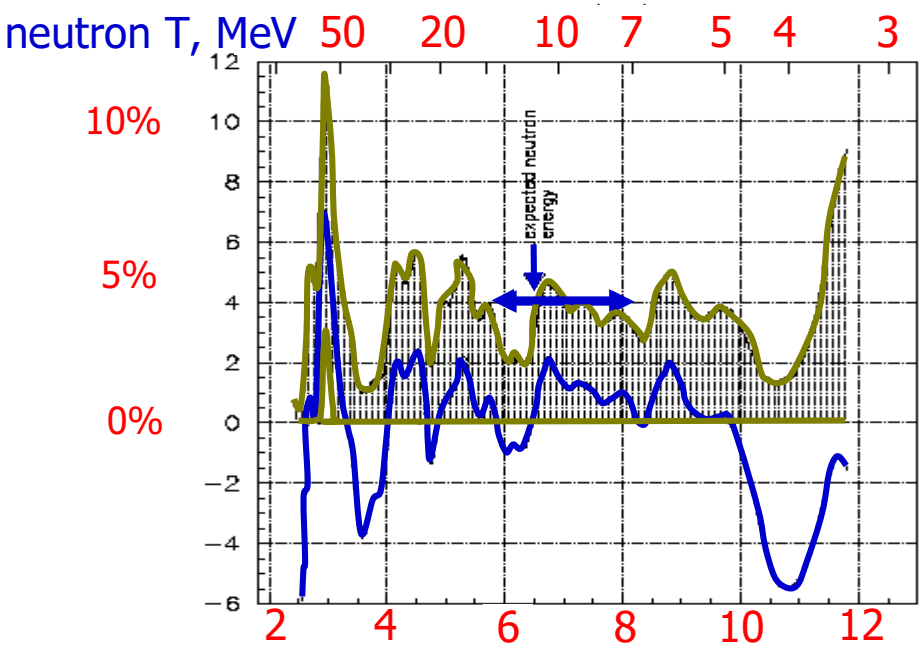
neut. detection eff. vs. β inverse

Double-Λ hypernuclei formation via Ξ^- capture on carbon



# of neutrons vs. β inverse

expected neutron energy for $\Delta B_{\Lambda\Lambda} = 0$ and $(1s_\Lambda 1p_\Lambda)$ T=11.3 MeV



branching ratio vs. β inverse

Direct Ξ and double-Λ hypernuclei production in the (K^-,K^+) reaction

- Missing mass for $^{12}C(K^-,K^+)X$ is invariant mass of X
- Hypernuclei production signal maps to $M < M_{\Xi^-} + M_{^{11}B}$
- Free Ξ^- production maps to $M > M_{\Xi^-} + M_{^{11}B}$

$K^- + {}^{12}C \rightarrow {}^{11}B + \Xi^- + K^+$	E > 0 MeV
$K^- + {}^{12}C \rightarrow {}^{12}_{\Xi}Be + K^+$	E ~ [-20,0]
$K^- + {}^{12}C \rightarrow {}^{12}_{\Lambda\Lambda}Be + K^+$	E ~ -42 MeV
$K^- + {}^{12}C \rightarrow {}^{11}_{\Lambda}Be + K^+ + \Lambda$	E > -27 MeV
$K^- + {}^{12}C \rightarrow {}^{10}Be + K^+ + \Lambda + \Lambda$	E > -17 MeV

- Background suppression - 20% of data survive the cuts
- Normalization - use calibration data taken with CH_2 target and get the normalization scale according to:

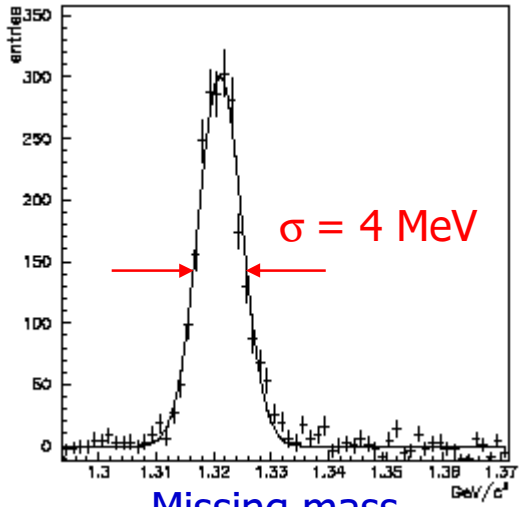
$$\left\langle \frac{d^2\sigma}{d\Omega dE} \right\rangle^C = \left(\frac{dN}{dE}\right)^C_{diam} \frac{\alpha^H}{\alpha^C(E)} \frac{\lambda^H_{CH_2}}{\lambda^C_{CH_2}} \frac{N^C_{CH_2}}{N^C_{diam} N^H_{CH_2}} \left\langle \frac{d\sigma}{d\Omega} \right\rangle^H = A \left(\frac{dN}{dE}\right)^C_{diam};$$

A = (0.66 $\pm$0.05) nb/sr for averaging over θ < 14 deg

- Comparison with theory

Cross section calculated using Distorted Wave Impulse Approximation for $V_{0\Xi}$ = -16 MeV, -20 MeV, folded with 6 MeV resolution and angle-averaged

Direct Ξ and double-Λ hypernuclei production in the (K^-,K^+) reaction

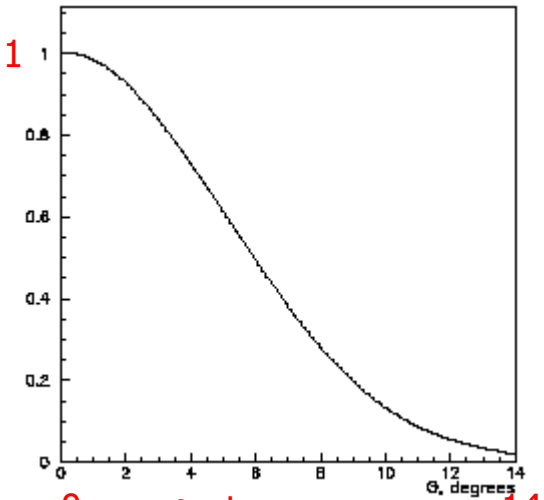


Missing mass

Missing mass resolution for

$K^- + p \rightarrow K^+ + \Xi^-$ σ = 4 MeV

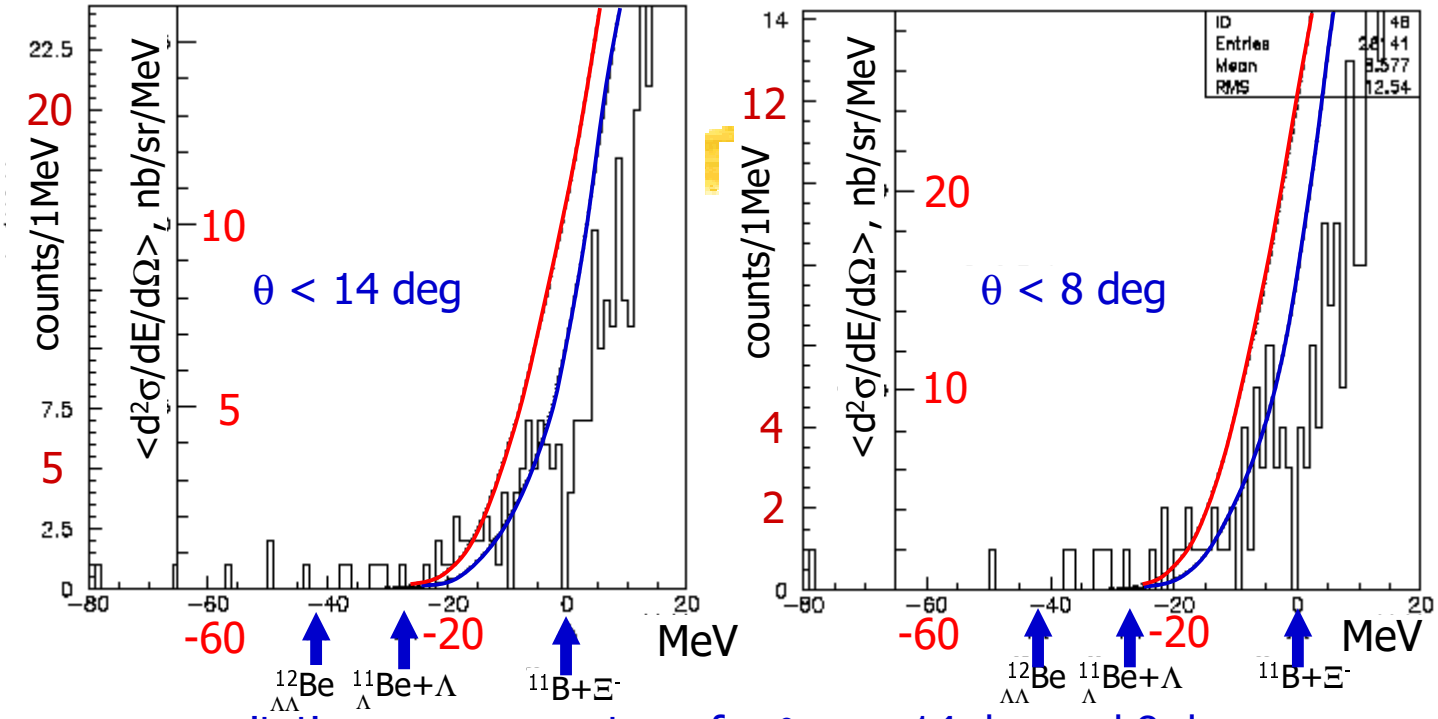
$K^- + {}^{12}C \rightarrow K^+ + X$ σ = 6 MeV



Angular dependence for hypernuclear production cross section

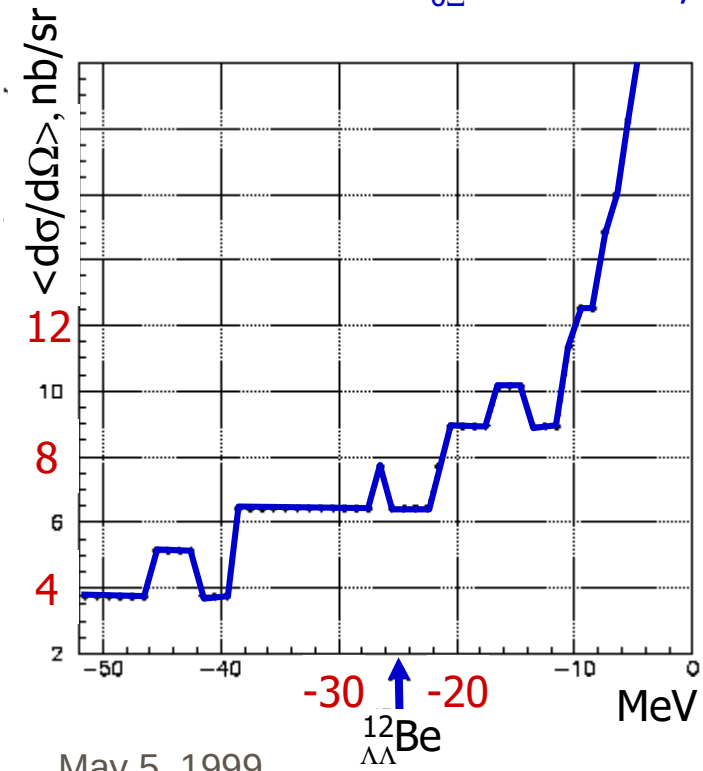
average = 0.25

Direct Ξ and double-Λ hypernuclei production in the (K^-,K^+) reaction



excitation energy spectrum for θ_{max} = 14 deg and 8 deg

blue curve $V_{0\Xi}$ = -16 MeV, red curve $V_{0\Xi}$ = -20 MeV



90% C.L. upper limit on direct double-Λ hypernuclei production cross section vs. $-B_{\Lambda\Lambda}$

for ground state ~ 6.5 nb/sr

for 10 MeV excitation ~ 10.2 nb/sr

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Conclusions

- The branching ratio of the neutron-emission decay channel of double-Λ hypernuclei formation

  $(\Xi^-, {}^{12}C)_{atom} \longrightarrow {}^{12}_{\Lambda\Lambda}B^* + n$

  is at or below 4% at 90% C.L.
- Strong evidence of Ξ hypernuclei existence presented. Data favor $V_{0\Xi} \sim -16$ MeV.
- The direct double-Λ production differential cross section is below 6.5 nb/sr for ground state and 10.2 nb/sr for a 10 MeV excitation.