

Coherent Meson Production in Antinucleon Annihilation on Nuclei

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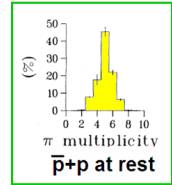


Deutsche
Forschungsgemeinschaft



what has been studied:

- low energy antiproton-nucleus scattering (LEAR)
- energy spectra of antiprotonic atoms
- meson multiplicities



upcoming experiments at the Facility of Antiproton Ion Research

- Anti-**P**roton **AN**ihilation at **DA**rmstadt
- Antiproton-**I**on-**C**ollider



Challenge

Large variety of reactions possible with antiprotons

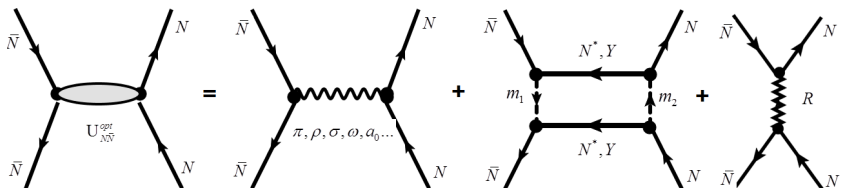
- many possible channels to study
- not only experimentally but also theoretically a challenge!

Tool

- Selection
- Phenomenology



Diagram-classes of $\bar{N}N$ -interactionsn (Born Terms)



Selection

elastic part:

G-parity-transformation of the NN (Paris [1], Bonn [2]) interaction (charge conjugation plus 180° rotation around the y axis in isospin space):

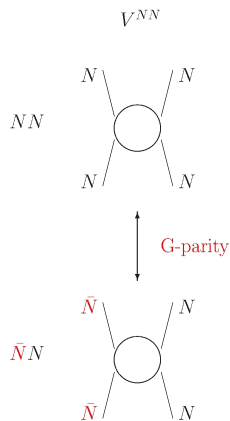
odd G-Parity vertices

$$V_{NN}(\pi, \omega, \delta) = -V_{\bar{N}N}(\pi, \omega, \delta)$$

even G-parity vertices

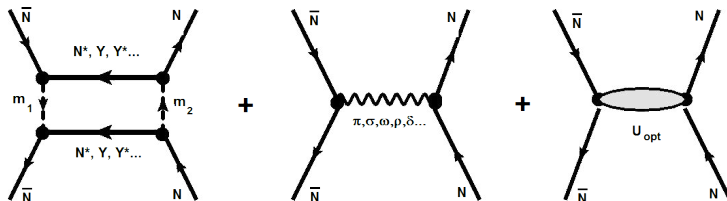
$$V_{NN}(\sigma, \rho, \eta) = V_{\bar{N}N}(\sigma, \rho, \eta)$$

[1] Phys. Rev C 79 (2009) 054001, [2] Phys. Rev. C 51 (1995) 2360



$V_{el}^{\bar{N}N}$

Juelich Model Feynman Graphs



dispersive parts + one meson exchange + optical potential

Phenomenology

Ansatz for the potential:

$$V(r|k) = U(r|k) - iW(r|k) \quad (1)$$

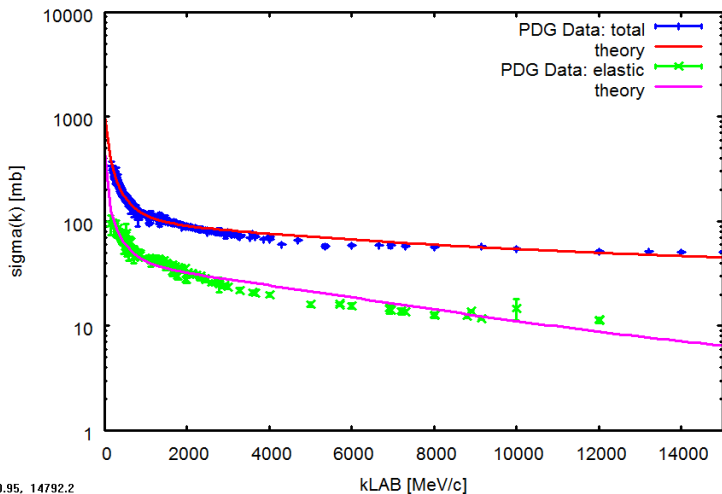
$$U(r|k) = U(k)e^{-r^2/a^2(k)} \quad W(r|k) = W(k)e^{-r^2/b^2(k)}$$

energy dependence:

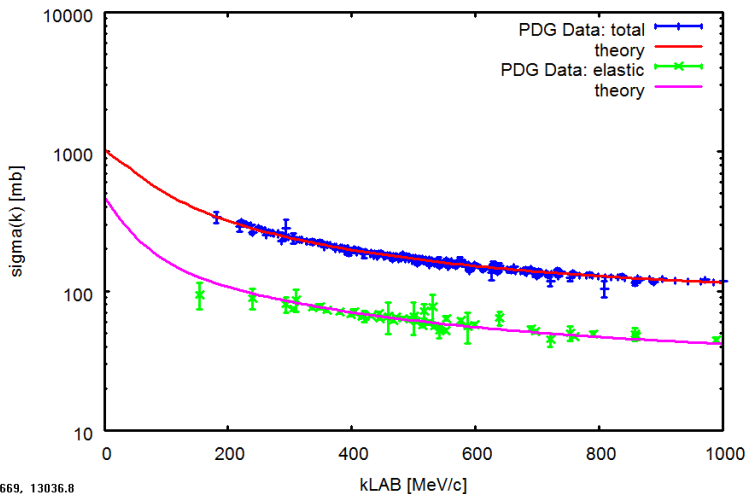
$$U(k) = U_1 f(k) + U_2 (1 - f(k)) \quad (2)$$

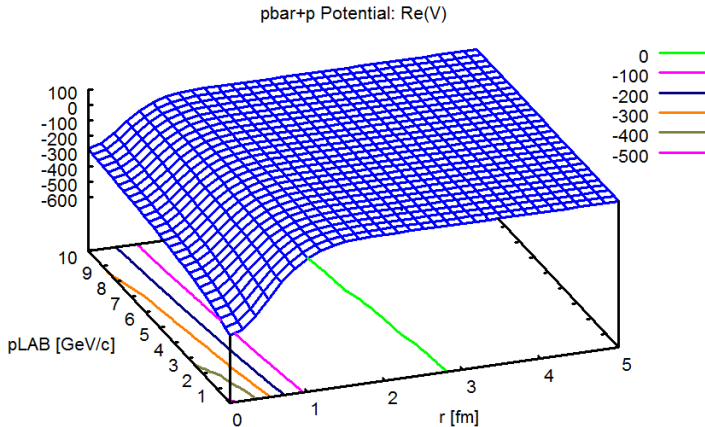
$$W(k) = W_1 f(k) + W_2 (1 - f(k)) \quad (3)$$

$$f(k) = \frac{1}{1 + e^{(k-Q)/q}} \quad (4)$$

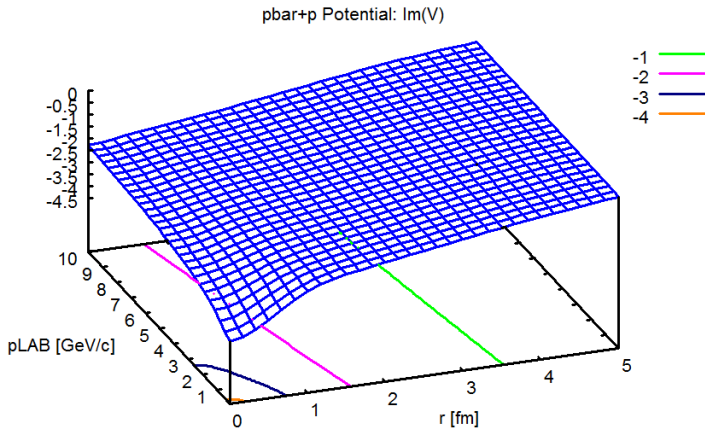


-2890.95, 14792.2





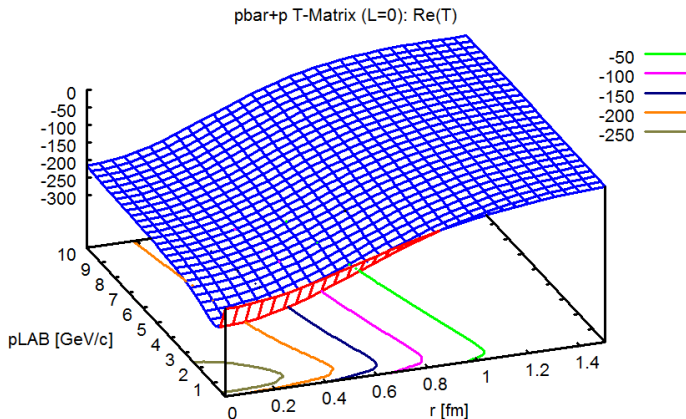
view: 45.0000, 340.000 scale: 1.00000, 1.00000



view: 45.0000, 340.000 scale: 1.00000, 1.00000

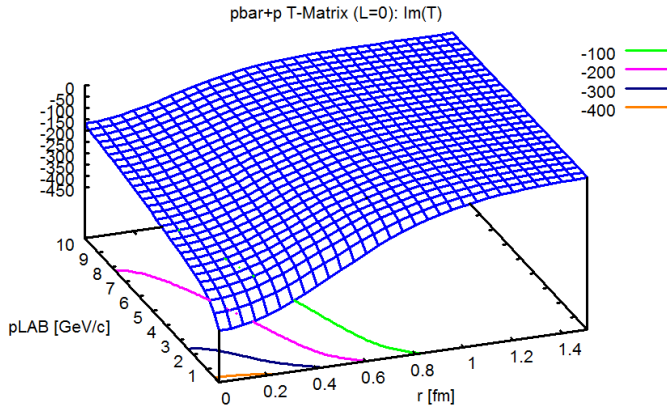
$$T(\rho, z|k) = V(\rho, z|k)e^{iS(\rho, z|k)} \quad S = \phi + i\kappa \quad V = U - iW$$

$$\Re(T) = (U \cos(\phi) + W \sin(\phi)) e^{-\kappa}$$

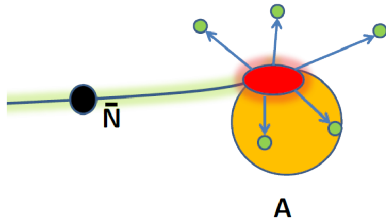


$$T(\rho, z|k) = V(\rho, z|k)e^{iS(\rho, z|k)} \quad S = \phi + i\kappa \quad V = U - iW$$

$$\Im(T) = (U \sin(\phi) - W \cos(\phi)) e^{-\kappa}$$

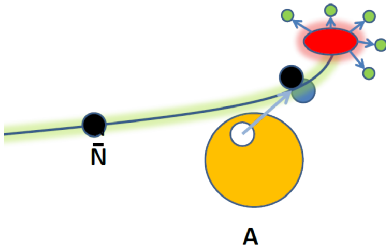


In the Nucleus - Reaction Mechanisms



In-Situ Annihilation

- stopped antinucleon
- annihilation on bound target nucleon(s)
- in-medium meson production



In-Flight Annihilation

- pickup of a target nucleon
- formation of an intermediate $\bar{N}N$ (bound?) state
- subsequent annihilation
- free space meson production

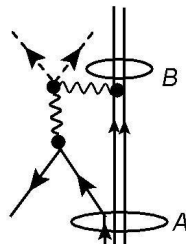
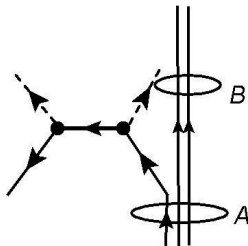
Two-Meson Production on a Nucleus

2-Meson Production Recipe

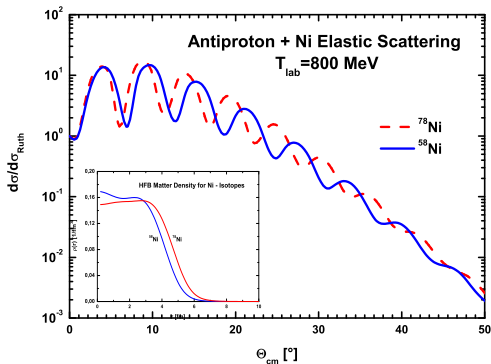
- $\bar{N}A$ interaction
- Production Vertex
- $B \ m_1 \ m_2$ interaction

$$\bar{N} + A \rightarrow m_1 + m_2 + B$$

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$$U_{opt}(\mathbf{r}) = V(r) - iW(r) = \sum_{N=p,n} \int \frac{d^3q}{(2\pi)^3} \rho_N(q) t_{\bar{p}N}(T_{Lab}, q^2) e^{i\mathbf{q}\cdot\mathbf{r}}$$

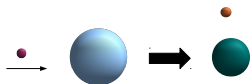


$$\bar{N} + A \rightarrow \pi_1 + \pi_2 + B$$

$$d^9\sigma_{\alpha\beta} = N_{\alpha\beta} \left(\frac{\hbar c}{2\pi} \right)^9 \frac{d^3k_1}{E_1} \frac{d^3k_2}{E_2} \frac{d^3k_B}{E_B} \left| M_{\alpha\beta} \left(\vec{k}_1, \vec{k}_2, \vec{k}_B; \vec{k}_\alpha \right) \right|^2 \\ \delta \left(\vec{k}_1 + \vec{k}_2 + \vec{k}_B \right) \delta \left(E_1 + E_2 + E_B - \sqrt{s} \right)$$

$$M_{\alpha\beta} \approx t_{\bar{N}N \rightarrow 2\pi}(s) \langle \chi_{1\beta}^{(-)} \chi_{2\beta}^{(-)} | \varphi_B | \chi_{\bar{N}A}^{(+)} \rangle \quad (5)$$

$$\varphi_B = \langle B | \psi_N | A \rangle = \sum_i \varphi_i \langle B | a_i | A \rangle \quad (6)$$



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Final State Interaction

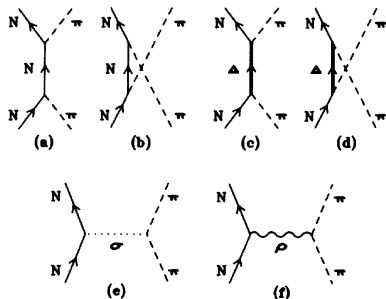
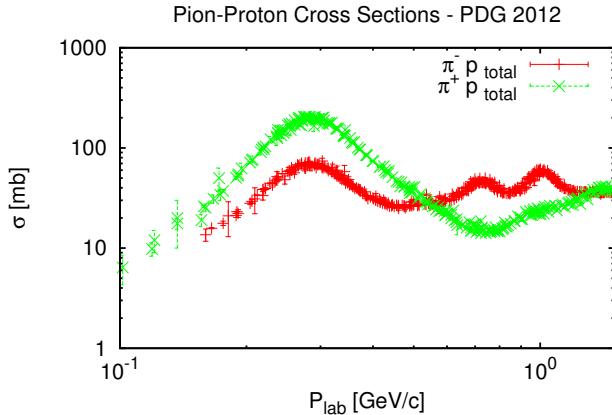


FIG. 1. Direct (a,c) and exchange (b,d) nucleon (N) and delta-isobar (Δ) pole diagrams together with σ , ρ -exchange processes (e,f) used in πN interaction models.

$$U(r) = 4\pi f_{\pi N} \rho(r) + \delta U(\rho^2) \quad (7)$$



Final State Interaction

Pion-nucleus potential of Kisslinger type:

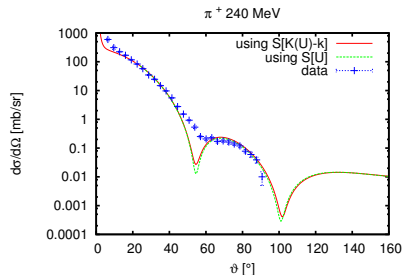
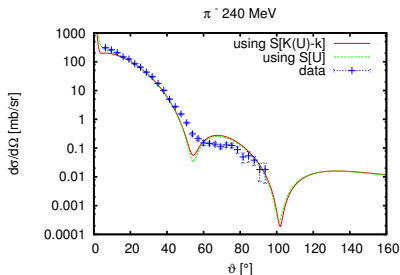
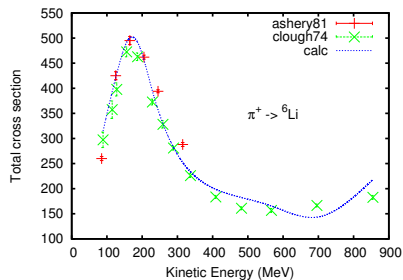
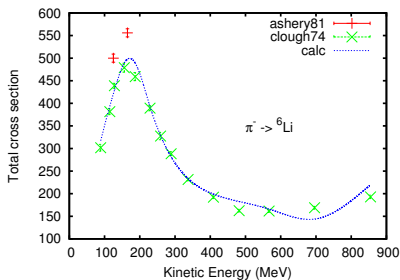
$$[-\nabla^2 - k^2 + U_s + \vec{\partial} U_p \vec{\partial}] \Phi = 0 \quad (8)$$

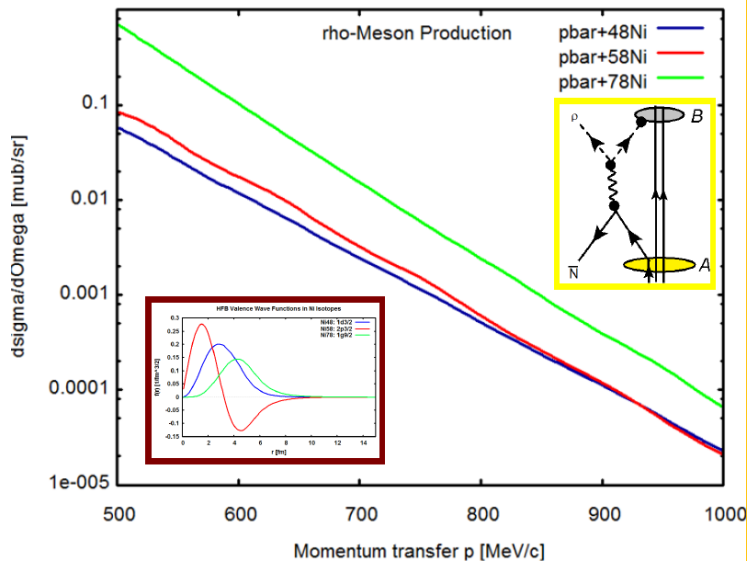
After Krell-Ericson transformation $\Phi = (1 - U_p)^{-1/2} \psi$ the local potential is transformed into (Johnson and Satchler):

$$U_N(r) = \frac{(\hbar c)^2}{2\omega} \left\{ \frac{U_s}{1 - U_p} - \frac{k^2 U_p}{1 - U_p} - \left[\frac{\frac{1}{2} \vec{\nabla}^2 U_p}{1 - U_p} + \left(\frac{\frac{1}{2} \vec{\nabla} U_p}{1 - U_p} \right)^2 \right] \right\} \quad (9)$$

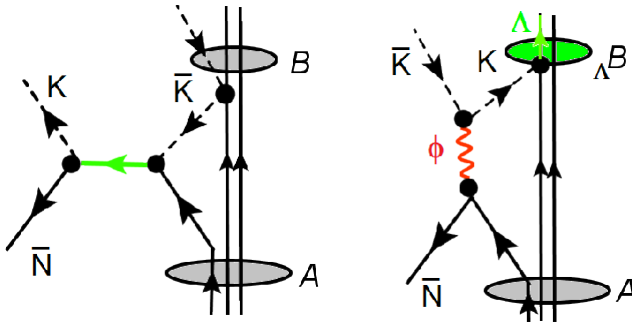
Pion-Nucleus interactions beyond the Δ -resonance require higher resonances.

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New Feature of Nuclear Annihilation: Strangeness Production



Summary

- the $\bar{p}N$ amplitudes are obtained from a (semi-)microscopic model
- as an alternative a phenomenological ansatz is shown
- the $\bar{p}A$ amplitudes are derived in $t\rho$ -approximation by folding the $\bar{p}N$ amplitudes with the *HFB*-nucleus densities
- two types of annihilation in the nucleus: *in-situ* and *in-flight*
- in preparation: antinucleon annihilation for strangeness production

In collaboration with J. Haidenbauer (FZ-Juelich).

Thank you!

Table: Higher $I = 1/2$ resonance parameters, PDF data.

Name (E_r)	Γ [MeV]	R	$I \ J^P$	rank
$N(1440)$	300	0.6	$1/2 \ 1/2^+$	* * *
$N(1535)$	150	0.35	$1/2 \ 1/2^-$	
$N(1650)$	165	0.60	$1/2 \ 1/2^-$	
$N(1675)$	150	0.60	$1/2 \ 5/2^-$	* * *
$N(1680)$	130	0.68	$1/2 \ 5/2^+$	* * *
$N(1700)$	100	0.15	$1/2 \ 3/2^-$	* * *

Table: Higher $I = 3/2$ resonance parameters, PDF data.

Name (E_r)	Γ [MeV]	R	$I \ J^P$	rank
$\Delta(1600)$	350	0.10 – 0.25	$3/2 \ 3/2^+$	* * *
$\Delta(1620)$	145	0.20 – 0.30	$3/2 \ 1/2^-$	* * **
$\Delta(1700)$	300	0.10 – 0.20	$3/2 \ 3/2^-$	* * **
$\Delta(1750)$	300	0.10 – 0.20	$3/2 \ 1/2^+$	*
$\Delta(1900)$	200	0.10 – 0.30	$3/2 \ 1/2^-$	**
$\Delta(1905)$	330	0.09 – 0.15	$3/2 \ 5/2^+$	* * **
$\Delta(1910)$	250	0.15 – 0.30	$3/2 \ 1/2^+$	* * **
$\Delta(1920)$	200	0.05 – 0.20	$3/2 \ 3/2^+$	* * *
$\Delta(1930)$	270	0.05 – 0.15	$3/2 \ 5/2^-$	* * *
$\Delta(1940)$	~ 200	0.05 – 0.15	$3/2 \ 3/2^-$	*
$\Delta(1950)$	285	0.35 – 0.45	$3/2 \ 7/2^+$	* * **
$\Delta(2000)$	~ 200	0.00 – 0.07	$3/2 \ 5/2^+$	**

relation between the optical potential and the scattering amplitude:

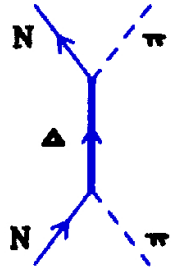
$$U(r) = 4\pi f_{\pi N} \rho(r) \quad (10)$$

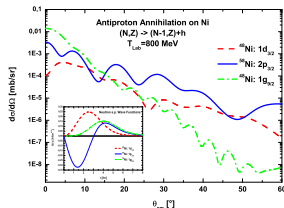
$$U(r) = \underbrace{4\pi f_S \rho(r)}_{U_S} + \underbrace{4\pi 2f^P \frac{\vec{\partial}}{\partial} \rho(r) \frac{\vec{\partial}}{\partial}}_{\frac{\vec{\partial}}{\partial} U_P \frac{\vec{\partial}}{\partial}} \quad (11)$$

$$f^P(k, k') = \frac{\gamma v(k)v(k')}{(E_r - E - i\gamma k^3 [v(k)]^2)} \quad (12)$$

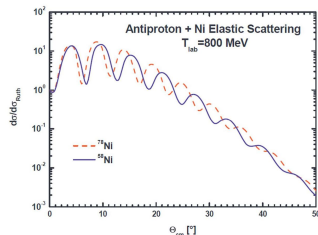
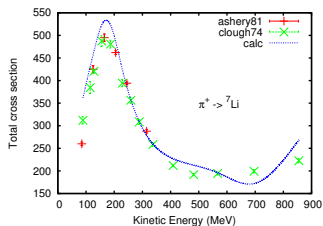
where the form-factor is

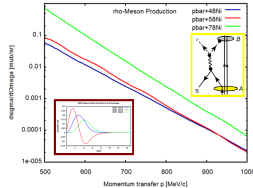
$$v(k) = [1 + \frac{k^2}{\kappa^2}]^{-2}, \quad (13)$$



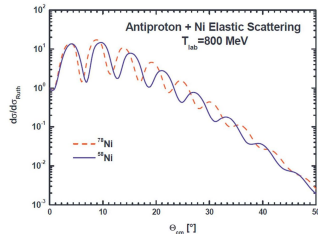
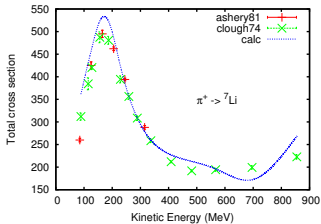


$$M_{\alpha\beta} \approx t_{\overline{N}N \rightarrow 2\pi}(s) \langle \chi_{1\beta}^{(-)} \chi_{2\beta}^{(-)} | \varphi_B | \chi_{\overline{N}A}^{(+)} \rangle \quad (14)$$





$$M_{\alpha\beta} \approx t_{\bar{N}N \rightarrow 2\pi}(s) \langle \chi_{1\beta}^{(-)} \chi_{2\beta}^{(-)} | \varphi_B | \chi_{\bar{N}A}^{(+)} \rangle \quad (15)$$



Phenomenology

Definition of the T -matrix and the transition operator:

$$\hat{T} = (\vec{k}', \vec{k}) = \langle \varphi_{k'} | V | \psi_k^{(+)} \rangle = \langle \varphi_{k'} | T | \varphi_k \rangle \quad (16)$$

assuming a local operator:

$$\hat{T}(k', k) = \int d^3r T(\vec{r}|k) e^{i(\vec{k}-\vec{k}')\cdot\vec{r}} = T(k-k'|k) \quad (17)$$

$$\rightarrow T(r|k) = \int \frac{d^3q}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} T(q|k) \quad (18)$$

**The parameter values derived by the present fit
(simultaneously fitting total and elastic cross sections):**

a1	= 1.09183 ; a2	= 0.625668
b1	= 3.81919 ; b2	= 2.84015
U1	= -352.382 ; U2	= -195.078
W1	= 4.02133 ; W2	= 2.53203
q	= 350.202 ; Q	= 7839.6