

Meson Production in Antinucleon Annihilation on Nuclei

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03.09.2012



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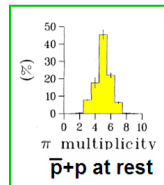
upcoming experiments at the Facility of Antiproton Ion Research

- Anti-**P**roton **AN**ihilation at **D**Armstadt
- **A**ntiproton-**I**on-**C**ollider

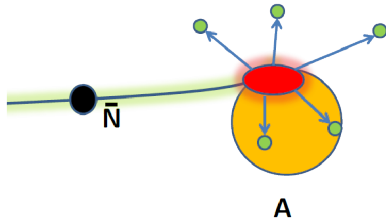


what has been studied:

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

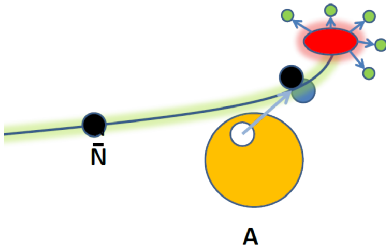


Reaction Mechanisms



In-Situ Annihilation

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



In-Flight Annihilation

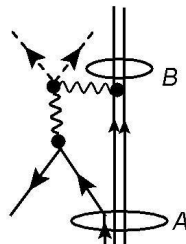
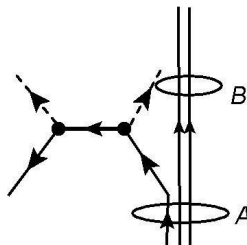
- pickup of a target nucleon
- formation of an intermediate $\bar{N}N$ (bound?) state
- subsequent annihilation
- free space meson production

Two-Meson Production on a Nucleus

2-Meson Production Recipe

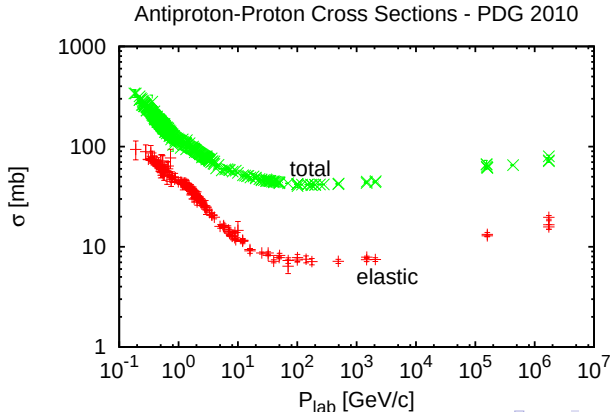
- $\bar{N}A$ interaction
- Production Vertex
- $B \ m_1 \ m_2$ interaction

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



PDG Cross Section

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



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):

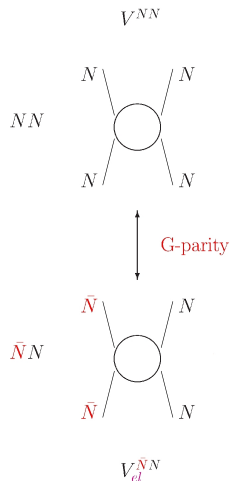
odd G-Parity vertices

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

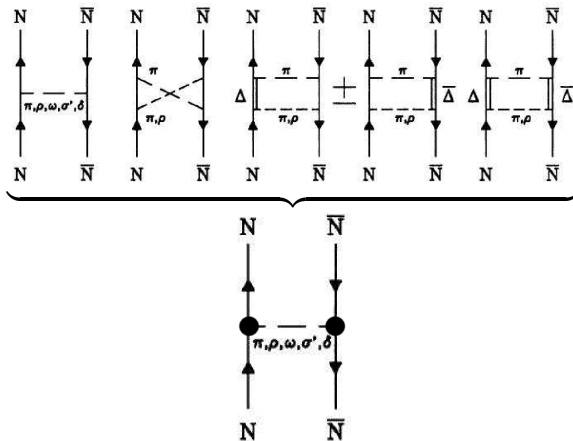
even G-parity vertices

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

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



2-Meson Diagrams Included in Bonn Model (elastic)



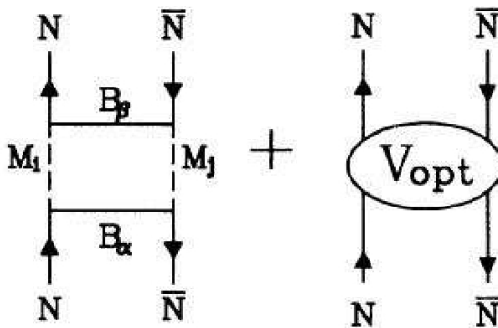
Diagrams Included in Bonn Model (annihilation)

$$V^{N\bar{N} \rightarrow M_i M_j} =$$

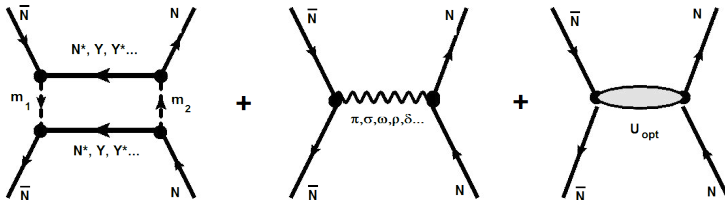
The diagram shows three Feynman diagrams for the annihilation of a nucleon (N) and an antinucleon ($\bar{N}$) into mesons (M_i and M_j). The diagrams are separated by plus signs. The first diagram shows a nucleon (N) and an antinucleon ($\bar{N}$) annihilating into a nucleon (N) and an antinucleon ($\bar{N}$) via a meson (M) exchange. The second diagram shows a nucleon (N) and an antinucleon ($\bar{N}$) annihilating into a nucleon (N) and an antinucleon ($\bar{N}$) via a meson (M) exchange. The third diagram shows a nucleon (N) and an antinucleon ($\bar{N}$) annihilating into a nucleon (N) and an antinucleon ($\bar{N}$) via a meson (M) exchange.

$$M_{i,j} = \pi, \eta, \rho, \omega, f_0, a_0, f_1, a_1, f_2, a_2$$

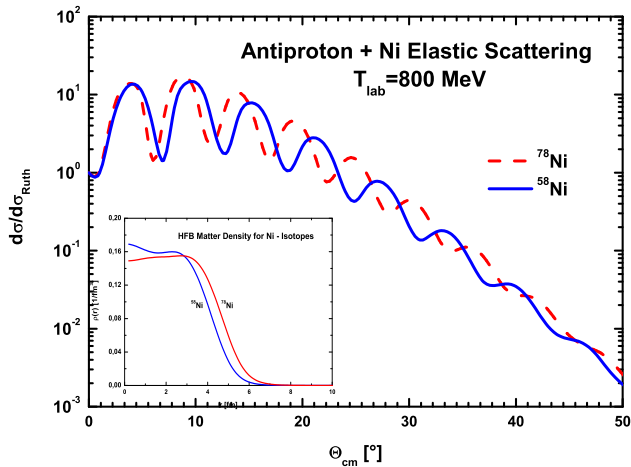
Diagrams Included in Bonn Model (dispersive)



Juelich Model Feynman Graphs



dispersive parts + one meson exchange + optical potential

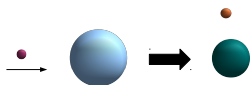


$$\bar{N} + A \rightarrow \pi_1 + \pi_2 + B$$

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

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

$$\varphi_B = \langle B | \psi_N | A \rangle = \sum_i \varphi_i \langle B | a_i | A \rangle \quad (2)$$



S. Lourenco et al., Hyperfine Interactions 209 (2012), 117

Final State Interaction

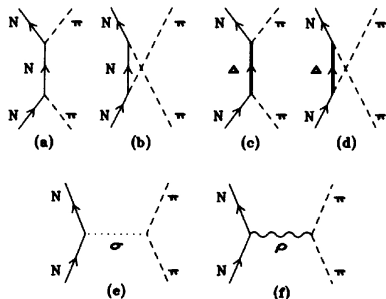


FIG. 1. Direct (a,c) and exchange (b,d) nucleon (N) and delta-isobar (Δ) pole diagrams together with σ , ρ -exchange processes (e,f) used in πN interaction models.

relation between the optical potential and the scattering amplitude:

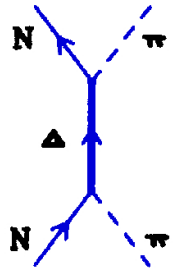
$$U(r) = 4\pi f_{\pi N} \rho(r) \quad (3)$$

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

$$f^P(k, k') = \frac{\gamma v(k)v(k')}{(E_r - E - i\gamma k^3 [v(k)]^2)} \quad (5)$$

where the form-factor is

$$v(k) = \left[1 + \frac{k^2}{\kappa^2}\right]^{-2}, \quad (6)$$



Pion-Proton Cross Sections - PDG 2010

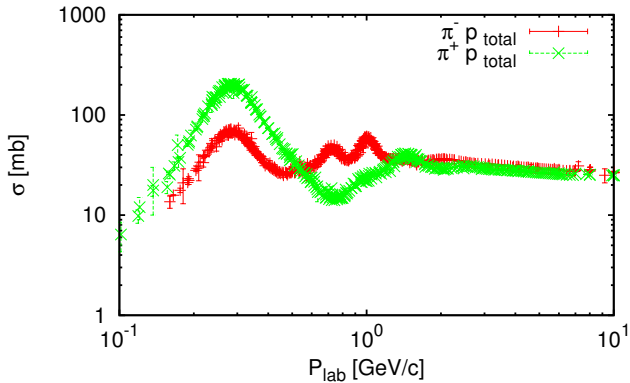


Table: Higher $I = 1/2$ resonance parameters, PDF data.

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	$3/2 \ 5/2^+$	**

Final State Interaction

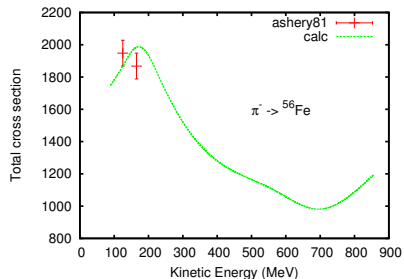
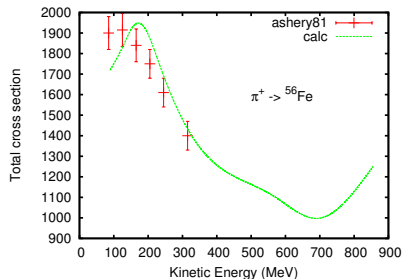
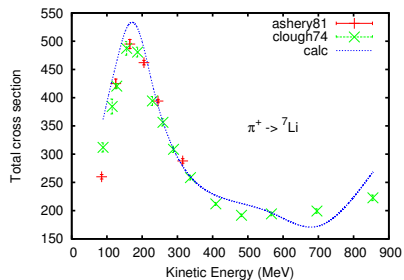
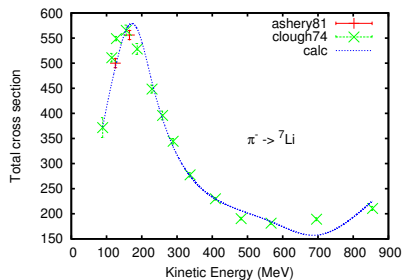
Pion-nucleus potential of Kisslinger type:

$$[-\nabla^2 - k^2 + U_s + \vec{\partial} U_p \vec{\partial}] \Phi = 0 \quad (7)$$

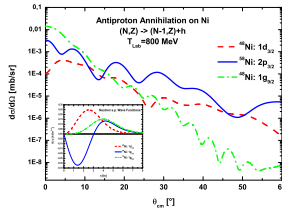
After Krell-Ericson transformation $\Phi = (1 - U_p)^{-1/2} \psi$ the local potential is transformed into (Johnson and Satchler):

$$U_N(r) = \frac{(\hbar c)^2}{2\omega} \left\{ \frac{U_s}{1 - U_p} - \frac{k^2 U_p}{1 - U_p} - \left[\frac{\frac{1}{2} \vec{\nabla}^2 U_p}{1 - U_p} + \left(\frac{\frac{1}{2} \vec{\nabla} U_p}{1 - U_p} \right)^2 \right] \right\} \quad (8)$$

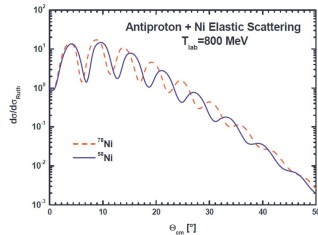
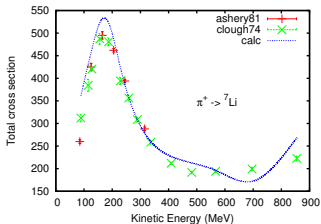
Pion-Nucleus interactions beyond the Δ -resonance require higher resonances.



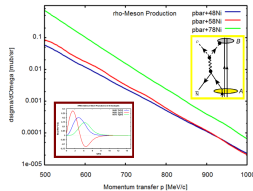
In-Flight Annihilation



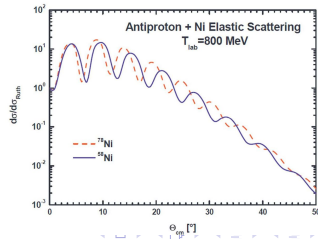
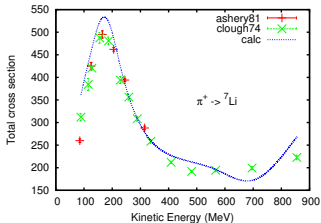
$$M_{\alpha\beta} \approx t_{\overline{N}N \rightarrow 2\pi}(s) \langle \chi_{1\beta}^{(-)} \chi_{2\beta}^{(-)} | \varphi_B | \chi_{\overline{N}A}^{(+)} \rangle \quad (9)$$



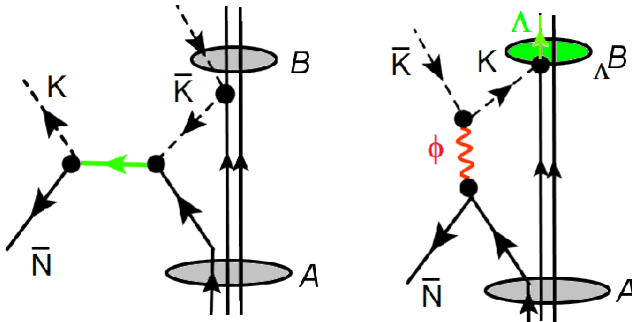
In-Situ Annihilation



$$M_{\alpha\beta} \approx t_{\bar{N}N \rightarrow 2\pi}(s) \langle \chi_{1\beta}^{(-)} \chi_{2\beta}^{(-)} | \varphi_B | \chi_{\bar{N}A}^{(+)} \rangle \quad (10)$$



New Feature of Nuclear Annihilation: Strangeness Production



Summary

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

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