Meson Production in Antinucleon Annihilation on Nuclei

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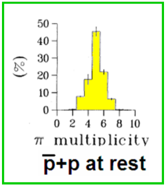
Deutsche Forschungsgemeinschaft
DFG

upcoming experiments at the **F**acility of **A**ntiproton **I**on **R**esearch

- Anti-**P**roton **AN**nihilation at **DA**rmstadt
- **A**ntiproton-**I**on-**C**ollider

what has been studied:

- low energy antiproton-nucleus scattering (Bachelor thesis: Thorsten Steinert)
- energy spectra of antiprotonic atoms (Bachelor thesis: Jan Haas)
- meson multipicities

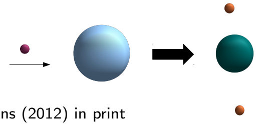


$\overline{N} + A \rightarrow \pi_1 + \pi_2 + B$

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

$$\boxed{M_{\alpha\beta} \approx t_{\overline{N}N\rightarrow 2\pi}(s)\langle\chi^{(-)}_{1\beta}\chi^{(-)}_{2\beta}\left|\varphi_B\right|\chi^{(+)}_{\overline{N}A}\rangle} \quad (1)$$

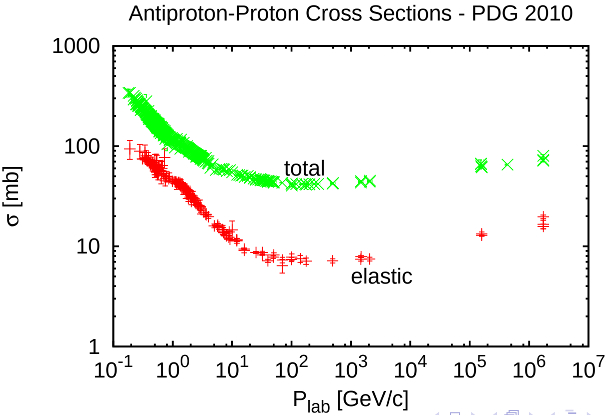
$$\varphi_B = \langle B\left|\psi_N\right|A\rangle = \sum_i \varphi_i\langle B\left|a_i\right|A\rangle \quad (2)$$



S. Lourenco et al., Hyperfine Interactions (2012) in print

PDG Cross Section

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


Antiproton-Proton Cross Sections - PDG 2010

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):

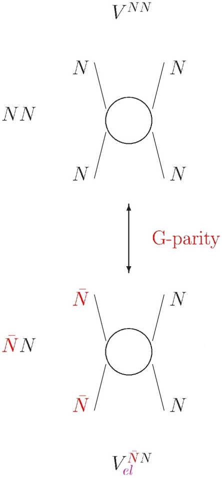
odd G-Parity vertices

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

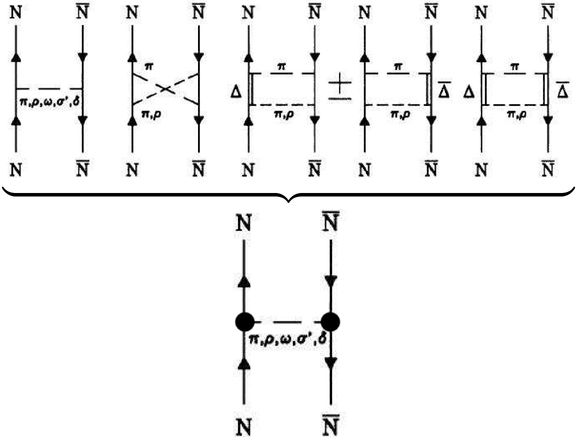
even G-parity vertices

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

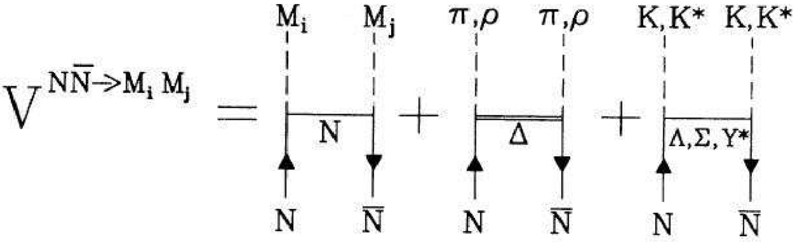
[1] Phys. Rev C 79 (2009) 054001, [2] Phys. Rev. C 51 (1995) 2360



2-Meson Diagrams Included in Bonn Model (elastic)

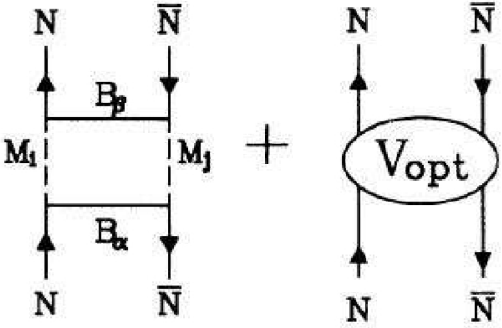


Diagrams Included in Bonn Model (annihilation)



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

Diagrams Included in Bonn Model (dispersive)

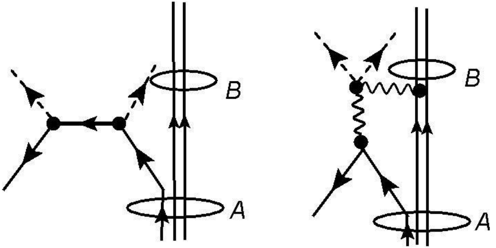


2-Meson Production on a Nucleus

2-Meson Production Recipe

- $\bar{N}A$ interaction
- Production Vertex
- Bm_1m_2 interaction

$$\bar{N} + A \rightarrow m_1 + m_2 + B \quad (3)$$



Final State Interaction

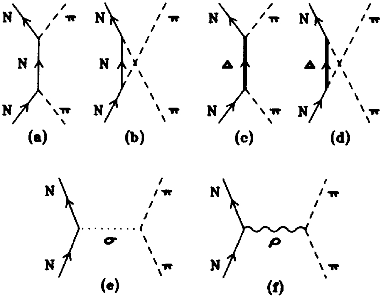


FIG. 1. Direct (a,c) and exchange (b,d) nucleon (N) and delta-isobar (Δ) pole diagrams together with σ, ρ-exchange processes (e,f) used in πN interaction models.

Final State Interaction

Pion-nucleus potential of Kisslinger type:

$$[-\Delta - k^2 + U_s + \overrightarrow{\partial}\ U_p\ \overrightarrow{\partial}\ ]\Phi = 0 \tag{4}$$

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

$$U_N(r) = \frac{(\hbar c)^2}{2\omega}\left\{\frac{U_s}{1-U_p} - \frac{k^2 U_p}{1-U_p} - \left[\frac{\frac{1}{2}\vec{\nabla}^2 U_p}{1-U_p} + \left(\frac{\frac{1}{2}\vec{\nabla} U_p}{1-U_p}\right)^2\right]\right\} \tag{5}$$

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

relation between the optical potential and the scattering amplitude:

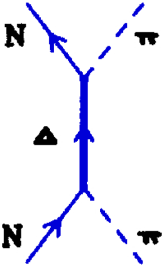
$$U(r) = 4\pi f_{\pi N}\rho(r) \tag{6}$$

$$U(r) = \underbrace{4\pi\ f_S\ \rho(r)}_{U_S} + \underbrace{4\pi\ 2f^P\ \overrightarrow{\partial}\ \rho(r)\ \overrightarrow{\partial}}_{\overrightarrow{\partial}\ U_p\ \overrightarrow{\partial}} \tag{7}$$

$$f^P(k,k') = \frac{\gamma\ v(k)v(k')}{(E_r - E - i\gamma k^3\ [v(k)]^2)} \tag{8}$$

where the form-factor is

$$v(k) = [1 + \frac{k^2}{\kappa^2}]^{-2}, \tag{9}$$



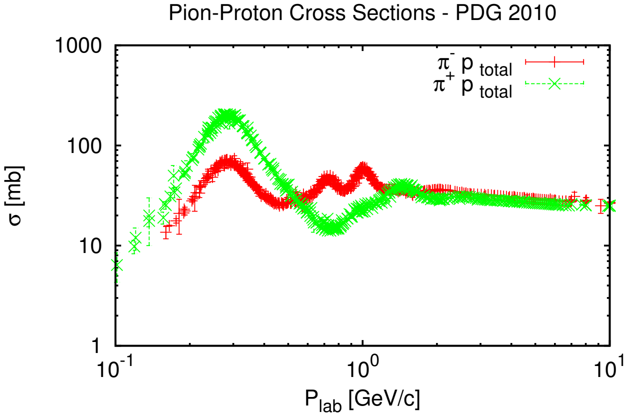
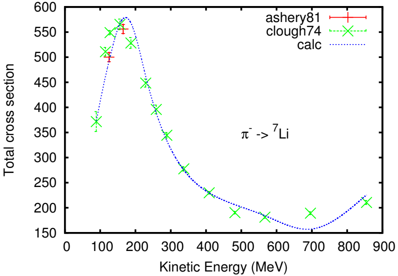

Pion-Proton Cross Sections - PDG 2010
$\pi^- p$ total
$\pi^+ p$ total
1000
100
10
1
σ [mb]
10^{-1}
10^0
10^1
P_{lab} [GeV/c]

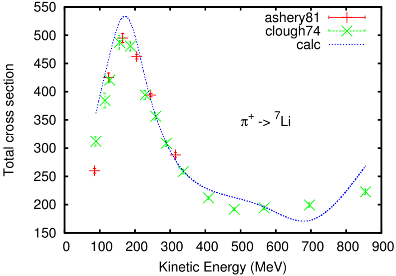
Table: Higher $I = 1/2$ resonance parameters, PDF data.

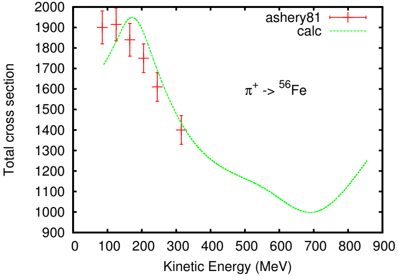
Name (E_r)	Γ [MeV]	R	$I \quad J^P$	rank
$N(1440)$	300	0.6	$1/2\ 1/2^+$	$***\,*$
$N(1535)$	150	0.35	$1/2\ 1/2^-$	
$N(1650)$	165	0.60	$1/2\ 1/2^-$	
$N(1675)$	150	0.60	$1/2\ 5/2^-$	$***\,*$
$N(1680)$	130	0.68	$1/2\ 5/2^+$	$***\,*$
$N(1700)$	100	0.15	$1/2\ 3/2^-$	$***$

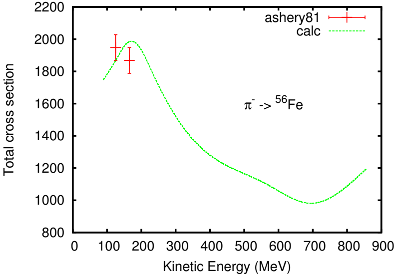
Table: Higher $I = 3/2$ resonance parameters, PDF data.

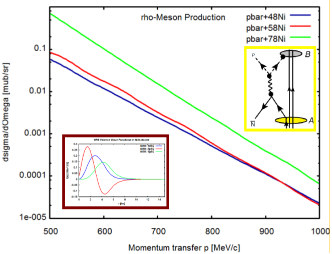
Name (E_r)	Γ [MeV]	R	$I \;\; J^P$	rank
$\Delta(1600)$	350	$0.10 - 0.25$	$3/2\ 3/2^+$	$* * *$
$\Delta(1620)$	145	$0.20 - 0.30$	$3/2\ 1/2^-$	$* * **$
$\Delta(1700)$	300	$0.10 - 0.20$	$3/2\ 3/2^-$	$* * **$
$\Delta(1750)$	300	$0.10 - 0.20$	$3/2\ 1/2^+$	$*$
$\Delta(1900)$	200	$0.10 - 0.30$	$3/2\ 1/2^-$	$**$
$\Delta(1905)$	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	$0.00 - 0.07$	$3/2\ 5/2^+$	$**$


ashery81
clough74
calc
$\pi^- \to {}^7$Li
Total cross section
Kinetic Energy (MeV)
600
550
500
450
400
350
300
250
200
150
0
100
200
300
400
500
600
700
800
900

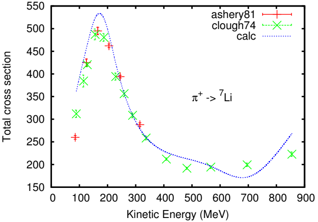

ashery81
clough74
calc
$\pi^+ \to {}^7$Li
Total cross section
Kinetic Energy (MeV)
550
500
450
400
350
300
250
200
150
0
100
200
300
400
500
600
700
800
900

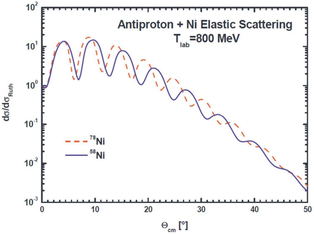

ashery81
calc
$\pi^+ \to {}^{56}$Fe
Total cross section
Kinetic Energy (MeV)
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
0
100
200
300
400
500
600
700
800
900


ashery81
calc
$\pi^- \to {}^{56}$Fe
Total cross section
Kinetic Energy (MeV)
2200
2000
1800
1600
1400
1200
1000
800
0
100
200
300
400
500
600
700
800
900

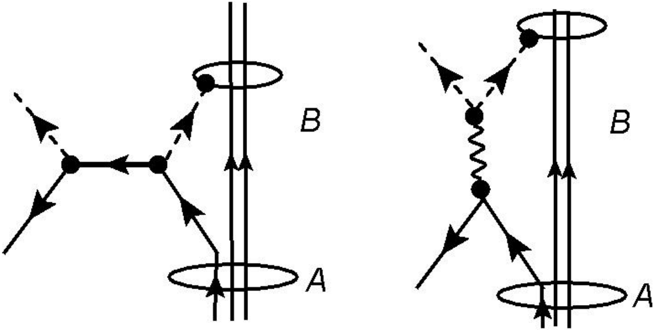


$$\boxed{M_{\alpha\beta} \approx t_{\overline{N}N\to 2\pi}(s)\langle \chi^{(-)}_{1\beta}\chi^{(-)}_{2\beta}\,|\varphi_B|\,\chi^{(+)}_{\overline{N}A}\rangle} \tag{10}$$





New Feature of Nuclear Annihilation: Single Meson Production



Summary

- 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 progress: meson production as probe for nuclear spectroscopy

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