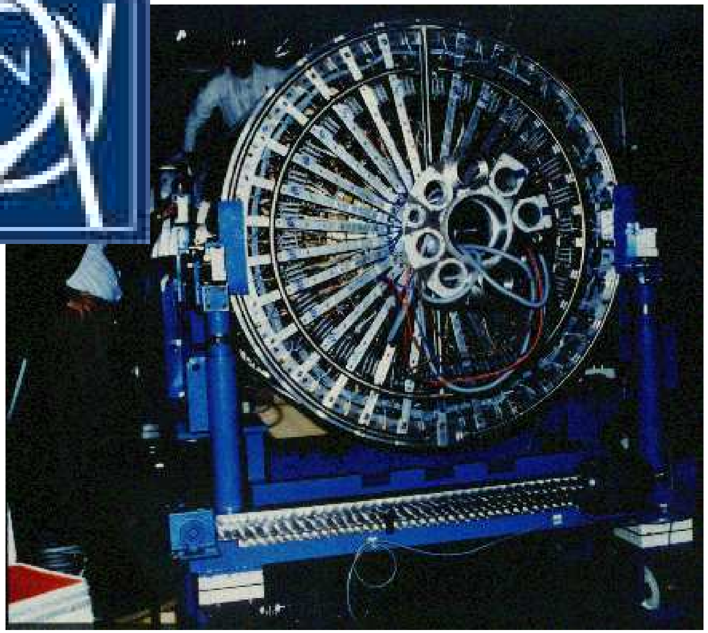
Test of $N\overline{N}$ – Potential Models:

Isospin relations in $\overline{p}d$ annihilations at rest and search for quasinuclear bound states with the Crystal–Barrel Detector

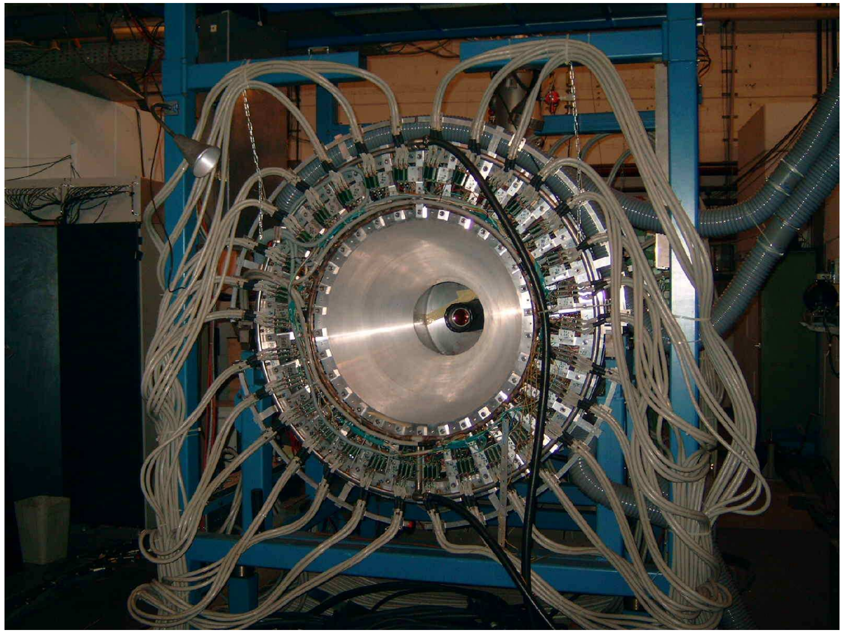
- Nucleon–Antinucleon Interaction
  - Atomic Cascade of the Protonium Atom
  - Meson–Exchange Potentials
- Predictions of $N\overline{N}$ Potential Models (Resurrection of Bound States ?):
  1. Fine structure of the atomic $p\overline{p}$ spectrum
  2. Isospin decomposition of the $p\overline{p}$ wave function
  3. Observation of ρ-ω interference:
     - $p\overline{p} \rightarrow \pi^+\pi^-\eta$, $p\overline{p} \rightarrow \pi^+\pi^-\pi^0$ and e^+e^- annihilation
  4. Search for quasinuclear $N\overline{N}$ bound states
- Summary and Outlook

Spectroscopy with the Crystal–Barrel Detector



2000 - present (University of Bonn)

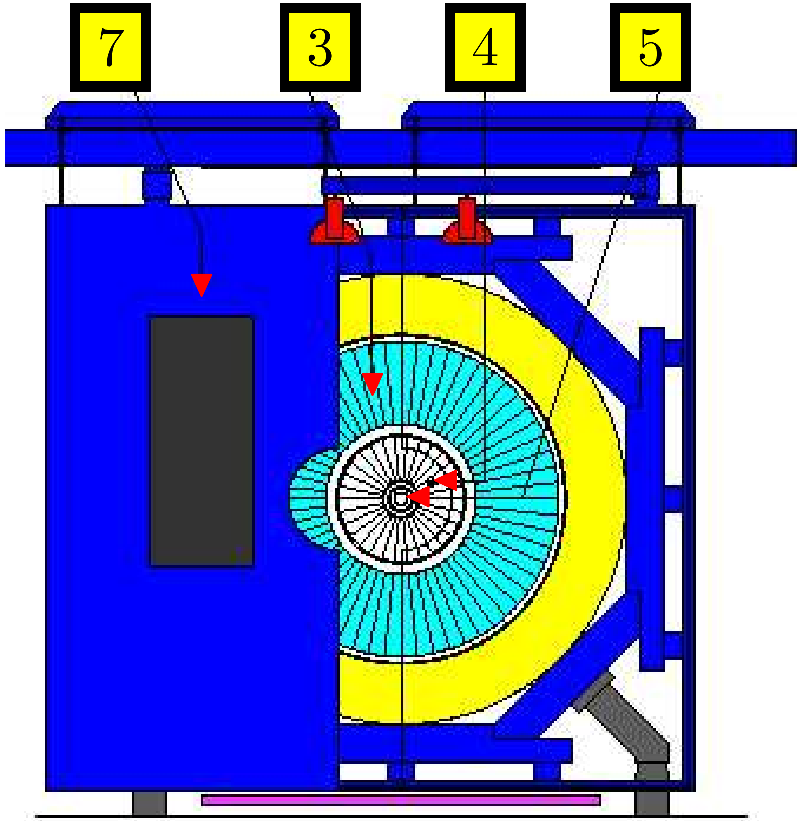
- Photoproduction experiments at ELSA
  ⇒ Spectroscopy of light baryons
  (... and mesons)

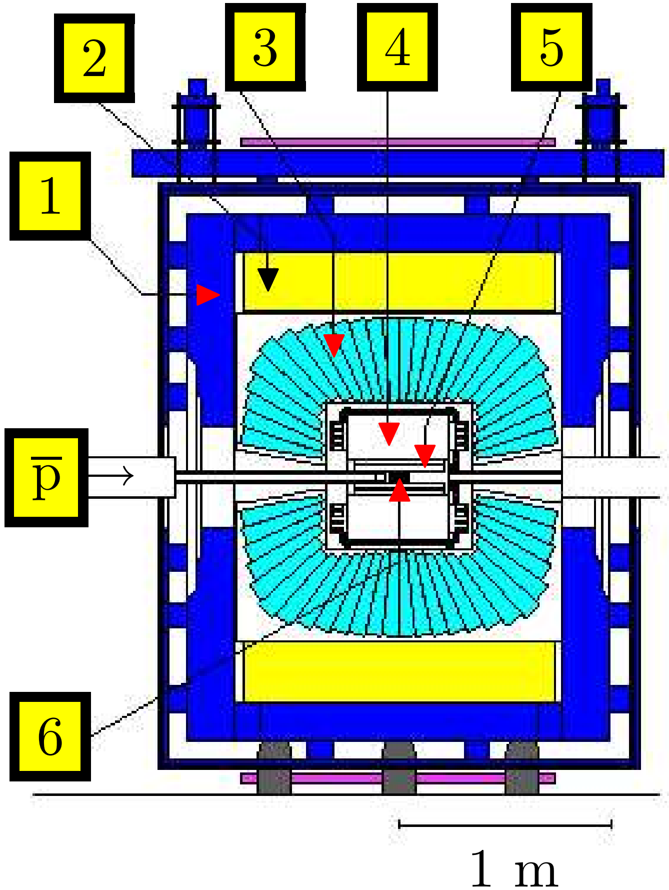


1989 - 1996 (at LEAR/CERN)

- Investigation of $\bar{p}p$ and $\bar{p}d$ annihilations
  ⇒ Annihilation dynamics in the non-perturbative regime of QCD
  ⇒ Search for *baryonium* ($\bar{p}p$ bound states)
- Spectroscopy of light mesons

The Crystal–Barrel Detector at LEAR





(1) magnet yoke

(2) magnet coils

(3) CsI barrel calorimeter

(4) jet drift chamber (JDC)

(5) proportional wire chamber

(6) target (liquid H_2, deuterium)

(7) one half of the endplate

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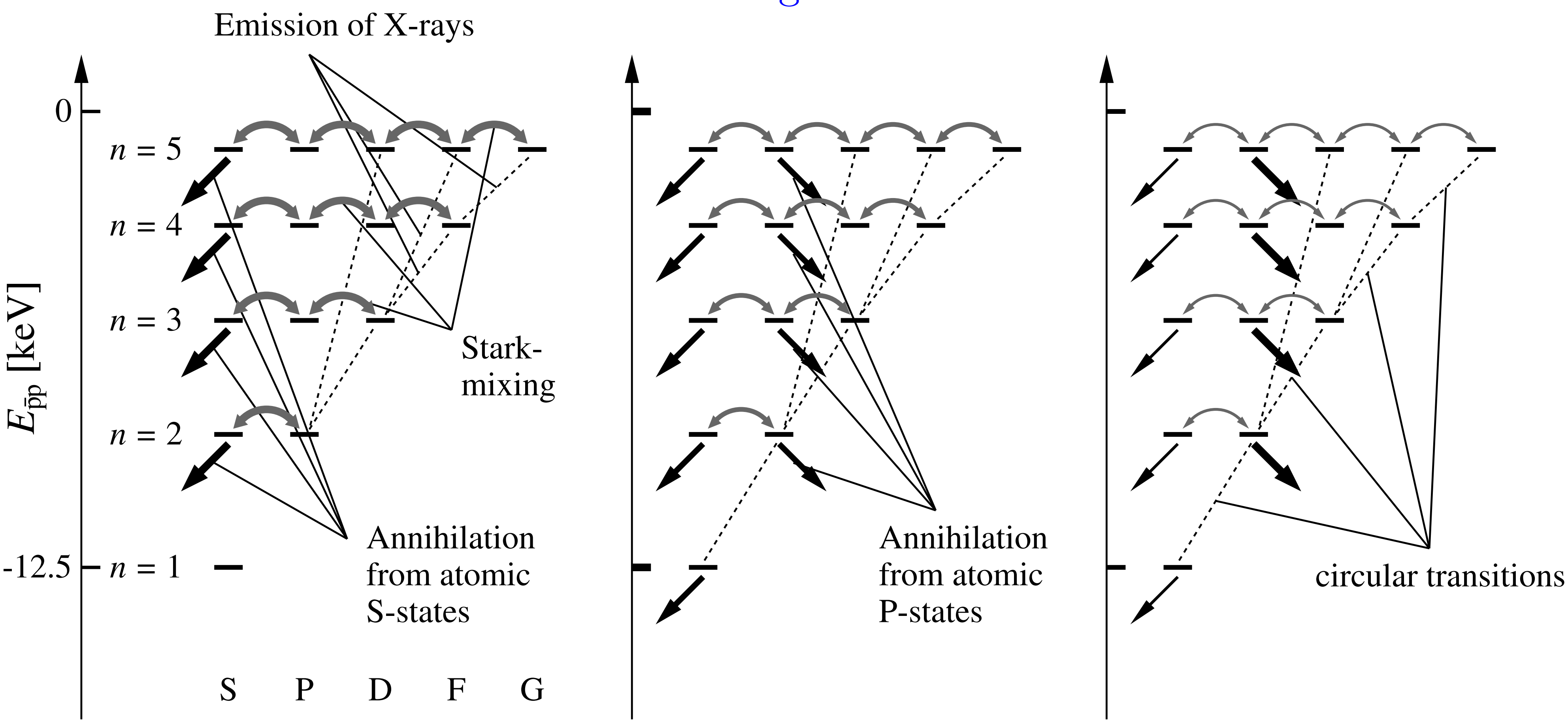
The Atomic Cascade of the Protonium Atom

$\overline{\mathrm{p}} + \mathrm{H}_2 \rightarrow \boxed{\overline{\mathrm{p}}\mathrm{p}} + \mathrm{H} + e^-$

Atomic Cascade $(n \approx 30, l \approx \frac{n}{2}) \rightarrow (n < 30, l \leq 2)$:

- Electromagnetic Transitions
- Auger Effect
- Chemical Effects



(a) (b) (c)

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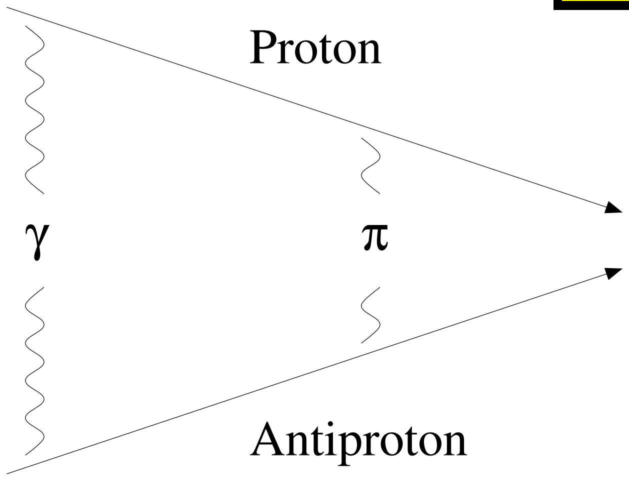
The $N\overline{N}$ Interaction



Description of wave function by potentials:

- Coulomb Potential
- OBEP

Extrapolation of OBEP to small distances:
(OBEP: **O**ne **B**oson **E**xchange **P**otential)

- π Exchange responsible for $|p\overline{p}\rangle \rightarrow |n\overline{n}\rangle$
  $\Rightarrow$ $n\overline{n}$ contribution to the protonium wave function
- Formation of quasinuclearer bound states:
  - First predictions in 1949 before the discovery of the antiproton (Fermi/Yang)
  - Precise calculations in 1960/1970
  - Description of meson spectrum by $N\overline{N}$ bound states (π, ρ, etc.)

Concept of $\mathrm{N\overline{N}}$ Potential Models

NN and $\mathrm{N\overline{N}}$ Interaction:

- Exchange of the same mesons
- Sign change in potential (G Parity)

$$\Rightarrow \quad \mathrm{V(NN)}(r) = \sum_M V_M(r) \;\rightarrow\; \mathrm{V(N\overline{N})}(r) = \sum_M G_M \; V_M(r)$$

NN interaction repulsive → Pauli Principle

⇓

$\mathrm{N\overline{N}}$ interaction dominated by annihilation

- **NN Interaction:**
  No bound state
  (only loosely bound Deuteron)
- **$\mathrm{N\overline{N}}$ Interaction:**
  - Strongly attractive ($r \lesssim 0.5$ fm)
  - Formation of bound states ($M < 2m$) and resonances ($M > 2m$)

Analogy:
Positronium (e^+e^-)

C conjugation transforms $e^- - e^-$ and $e^- - e^+$ into each other

- Charge conjugation transforms a particle into the corresponding antiparticle
  $\Rightarrow$ Only neutral particles can be eigenstates ...
- G parity is a mixture of charge conjugation and rotation of isospin
  $\Rightarrow$ Application to non–neutral systems ...

Protonium: Energy Spectrum

Schrödinger Equation:

($V = V^C$, $\mu = \frac{m_1 m_2}{m_1 + m_2}$)

- $E_n(\bar{\mathrm{p}}\mathrm{p}) = -12.491 \cdot \frac{1}{n^2}$ keV
- $E_n(\bar{\mathrm{p}}\mathrm{d}) = -16.653 \cdot \frac{1}{n^2}$ keV

  \+ QED corrections

  and relativistic effects

	DR1	DR2	KW	Experiment
$\Delta_{1\mathrm{S}}$	0.71	0.76	0.71	0.73 ± 0.03 keV
$\Gamma_{1\mathrm{S}}$	0.93	0.95	1.05	1.06 ± 0.08 meV
$\Gamma_{^3\mathrm{P}_0}$	114	80	96	120 ± 25 meV
$\Gamma_{^3\mathrm{P}_2,^3\mathrm{P}_1,^1\mathrm{P}_1}$	26	27	29.5	30.5 ± 2.0 meV
$\Gamma_{^3\mathrm{P}_1}$	26	28	26	51 ± 18 meV

Principle quantum number n small: $V = V^C + V^{\mathrm{p}\bar{\mathrm{p}}}$

- Broadening and shift of low–energy levels
  - Only very small descrepancies between models for $(\Delta E, \Gamma)$
  - Good agreement with data

Isospin Structure of the $\mathrm{p\overline{p}}$ Wave Function (1)

Description in potential model by coupled Schrödinger Equation:

$$H\Psi = E\Psi \qquad \text{mit} \qquad \Psi = \begin{pmatrix} \Psi_{\mathrm{p}} \\ \Psi_{\mathrm{n}} \end{pmatrix} \equiv \begin{pmatrix} \Psi(\mathrm{\overline{p}p}) \\ \Psi(\mathrm{\overline{n}n}) \end{pmatrix}$$

$$H = T + V = \begin{pmatrix} \frac{p^2}{2m} & 0 \\ 0 & \frac{p^2}{2m} \end{pmatrix} + \begin{pmatrix} V_c + V_0 & V_{\mathrm{pn}} \\ V_{\mathrm{np}} & 2\delta m + V_0 \end{pmatrix}$$

$\Rightarrow$ Mixture of $I = 0$ and $I = 1$ components of Isospin (ISI)

$$|\mathrm{p\overline{p}}(r)\rangle = \frac{1}{\sqrt{2}} \cdot \Big(a(r)|I = 0, I_3 = 0\rangle + b(r)|I = 1, I_3 = 0\rangle \Big)$$

- $a(r) = b(r) = 1$
  (without interaction in the initial state)
- $|a(r)|^2 + |b(r)|^2 = 2$

Isospin Structure of the $p\bar{p}$ Wave Function (2)

Determination of b^2 using branching ratios:

$$\text{e.g.}\quad {}^3S_1:\quad BR(\bar{p}d \rightarrow \pi^- \omega p) = \frac{1}{2} T^2_{\pi\omega} \qquad (|\bar{p}n\rangle = |I=1, I_3=-1\rangle)$$

$$BR(\bar{p}d \rightarrow \pi^0 \omega n) = \frac{1}{4} b^2 T^2_{\pi\omega} \qquad (|\bar{p}p\rangle \text{ involves } I=0)$$

$$BR(\bar{p}p \rightarrow \pi^0 \omega) = \frac{1}{2} b^2 T^2_{\pi\omega}$$

Results of different channels:

- ${}^3S_1$: $\pi\omega$ branching ratio
- ${}^1S_0$: $\pi\rho$ branching ratio

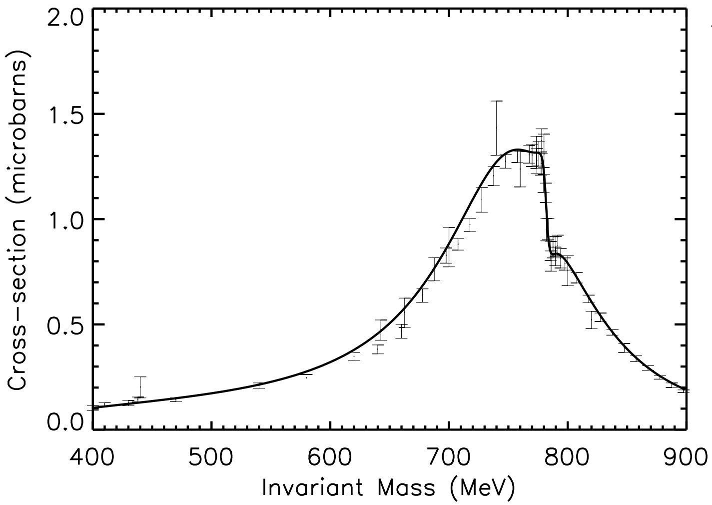
  $\Rightarrow$ ISI not necessary to describe data (but not excluded)
- ${}^3P_0$: $\pi\eta\,(\eta')$ - branching ratios

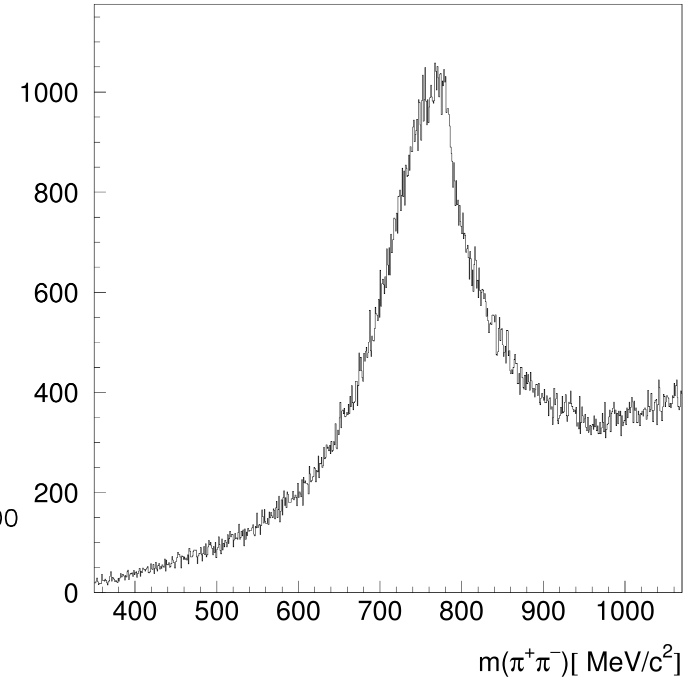
  $\Rightarrow$ In contradiction with potential models
  ($b^2_{\text{exp}} \gg b^2_{\text{theo}}$)

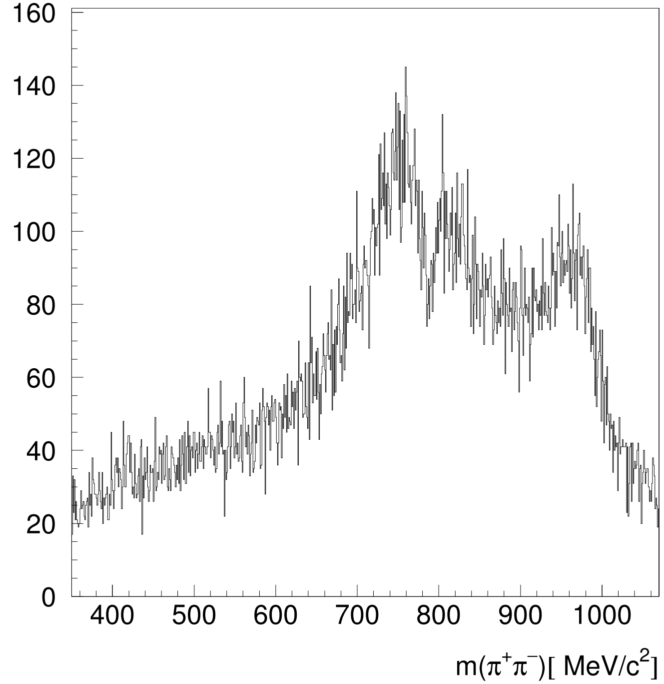
ρ-ω–Interference

Isospin invariance is broken

- ρ and ω are not isospin eigenstates $\Rightarrow$ ρ-ω interference







ω/ρ production ratios

e^+e^--Annihilation: $\sim 1/9$ $\quad$ $p\bar{p} \rightarrow \pi^+\pi^-\pi^0$: $\sim 1/3$ $\quad$ $p\bar{p} \rightarrow \pi^+\pi^-\eta$: $\sim 4/1$

$\Rightarrow$ No additional phase in $\bar{p}p$ annihilation between isovector and isoscalar component!

$N\bar{N}$ bound states

Quantitative Calculation of energy levels:

⇒ Schrödinger Equation with $V(N\bar{N})(r)$ (e. g. : Paris - Potential)

Large number of bound states at $N\bar{N}$ threshold:

- Exact prediction of energy levels difficult (model dependent)
- Order of levels only weakly model dependent

Experimentel evidences ?

- $f_2(1565)$ interpreted as $^{13}P_2$ - $^{13}F_2$
- $N\bar{N}(1870) \rightarrow 5\pi$ (Asterix Data) (Interpretation as $^{13}P_0$)
- Reports on $N\bar{N}$ (2020) resonance
- $J/\psi \rightarrow \gamma\, p\bar{p}$ at BES II (HADRON 2003) ($m \approx 1859\,^{+3}_{-10}\,^{+3}_{-25}$ MeV/c^2)

⇒ Broadening of states due to annihilation (experimentally not observable ?)

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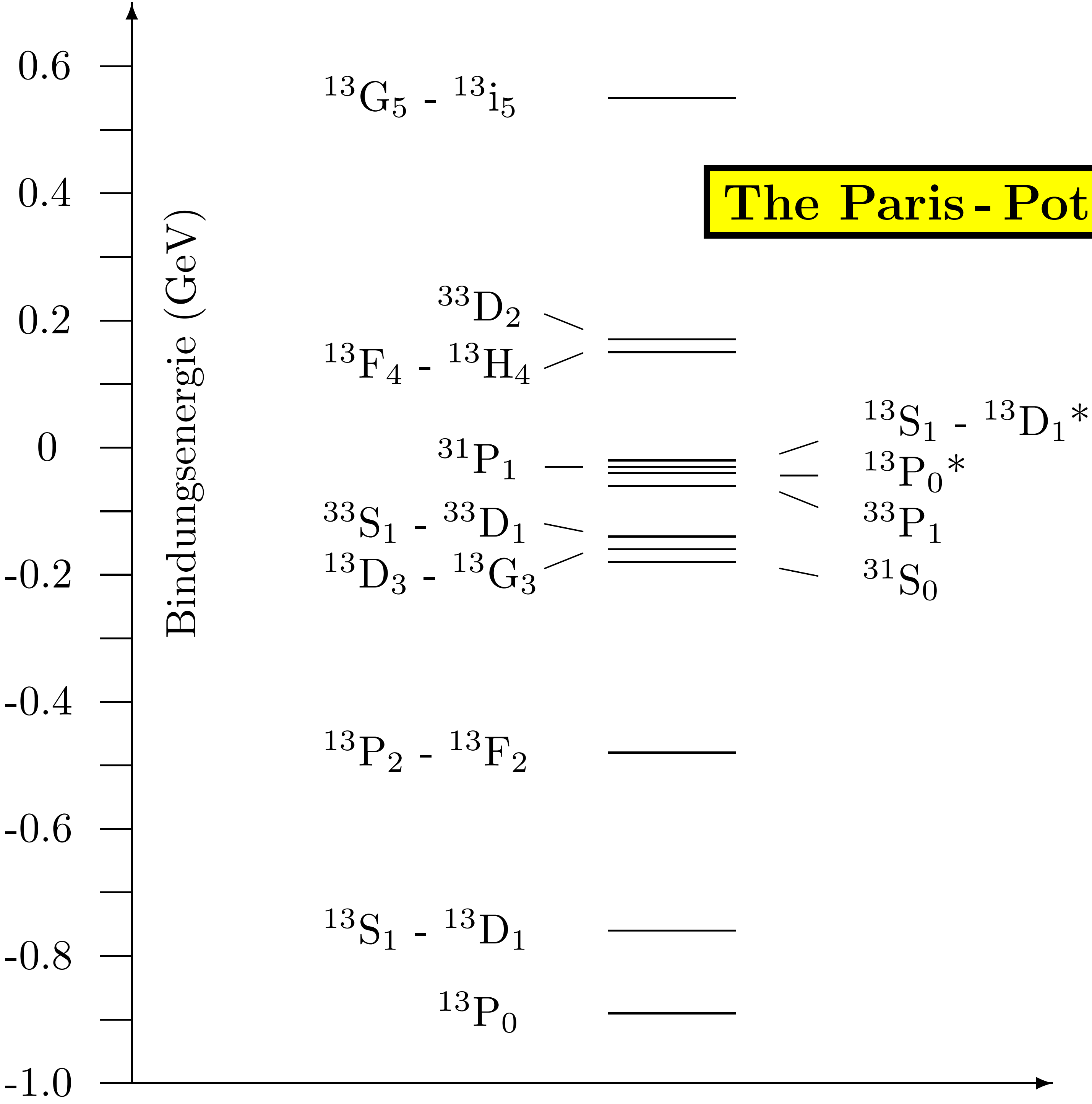
The Paris - Potential



Experimental Method

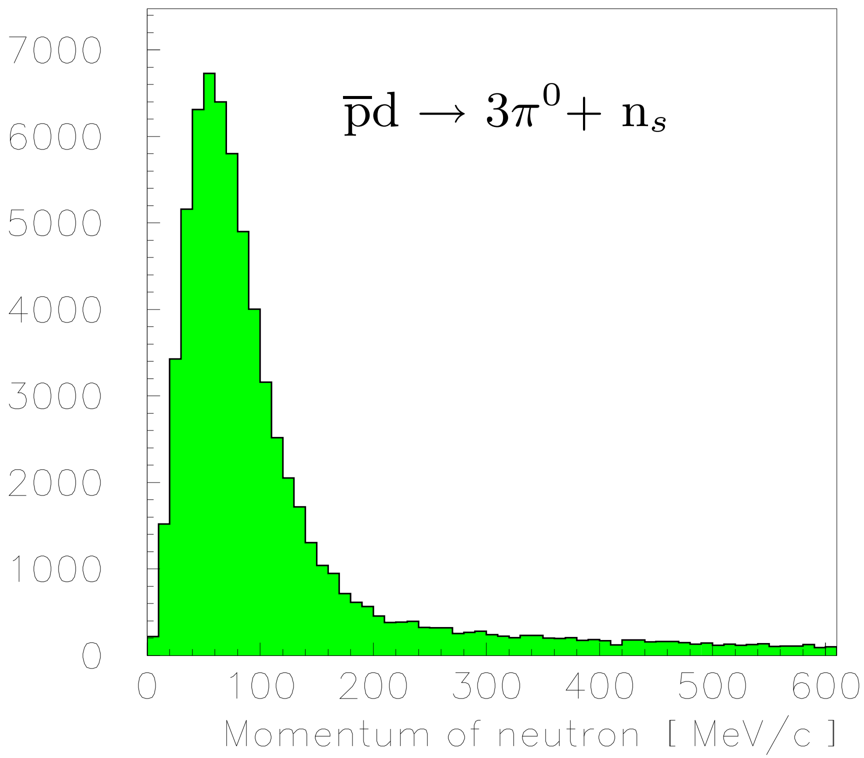
Sensitive experimental method:

$$\overline{p}d \;\rightarrow\; X \;+\; N, \qquad X = N\overline{N} \text{ bound state}$$

$$\overline{p}d \rightarrow (\,\overline{p}p \rightarrow X\,)\,n,\; (\,\overline{p}n \rightarrow X\,)\,p$$

- N removes energy in the formation of X
- Main contribution: quasifree annihilation

Experimental Method



→ Characteristic shape due to Fermi motion in the deuteron

→ Position and width of maximum determined by angular momentum of a dominantly bound state [Dalkarov, Shapiro]

Search for $N\overline{N}$ bound states with the Crystal–Barrel Detector

$N\overline{N}$ bound state has a well defined G parity

$\Rightarrow$ Determined by number of decay pions

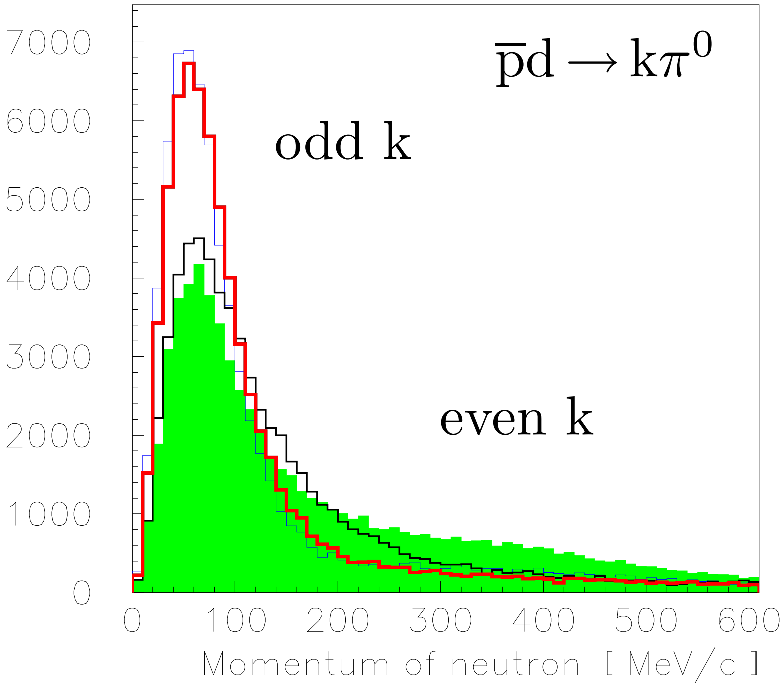
a) Investigation of the reactions: $k\pi^0 + \text{n}, \quad k = 2, 3, 4, 5$

$\Rightarrow$ Striking agreement of channels with even and odd G parity

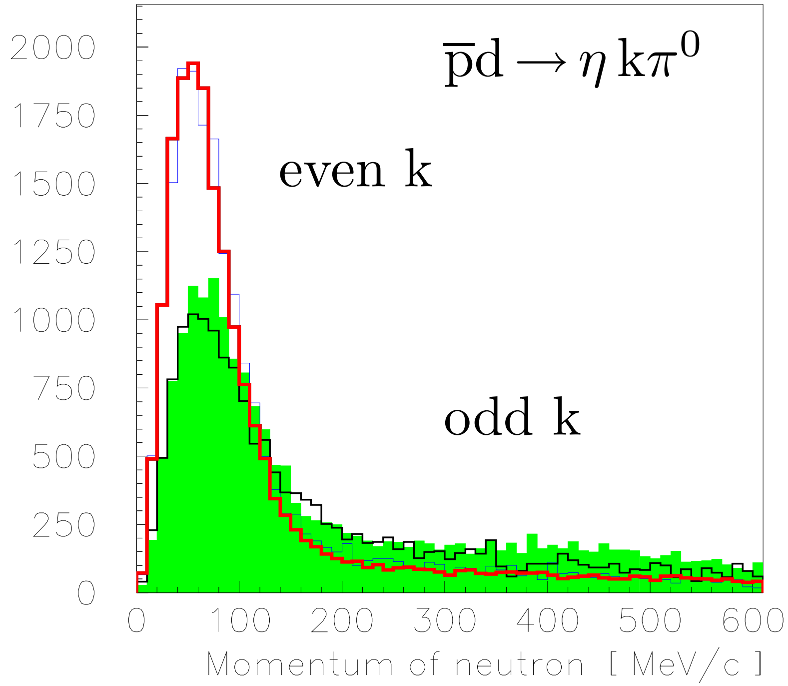
b) Investigation of the reactions: $\eta(k\pi^0) + \text{n}, \quad k = 1, 2, 3, 4$

$\Rightarrow$ Same effect, however, interchanged G parity

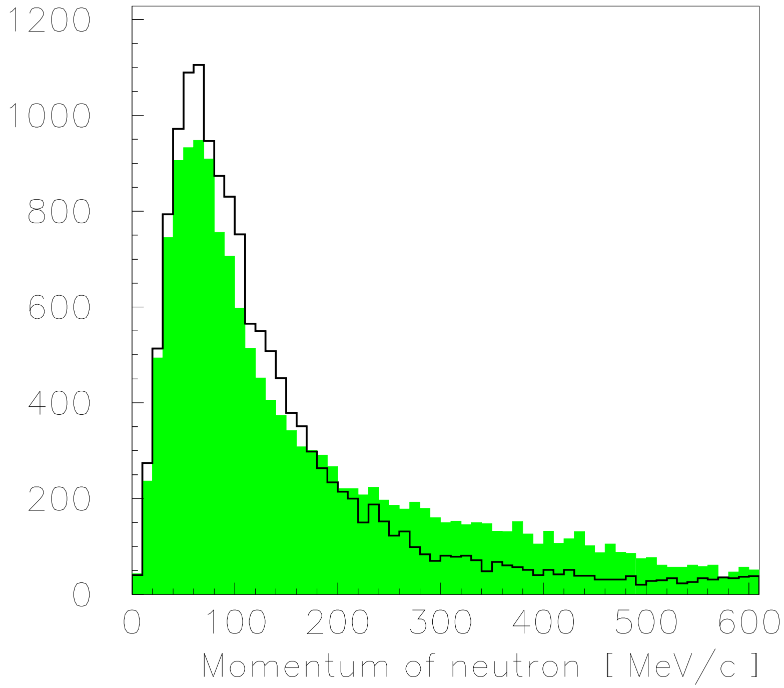
No observation of quasinuclear bound states!



$\overline{p}d \rightarrow k\pi^0$
odd k
even k
0
1000
2000
3000
4000
5000
6000
7000
0
100
200
300
400
500
600
Momentum of neutron [MeV/c]



$\overline{p}d \rightarrow \eta\, k\pi^0$
even k
odd k
0
250
500
750
1000
1250
1500
1750
2000
0
100
200
300
400
500
600
Momentum of neutron [MeV/c]



0
200
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800
1000
1200
0
100
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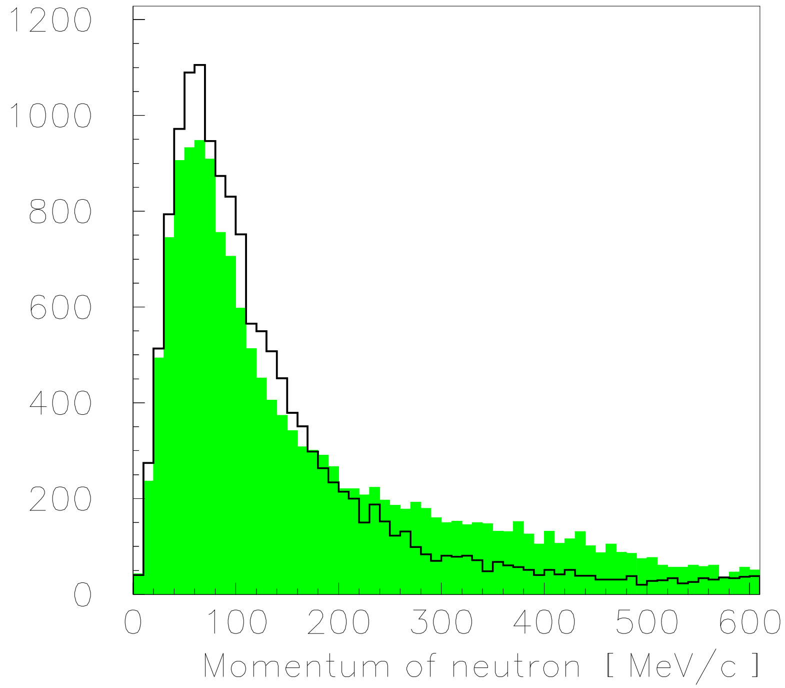
400
500
600
Momentum of neutron [MeV/c]



0
200
400
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1200
0
100
200
300
400
500
600
Momentum of neutron [MeV/c]

Interpretation of Distributions

Distributions with $2\pi^0$ and $4\pi^0$:

- Higher intensities at higher momenta
- $\overline{\mathrm{p}}\mathrm{p}\,(\,\mathrm{S\ wave}\,) \not\longrightarrow 2\pi^0$ (not allowd)
- $\overline{\mathrm{p}}\mathrm{p}\,(\,\mathrm{S\ wave}\,) \longrightarrow 4\pi^0$ (complex cascade)

$$
\begin{array}{llllll}
\overline{\mathrm{p}}\mathrm{p} & \to \pi^0 & \mathrm{a}_2(1650) & & & \\
 & & \mathrm{a}_2(1650) & \to \pi^0 & \mathrm{f}_2(1270) & \\
 & & & & \mathrm{f}_2(1270) & \to 2\pi^0
\end{array}
$$

- $\overline{\mathrm{p}}\mathrm{p}\,(\,\mathrm{P\ state}\,)$: allowed from S wave of $\overline{\mathrm{p}}\mathrm{d}$ atom

$\Rightarrow$ Different probabilities for annihilation from S and P wave

$\Rightarrow$ Confirmed by distributions with η mesons

- $\overline{\mathrm{p}}\mathrm{p}\,(\,\mathrm{S\ state}\,) \not\longrightarrow \pi^0\eta$ (forbidden)
- $\overline{\mathrm{p}}\mathrm{p}\,(\,\mathrm{S\ state}\,) \longrightarrow 3\pi^0\eta$ (rare decay)

Summary

$N\overline{N}$ potential models describe scattering processes at large distances and small momentum transfer

- Correct prediction of energy shifts
- Determination of $NN\pi$ coupling constant from the reaction $p\overline{p} \rightarrow n\overline{n}$

One–Boson–Exchange models are not able to describe annihilation

- Predicted isospin decomposition of $p\overline{p}$ wave function not confirmed
- No observation of quasinuclear $N\overline{N}$ bound states
- No consistent description of measured branching ratios

Summary

- Potential models don't give insight into dynamics of annihilation process
- At large momentum transfer, quark–quark interaction plays the dominant role in strong interaction

$\Rightarrow$ Predictions for resonances from the same potentials
$\Rightarrow$ There is a problem with these potentials ...

$\Rightarrow$ If states, why not in $\overline{\mathrm{p}}\mathrm{N}$ reactions?

$\Rightarrow$ Whatever there is in the BES data: no $\mathrm{p}\overline{\mathrm{p}}$ state, I believe!

$\Rightarrow$ Annihilation width of $\mathrm{N}\overline{\mathrm{N}}$ resonances predicted to be much larger than $\Gamma_{\mathrm{N}\overline{\mathrm{N}}}$
$\Rightarrow$ They have not been found in annihilation processes!