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MASTER

THE PHYSICS OF NUCLEON-ANTINUCLEON SYSTEMS*

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Notes for an Invited Talk given at the Workshop on Low Energy Separated Beams, Brookhaven National Laboratory, March 3, 1977

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DISCLAIMER

Questions:

1) Relation between NN and $\bar{N}N$ forces? (Fermi-Yang, Bethe, Ball + Chew, Shapiro)

2) Is there evidence for narrow $\bar{N}N$ resonances and bound states near threshold?

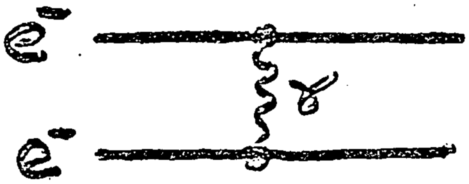
Interpretation as "quasimolecular" $\bar{N}N$ states?

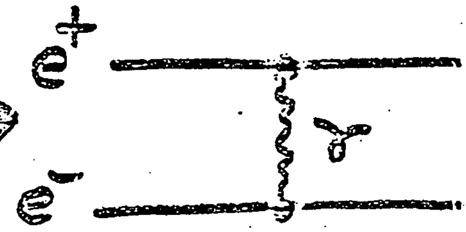
3) Constraints on NN potentials from $\bar{N}N$ scattering?

4) What are the important experiments?

RELATION BETWEEN NN AND $\bar{N}N$ FORCES:

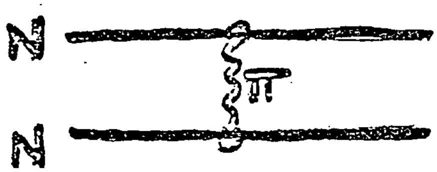
EM ANALOGY:

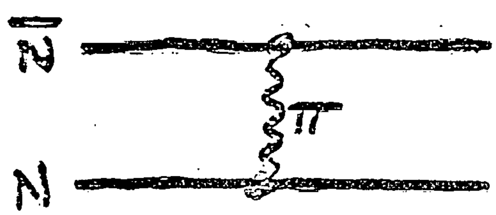




$$V(r) = \frac{e^2}{r} \qquad V(r) = -\frac{e^2}{r}$$

FOR STRONG INTERACTIONS: $e \rightarrow g$





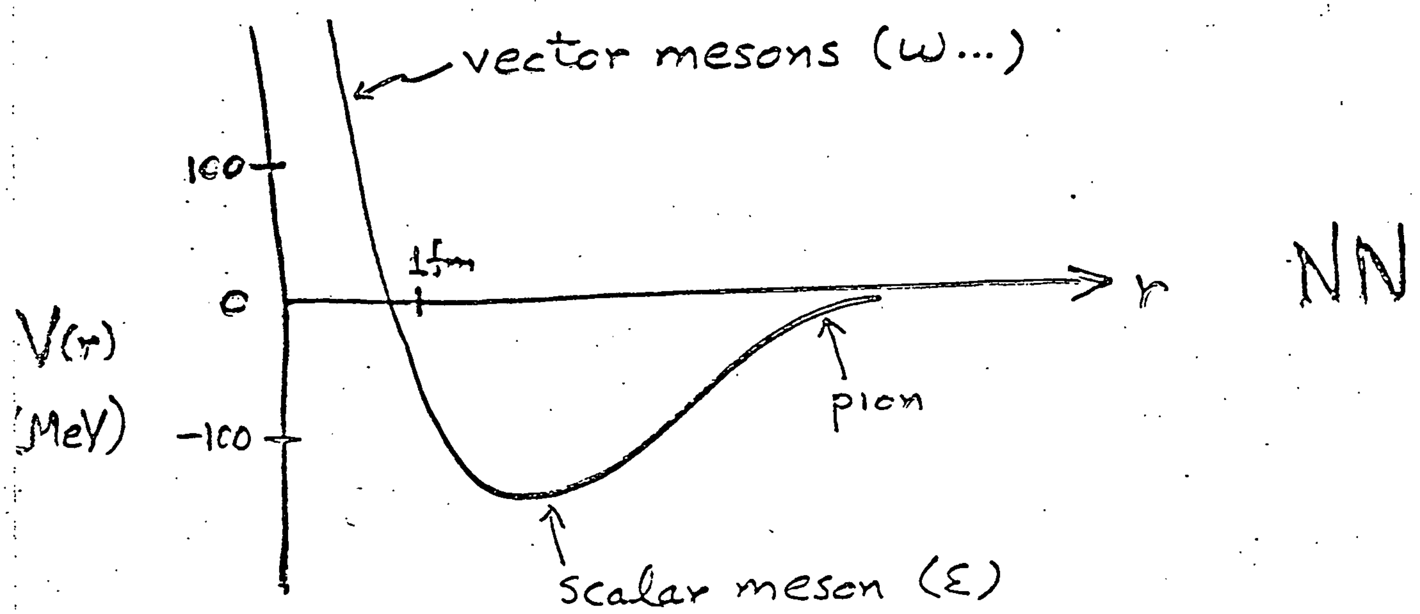
$$V(r) \sim g^2 \frac{e^{-\mu r}}{r} \qquad V(r) \sim -g^2 \frac{e^{-\mu r}}{r}$$

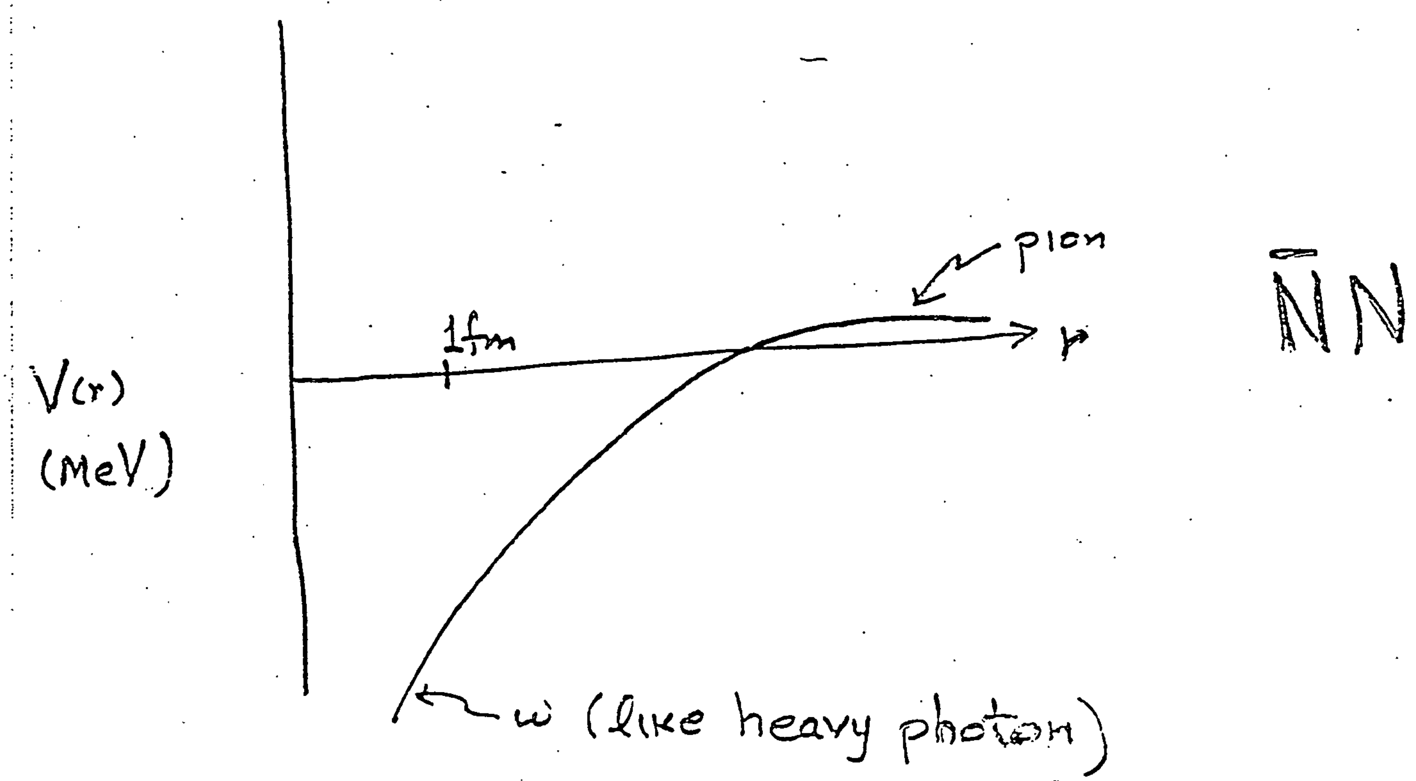
$$V_{NN} = \sum_i V_i(r)$$

$$V_{\bar{N}N} = \sum_i (-1)^{G_i} V_i(r)$$

$$i = \{\pi, \eta, \rho, \omega, \epsilon, \delta\}$$

Qualitative Features of NN and $\bar{N}N$ Potentials





FRAMEWORK:

1) non-relativistic Schrödinger Equation

$$\left[-\frac{\hbar^2}{2M}\frac{d^2}{dr^2} + \underbrace{L(L+1)\frac{\hbar^2}{2Mr^2} + V(r) - \frac{e^2}{r}}_{V_{TOT}(r)}\right]u(r) = E\,u(r)$$

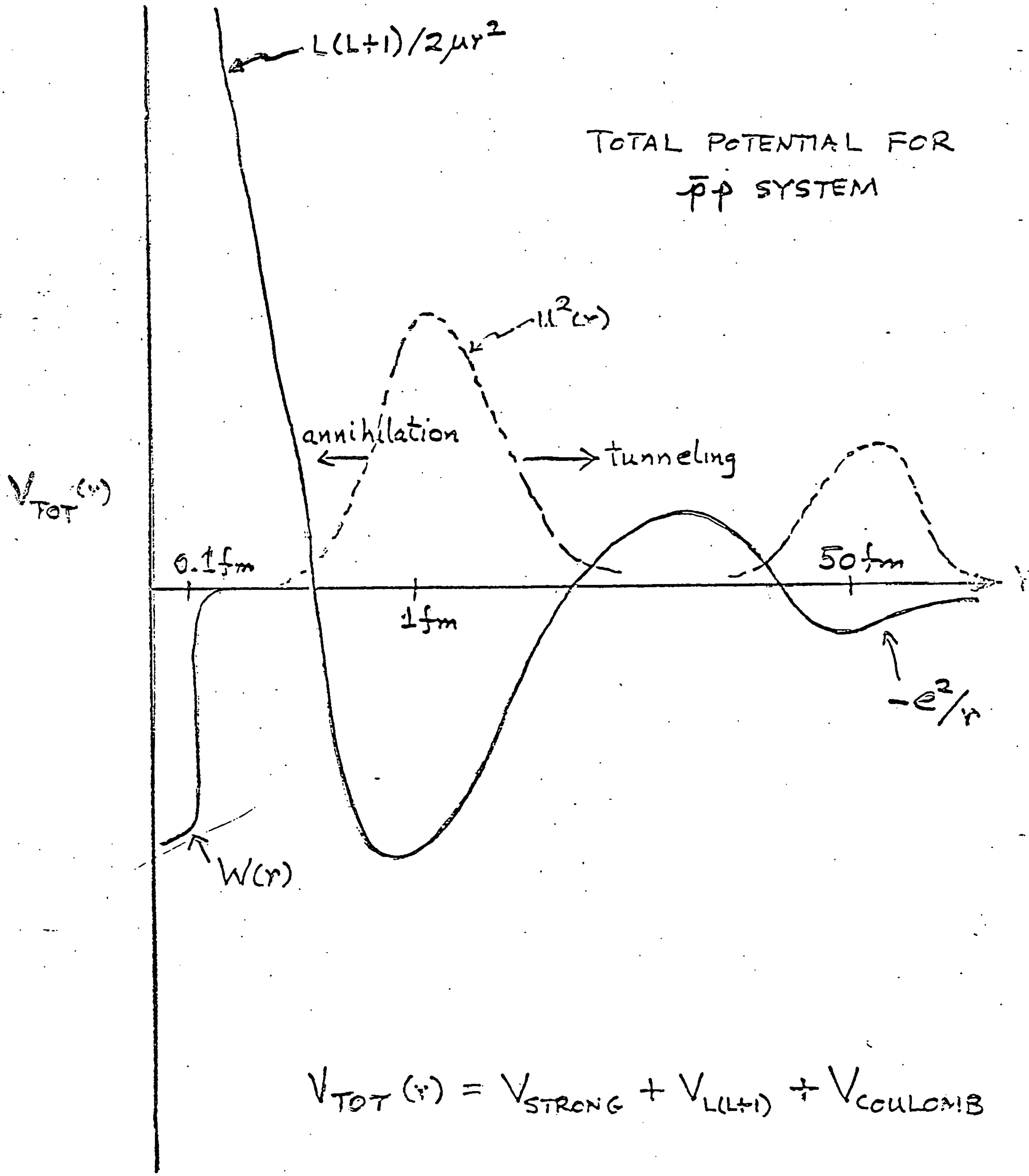
(shapiro) [J. M. RICHARD]

2) relativistic Blankenbecler-Sugar Eq.

$$\mathcal{T}(p,p',E) = \mathcal{V}(p,p',E) + \int \frac{d^3k}{(2\pi)^3}\,\mathcal{V}(p',k,E)\,\frac{m^2\Lambda_+(k)\Lambda_+(-k)}{E_k\,(E_k^2-E^2-i\varepsilon)}\,\mathcal{T}(k,p,E)$$

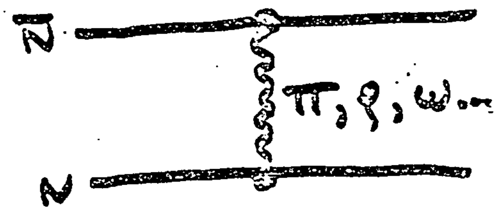
Nucl. Phys. A249 (1975) 397
(Stony Brook potential)

[W. BUCK]



$$V_{TOT}(r) = V_{STRONG} + V_{L(L+1)} + V_{COULOMB}$$

Form of NN and $\bar{N}N$ Potential $V(r)$



$$V(r) = V_0(r) + V_\sigma(r)\,\vec{\sigma}_1\cdot\vec{\sigma}_2$$

$$+ V_{LS}(r)\,\vec{L}\cdot\vec{S} + V_T(r)\,S_{12}$$

$$\vec{S} = \vec{\sigma}_1 + \vec{\sigma}_2$$

$$S_{12} = 3\,\vec{\sigma}_1\cdot\hat{r}\;\vec{\sigma}_2\cdot\hat{r} - \vec{\sigma}_1\cdot\vec{\sigma}_2$$

$V_0(r)$ = central pot.

$V_\sigma(r)$ = spin-flip pot.

$V_{LS}(r)$ = Spin-orbit pot.

$V_T(r)$ = tensor pot.

COHERENCES IN MESON EXCHANGE FORCE

NN

	I=0 V_0	I=0 V_σ	I=0 V_{LS}	I=0 V_T	I=1 V_0	I=1 V_σ	I=1 V_{LS}	I=1 V_T
π	0	−	0	−	0	+	0	+
η	0	+	0	+	0	+	0	+
ω	+	+	−	−	+	+	−	−
ρ	−	−	+	+	+	+	−	−
ε	−	0	−	0	−	0	−	0
δ	+	0	+	0	−	0	−	0

$\bar{N}N$

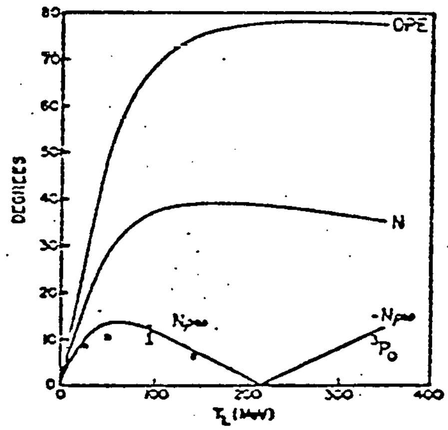
	I=0 V_0	I=0 V_σ	I=0 V_{LS}	I=0 V_T	I=1 V_0	I=1 V_σ	I=1 V_{LS}	I=1 V_T
π	0	+	0	+	0	−	0	−
η	0	+	0	+	0	+	0	+
ω	−	−	+	+	−	−	+	+
ρ	−	−	+	+	+	+	−	−
ε	−	0	−	0	−	0	−	0
δ	−	0	−	0	+	0	+	0

A. D. JACKSON, D. O. RISKA and B. VERWEST

Nuclear Physics A249 (1975) 397–444

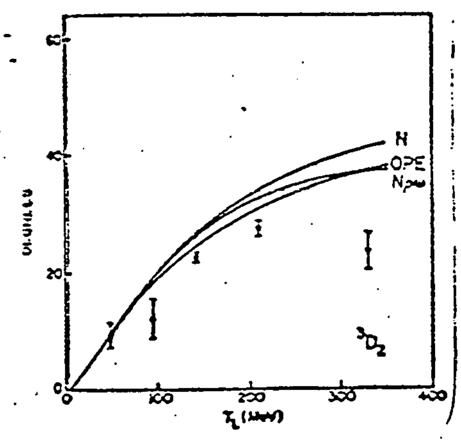
NN SYSTEM

$^{33}P_0$



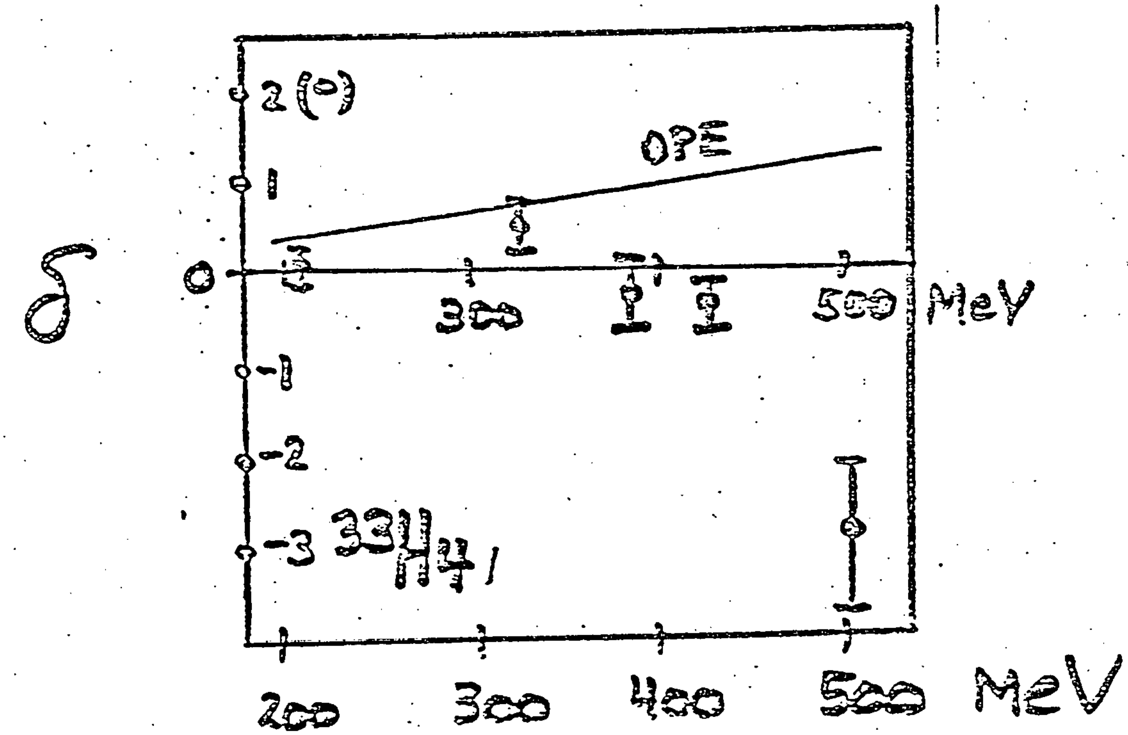
COHERENCE OF $\underset{\sim}{L}\cdot\underset{\sim}{S}$, $\underset{\sim}{\sigma}_1\cdot\underset{\sim}{\sigma}_2$ TERMS

$^{13}D_2$



NO COHERENCE

NN PHASE SHIFT FOR $^{33}H_4$



E. Amsler (TRIUMF)

Consequences of coherence for $\bar{N}N$ Level Ordering :

1) tensor pot. $\propto +V_T(r)\,S_{12}$

ex. $L=1$ $\quad \langle S_{12}\rangle = \begin{cases} +2 & {}^3P_1 \\ -2/5 & {}^3P_2 \\ -4 & {}^3P_0 \end{cases}$

$\longrightarrow$ ${}^{13}P_0$ lowest state for $L=1$

in general, get a natural parity band

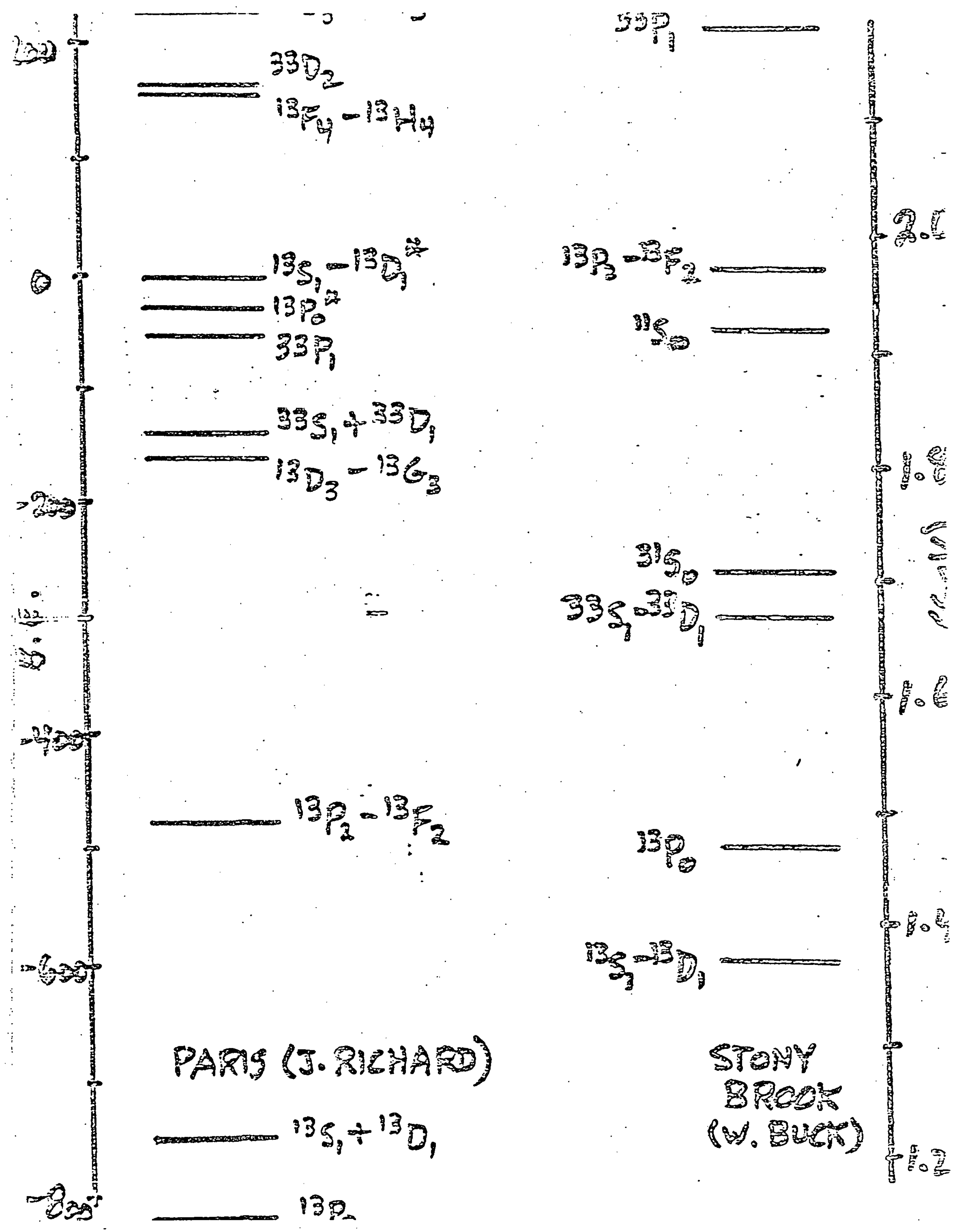
${}^{13}P_0$, ${}^{13}S_1 - {}^{13}D_1$, ${}^{13}P_2 - {}^{13}F_2$, ${}^{13}G_3 - {}^{13}D_3$, etc.

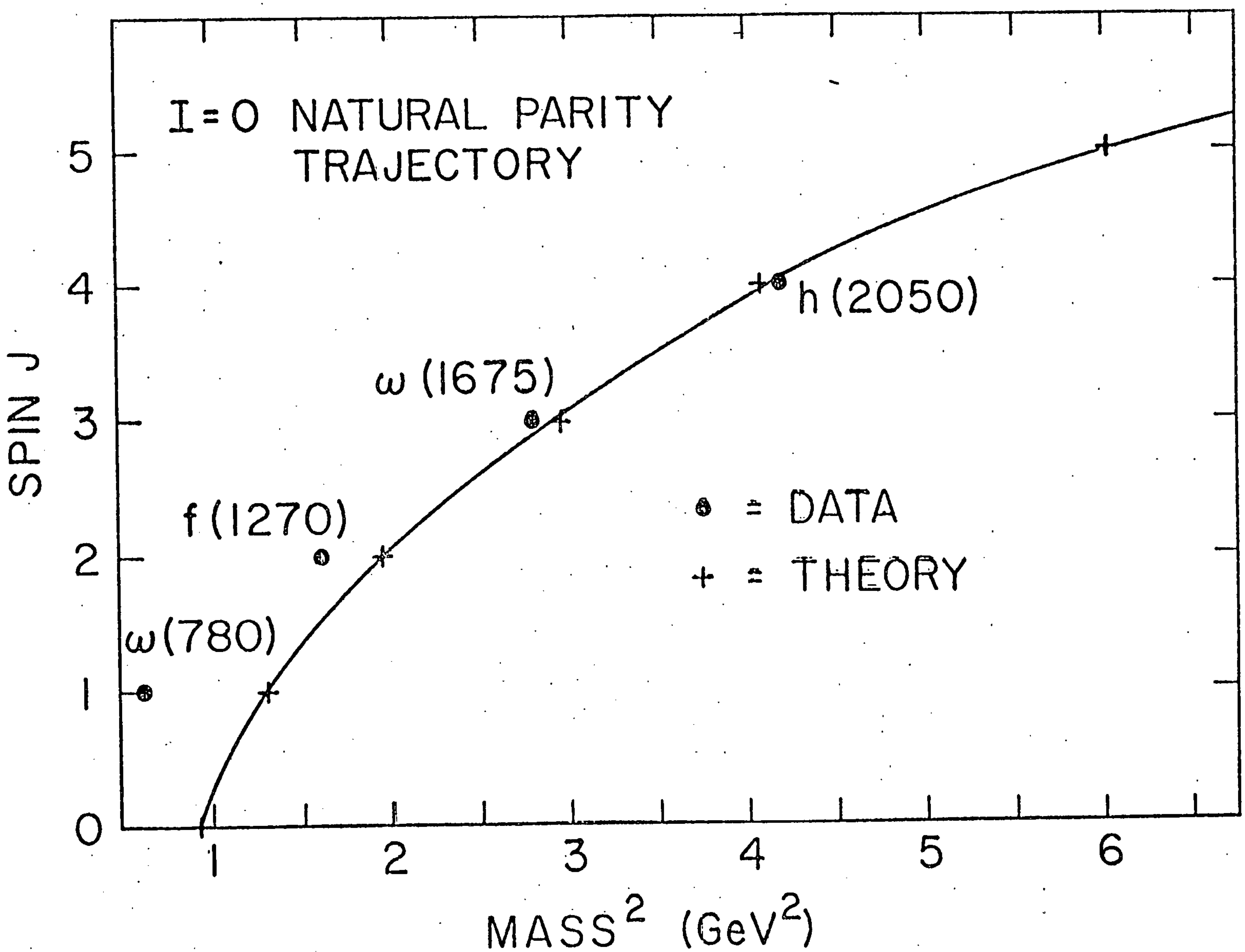
$0^+(\varepsilon)$ $\quad 1^-(\omega)$ $\quad 2^+(f)$ $\quad 3^-(\omega(1675))$

2) no coherence for $I=1$, so pion more important

$$V_\pi(r) = -\tau_1\cdot\tau_2\,\sigma_1\cdot\sigma_2\,V_\sigma(r) - \tau_1\cdot\tau_2\,V_T(r)\,S_{12}$$

$\rightarrow$ favors ${}^{33}P_1$ as lowest $L=1$ state


3^3D_2
$1^3F_4 - 1^3H_4$
$1^3S_1 - 1^3D_1$*
1^3P_0*
3^3P_1
$3^3S_1 + 3^3D_1$
$1^3D_3 - 1^3G_3$
$1^3P_2 - 1^3F_2$
$1^3S_1 + 1^3D_1$
1^3P_2
0
PARIS (J. RICHARD)
3^3P_1
$1^3P_2 - 1^3F_2$
1^1S_0
3^1S_0
$3^3S_1 - 3^3D_1$
1^3P_0
$1^3S_1 - 1^3D_1$
STONY
BROOK
(W. BUCK)
2.0
1.8
1.6
1.4
1.2



I = 0 NATURAL PARITY
TRAJECTORY
SPIN J
MASS^2 (GeV^2)
ω (780)
f (1270)
ω (1675)
h (2050)
= DATA
+ = THEORY
0
1
2
3
4
5
6

MOMENTUM SPECTRUM

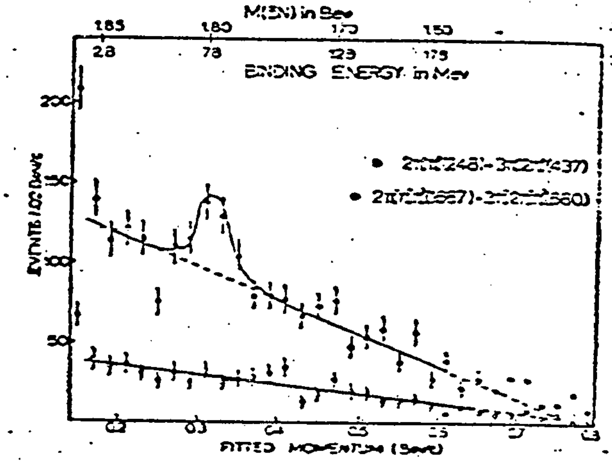
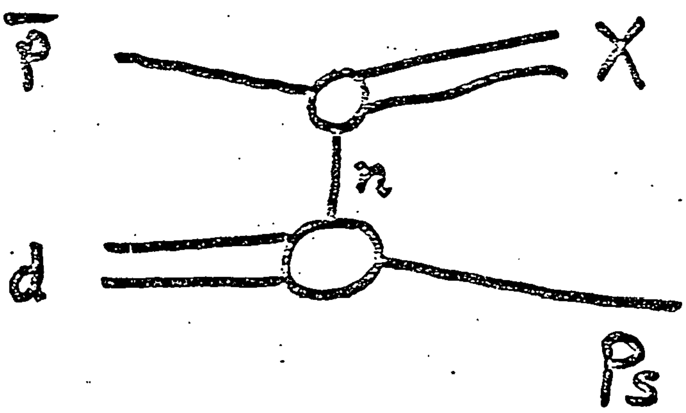


FIG. 2. Fitted momentum spectra

$$\bar{p} + d \rightarrow p_s + X$$



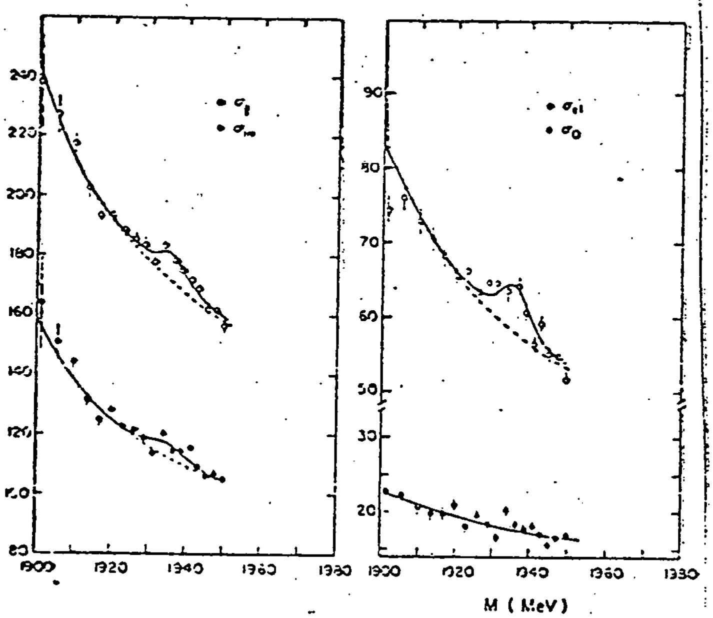
L. Gray, P. Hagerty, T. Kalogeropoulos
Phys. Rev. Letters 26, 1491 (1971)

MEASUREMENT OF THE TOTAL AND PARTIAL $\bar{p}p$ CROSS SECTION BETWEEN 1901 AND 1950 MeV*

V. CHALOUPKA et al (CERN)

σ_{TOT} →

σ_R →



← $\bar{p}p \rightarrow \bar{p}p$

← $\bar{p}p \rightarrow \bar{n}n$

S(1930) STRUCTURE IN $\bar{P}P$

$\Gamma_{TOT} \approx 9$ MeV (now ≤ 4 MeV)

FIRST SEEN BY A. CARROLL ET AL (BNL
PHYS. REV. LETT. 32, 247 (1974).

The S(1930) Meson as a doublet:
(Dover + Kahana, Phys. Lett. 62B, 293 (1976))

First note that $\sigma_{\bar{p}p\to\bar{p}p} \sim |A_{I=0} + A_{I=1}|^2$

$\sigma_{\bar{p}p\to\bar{n}n} \sim |A_{I=0} - A_{I=1}|^2$

Now $V_{\bar{N}N}(r) = V_{T=0}(r) + \tau_1\cdot\tau_2\, V_{T=1}(r)$

1) Suppose $V_{T=0} >> V_{T=1}$ for some L, S, J

Then if $V_{T=0}$ supports bound state in $I=0$, must also get $\approx$ degenerate $I=1$ state with $E(I=1) - E(I=0) = 4\int d^3\underset{\sim}{r}\, |\psi(r)|^2\, V_{T=1}(r)$

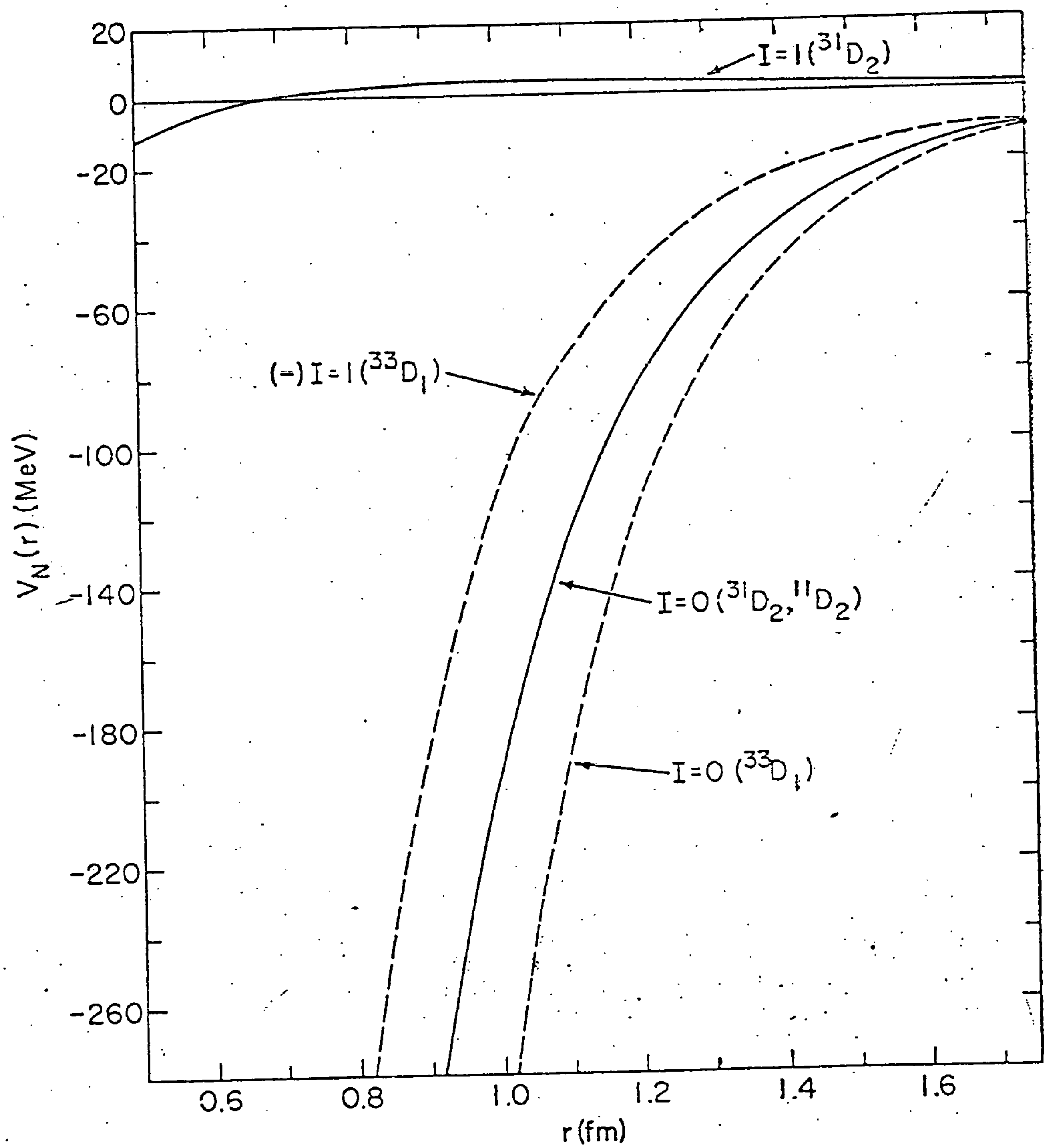
2) <u>Coherence</u> of $\tau_1\cdot\tau_2$ tensor forces (π, ρ) for $I=0$ would produce large splitting for any $S=1$ state $\Rightarrow$ <u>must</u> <u>have</u> <u>$S=0$</u>

3) For $S=0$, no S_{12}, L·S forces

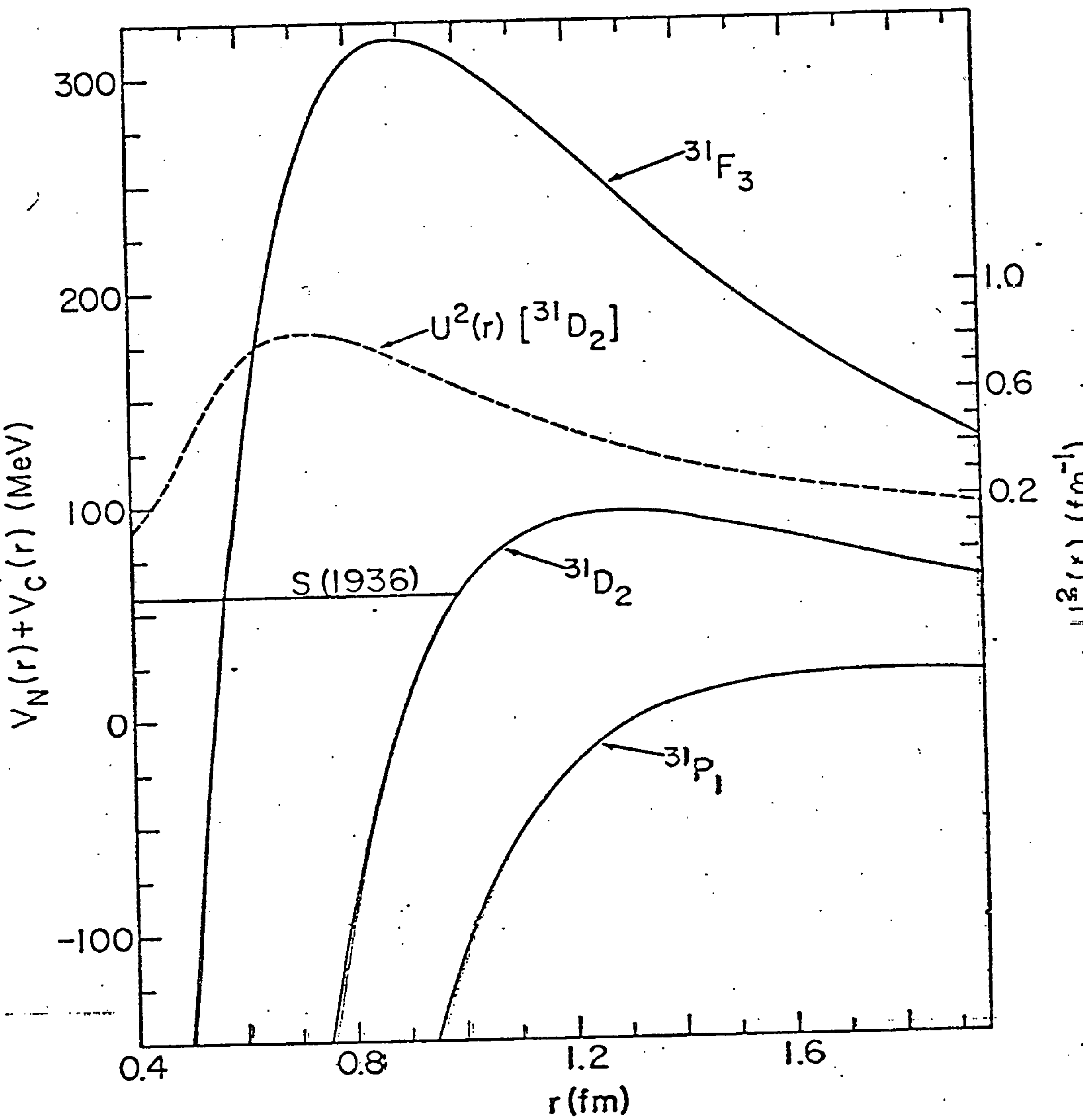
$V_{T=0}(r) \approx -V_0^{\epsilon}(r) - V_0^{\omega}(r)$ ← coherence!

$V_{T=1}(r) \approx 3\left(V_\sigma^{\pi}(r) - V_\sigma^{\rho}(r)\right) + V_0^{\delta}(r)$

↑ cancellation!

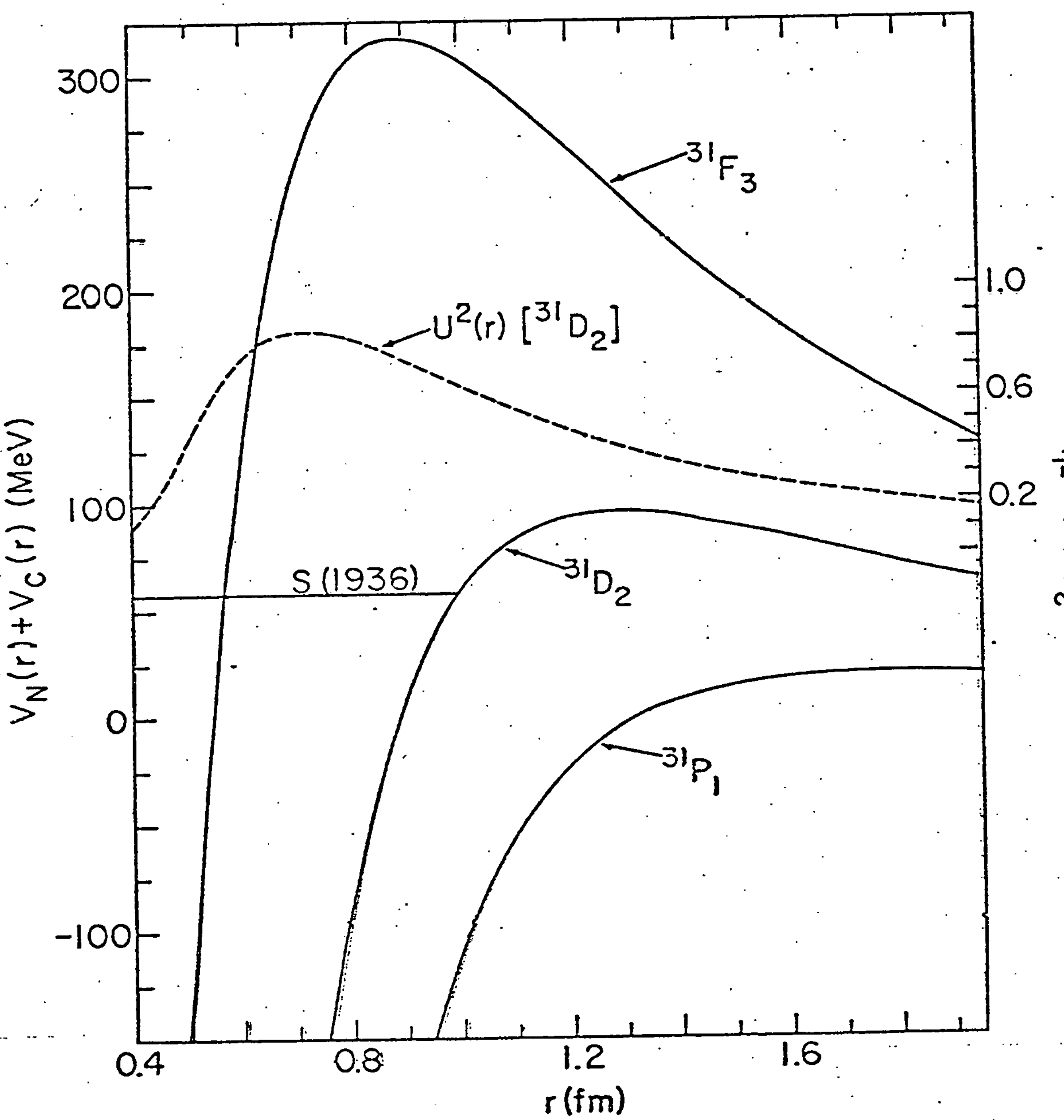


Bryan - Phillips pot. (Nucl. Phys. (1968))



∴ only possibility for S(1930) doublet is

$^{11}D_2, {}^{31}D_2 \quad (J^{\pi c}(I^G)) = 2^{-+}(0^+, 1^-)$



$\therefore$ only possibility for S(1930) doublet is

$^{11}D_2$, $^{31}D_2$ $\quad (J^{\pi C}(I^G)) = 2^{-+}(0^+, 1^-)$

Main Points :

1) $\bar{B}B$ and BB systems sensitive to <u>different</u> components of the strong force

a) $\bar{B}B$ registers summed $V_0, V_{S_{12}}$ strength for $I=0$

b) BB registers summed V_σ, V_{LS} strength for $I=1$

∴ $\bar{N}N$ can give strong constraints on NN pot
unified description necessary

2) Some narrow $\bar{B}B$ "quasimolecular" states should exist <u>near</u> <u>threshold</u>

distinct from $\bar{q}q$ (by $\langle r^2\rangle^{1/2}$)

could include "exotic" $I=2$ states of $\bar{\Sigma}\Sigma$ and $\bar{\Sigma}_c\Sigma_c$.

Future Program:

1) Unified description of NN, $\bar{N}N$ scattering data within a single potential model

Question of absorption in $\bar{N}N$:

$$\Delta V(r) - iW(r) = \int \rho(\underset{\sim}{r_1})\,\rho(\underset{\sim}{r_2})\; t^{ann.}_{\bar{N}N}(\underset{\sim}{r_1} - \underset{\sim}{r_2} + \underset{\sim}{r})\; d^3r_1\, d^3r_2$$

must fit background $\sigma_{EL}(E)$, $\sigma_R(E)$ and not destroy narrow resonances (Buck, Richard)

2) "Bootstrap"

use large basis $\bar{N}N, \bar{\Sigma}\Sigma, \bar{\Lambda}\Lambda \ldots$
$\pi\pi, \pi\rho \ldots$

relation to quark model
(ρ as $\bar{q}q$ or $\pi\pi$)

IMPORTANT EXPERIMENTS:

1) $\bar{p}d \to n_s + X \quad (I=0,1)$

$\qquad\quad p_s + X \quad (I=1)$

2) PARTICULAR CHANNELS NEAR LOW ENERGY RESONANCES

$\bar{p}p \to \pi^+\pi^- \quad (S=1)$

$\bar{p}p \to K_L K_S \quad (C=-1)$

$\bar{p}p \to \pi^0\eta \quad (I=1)$

$\qquad\quad \eta\eta \quad (I=0)$

3) VERY LOW ENERGY PHENOMENA (DEVIATIONS FROM $1/P_{lab}$)

4) DISCRETE γ's OR π's (hard)

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5) Polarization around a resonance

6) $\bar{p}$ - NUCLEUS σ_{TOT} ....

(sensitivity to $\rho(r)$ IN TAIL $\to \sigma_{TOT}/2\pi R^2 > 1$)