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ANTIPROTON PHYSICS IN THE NEXT DECADE*

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Antinucleon Physics in the next decade:

try to exhibit the rôle of $\bar{p}$ and $\bar{n}$ beams in shedding light on some fundamental problems in nuclear and particle physics

Some particle aspects:

a) $\bar{N}$ as a source of antiquarks
→ $\bar{N}N$ provides a well-suited entrance channel for formation of new kind of mesons

b) possibility of forming quark-gluon phase in $\bar{N}$ annihilations in nuclei

Some nuclear aspects:

a) medium and long range parts of NN and $\bar{N}N$ potentials related by G-parity

b) search for coherent tensor forces in $\bar{N}N$ spin observables

c) quasi-molecular resonance phenomena in $\bar{N}N$ and $\bar{N}$-nucleus systems

Prospects for $\bar{N}$ Physics:

The LEAR (Low Energy Antiproton Ring) project at CERN provides a qualitative advance in intensity over existing facilities

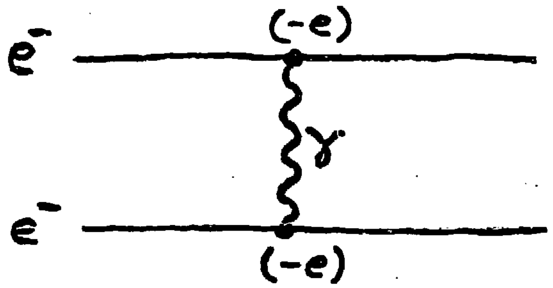
particularly attractive is the ability to explore the crucial low momentum domain below 400 MeV/c

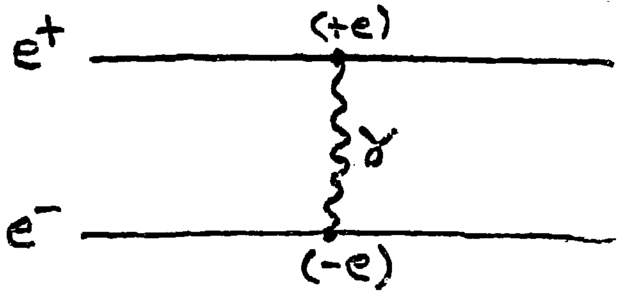
However, another qualitative leap may be possible with even <u>higher</u> <u>intensities</u> (LEAR ≈ few $\times 10^5$ for low momenta) and an <u>extended</u> <u>energy</u> <u>range</u> (beyond 2 GeV/c) at a <u>dedicated</u> <u>facility</u>.

try to indicate some directions here, but the field of $\bar{N}$ physics is very rich, and one should be on the lookout for new phenomena not anticipated by theorists

Relation between NN and $\bar{N}N$ Forces:

Analogy of electric potential:

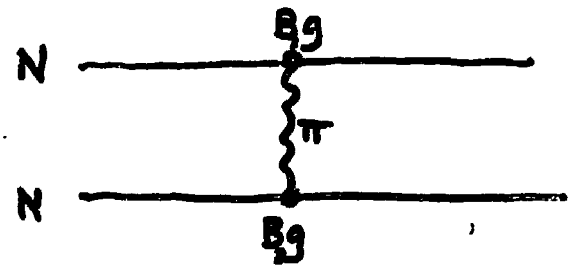


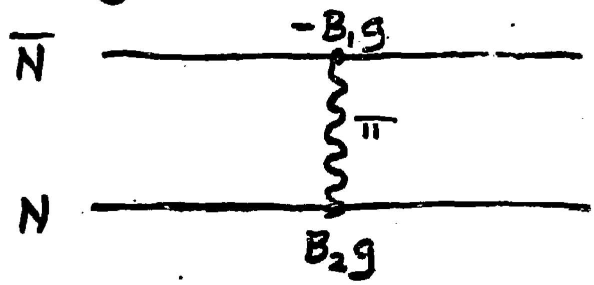


$$V(r) = \frac{(-e)(-e)}{r} = +\frac{e^2}{r}$$

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

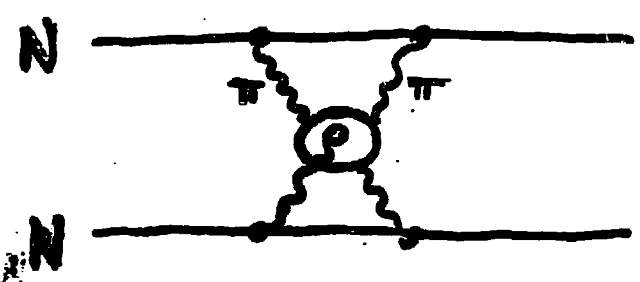
For strong interactions, baryon number B plays role of electric charge

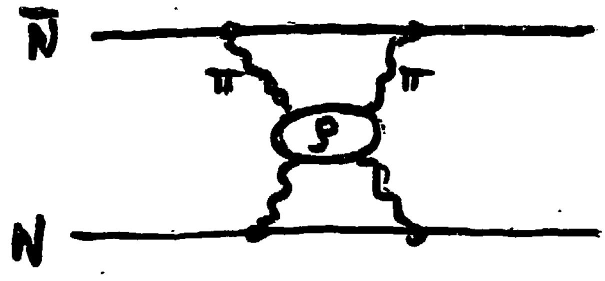




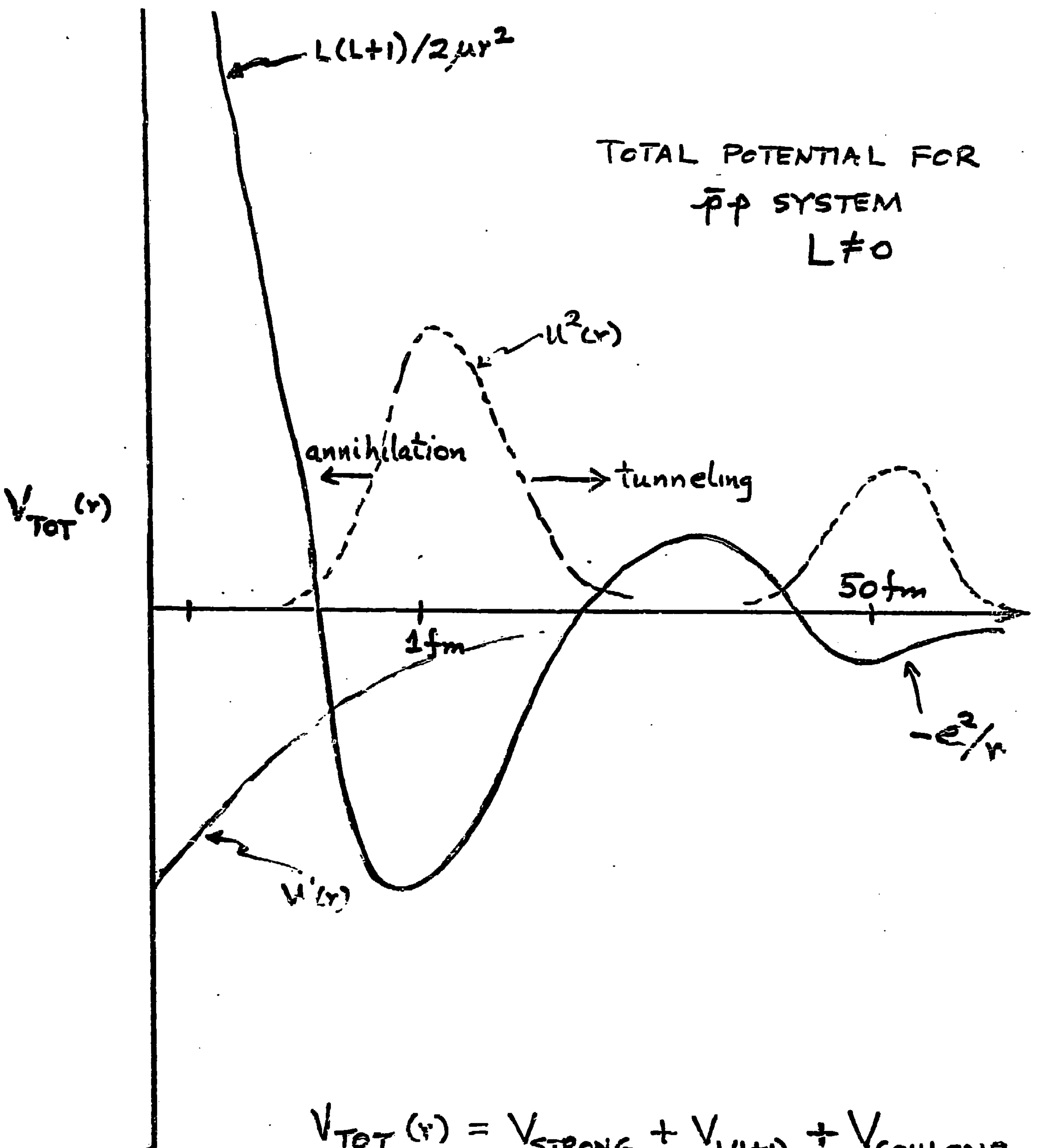
$$V(r) = (B_1 g)(B_2 g)\frac{e^{-\mu r}}{r}$$

$$V(r) = (-B_1 g)(B_2 g)\frac{e^{-\mu r}}{r}$$





$V(r) \sim B_1^2 B_2^2$ $\xleftrightarrow{\text{same}}$ $V(r) \sim B_1^2 B_2^2$



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

$W(r)$ = annihilation potential

Optical Model for $N\bar{N}$ Scattering and Annihilation

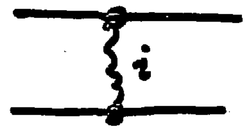
Experimental data:

$$\sigma_{EL} = 28 + 17/p_L \quad ; \quad \sigma_A = 38 + 35/p_L \quad \text{(in mb) for } \bar{p}p$$

$$\sigma_{CE} = 18\left(1 - \left(\frac{0.1}{p_L}\right)^2\right)^{1/2} / \left(1 - p_L/2 + 2.4\, p_L^2\right) \quad (\bar{p}p \to \bar{n}n)$$

Optical Potential:

$$V_{p\bar{p}}(r) = V_t(r) + V_{ANN}(r) \quad ; \quad V_t(r) = \sum_i$$



$$V_{ANN}(r) = -(V_0 + iW_0)/(1 + e^{(r-R)/a})$$

good fit with $R = 0$, $a = 1/5$ fm

$$V_0 \approx W_0 \approx 20 \text{ GeV}$$

$\text{Im}\, V_{ANN}(r) \approx \text{Re}\, V_{ANN}(r) \approx V_t(r) \approx 150$ MeV for $r \approx 1$ fm

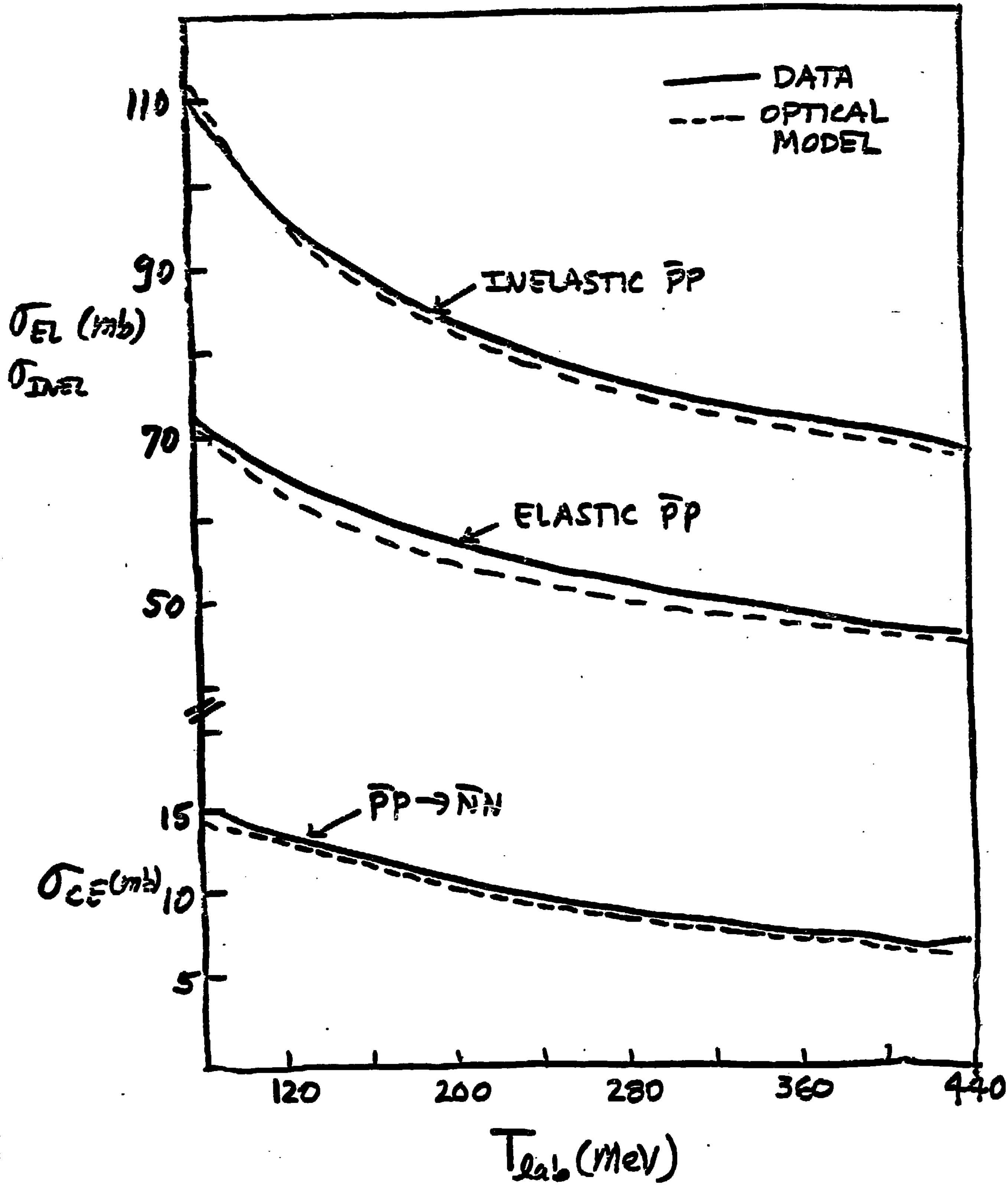
Naive estimate of bound state widths

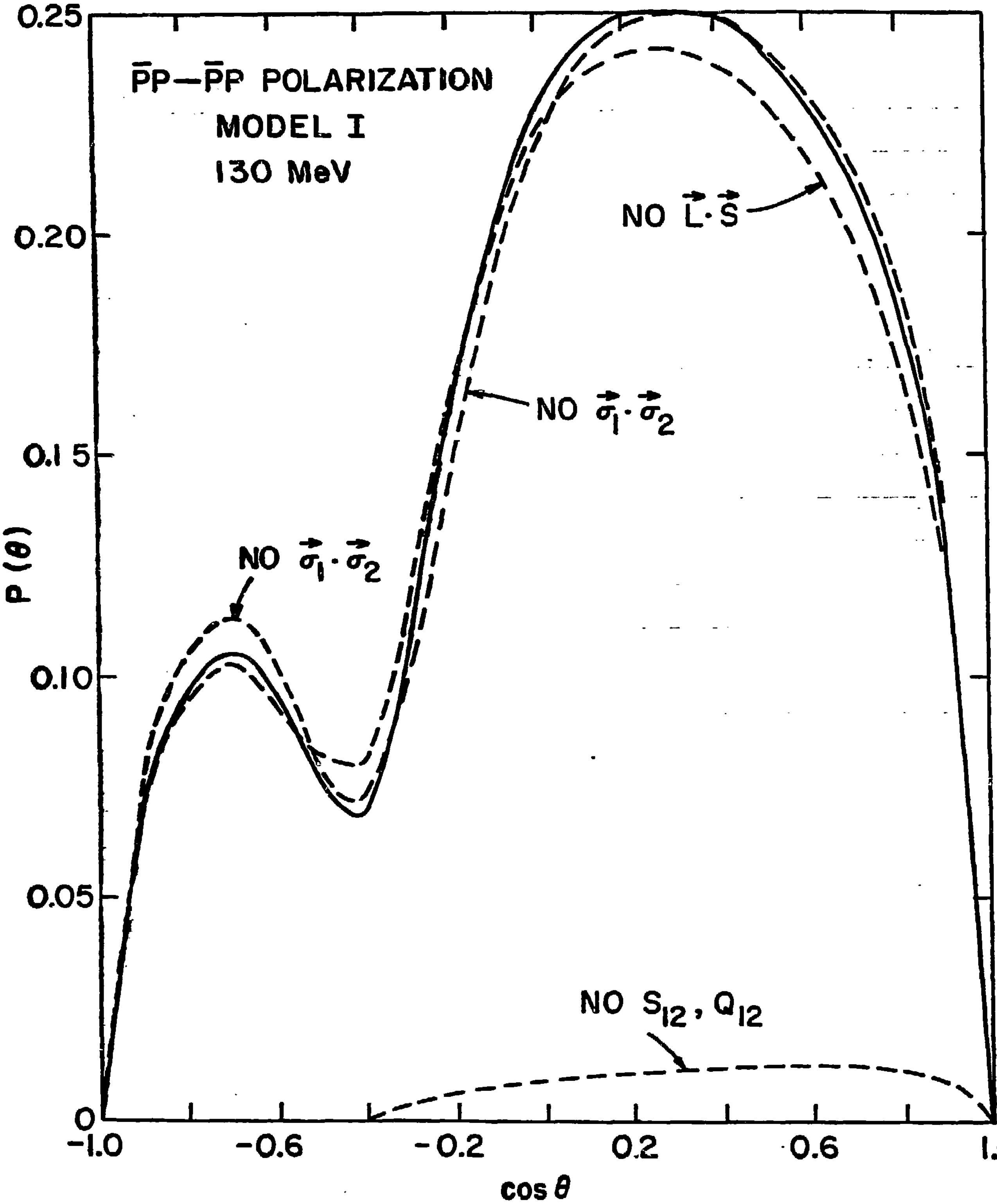
$$\Gamma \approx 2\, \text{Im}\, V_{ANN}(\hat{R}) \approx 300 \text{ MeV}$$

↑ localization radius

most $N\bar{N}$ bound states do not survive annihilation

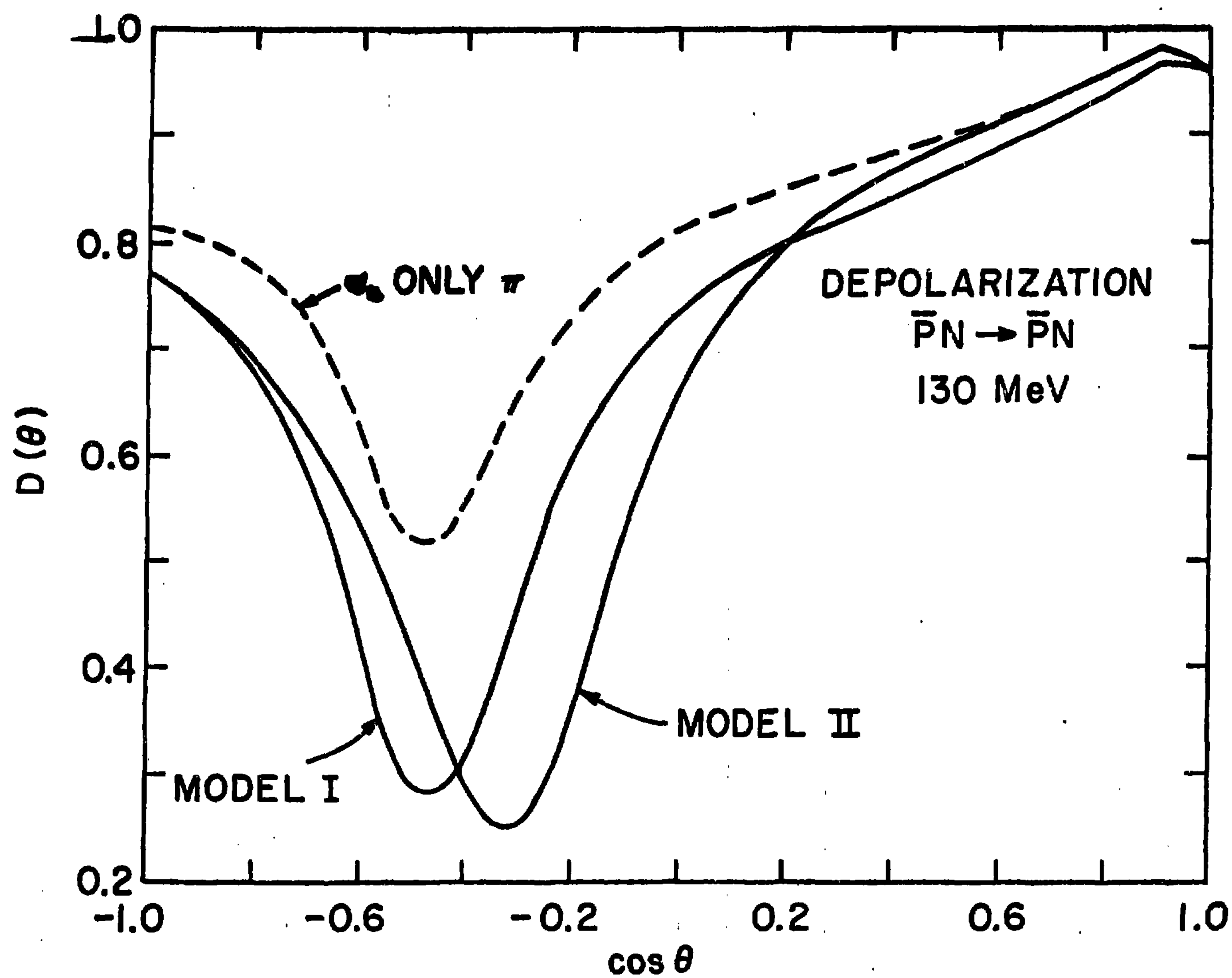
Dover + Richard.
Phys. Rev. C21 (1980)



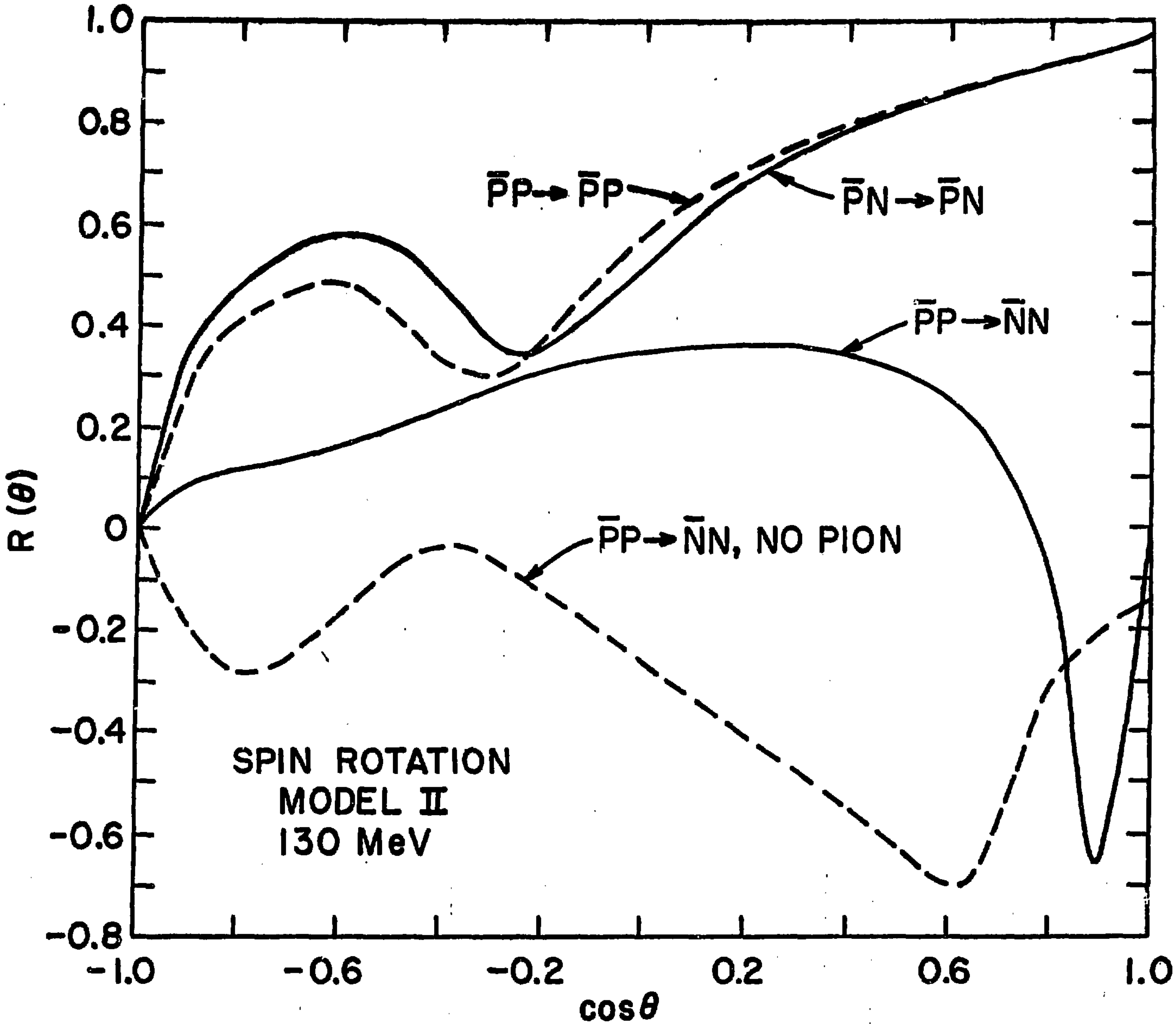


CBD + J.M. Richard, Phys. Rev. C

BNL NEG #9-946-

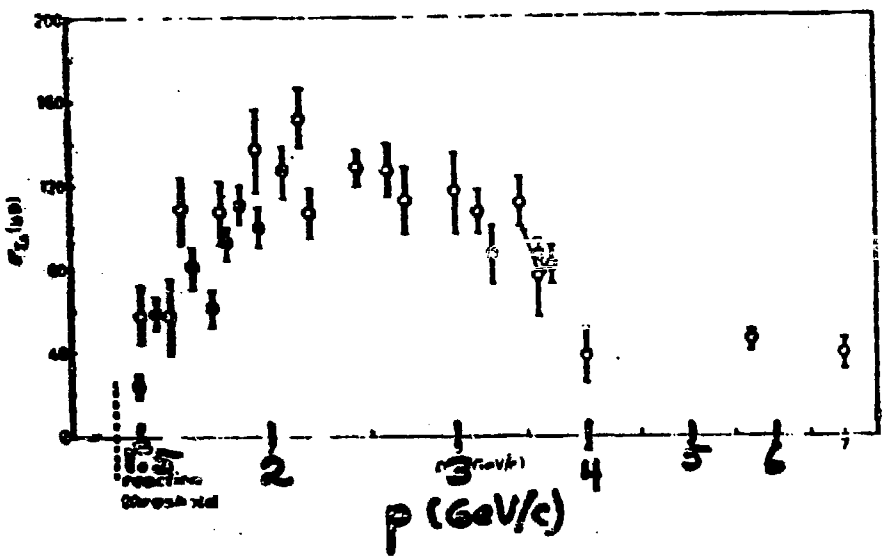


1.0
0.8
0.6
0.4
0.2
D (θ)
ONLY π
DEPOLARIZATION
P̄N → P̄N
130 MeV
MODEL I
MODEL II
-1.0
-0.6
-0.2
0.2
0.6
1.0
cos θ

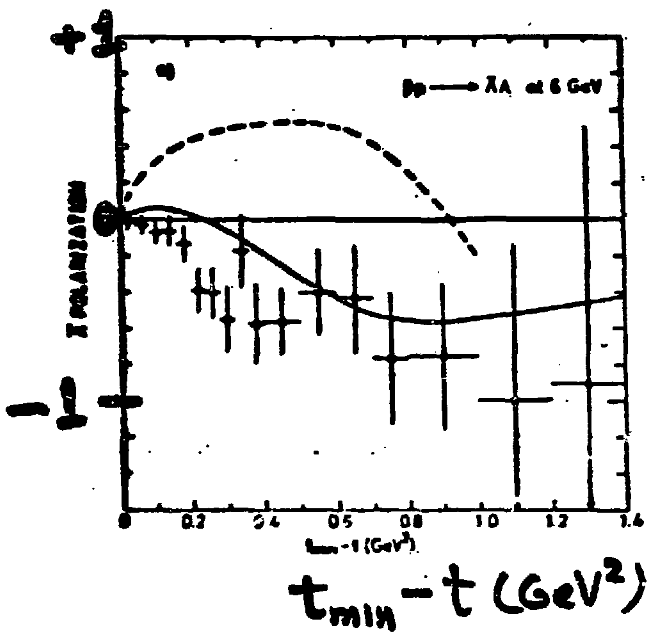


1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
R (θ)
-1.0
-0.6
-0.2
0.2
0.6
1.0
cosθ
P̄P → P̄P
P̄N → P̄N
P̄P → N̄N
P̄P → N̄N, NO PION
SPIN ROTATION
MODEL II
130 MeV

$\bar{p}p \to \bar{\Lambda}\Lambda$

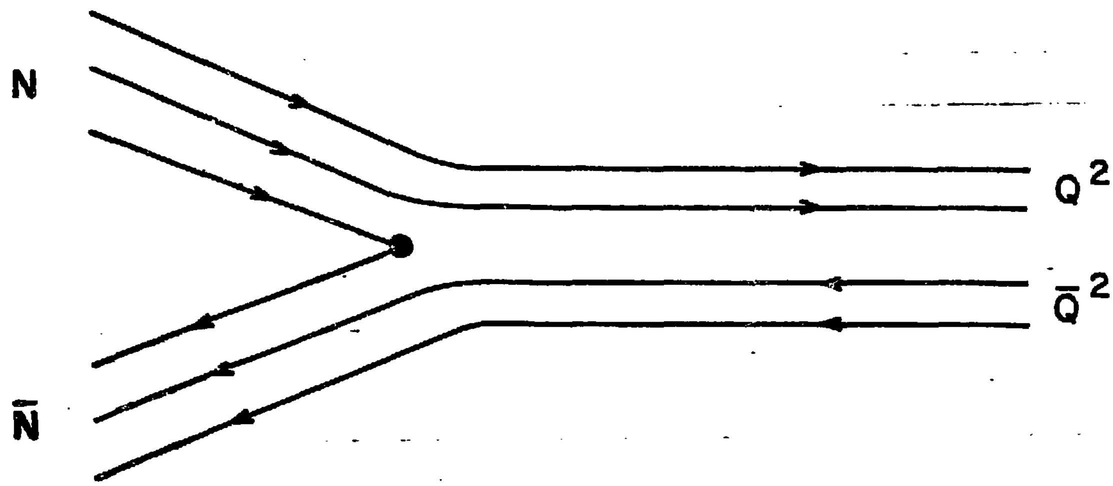


CROSS SECTION

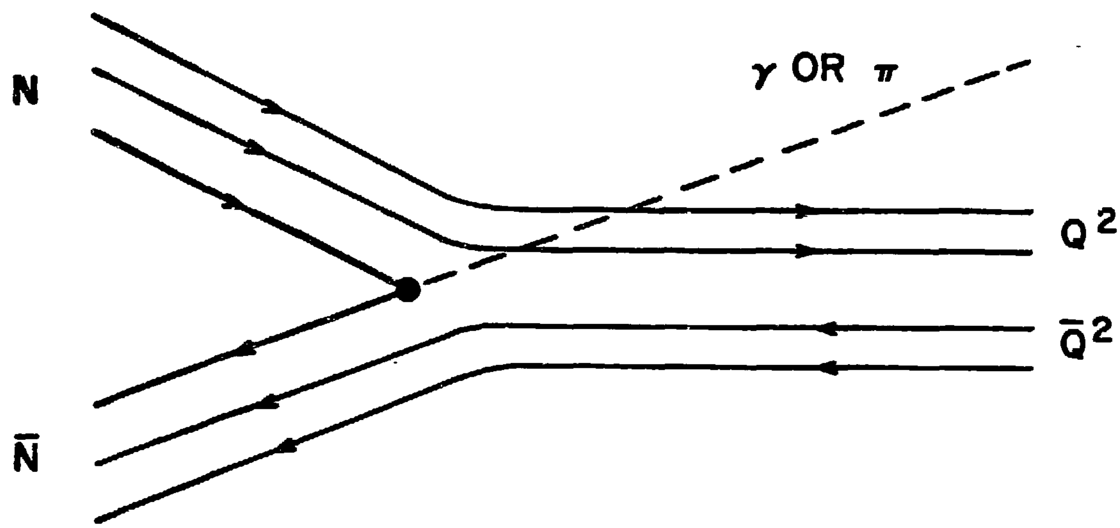


$\bar{\Lambda}$ POLARIZATIO at 6 GeV/c

B. Jayet et al, Nuovo Cim. 45A, 371 (1978)
H. Becker et al, Nucl. Phys. B141, 48 (1978)



(a)



(b)

DL NEG# 9-150-79

Allowed color, spin, and isospin configurations for diquark (Q^2) systems:

Recall $\{3\} \otimes \{3\} = \{\bar{3}\} + \{6\}$ for $SU(3)_c$

Now total $\psi = \psi_{space} \otimes \psi_{spin} \otimes \psi_{flavor} \otimes \psi_{color}$ must be antisymmetric

ψ_{space} symmetric if Q's in S-states

$\psi_{flavor} \sim \psi_{SU(2)}$ (isospin) if we consider u, d only

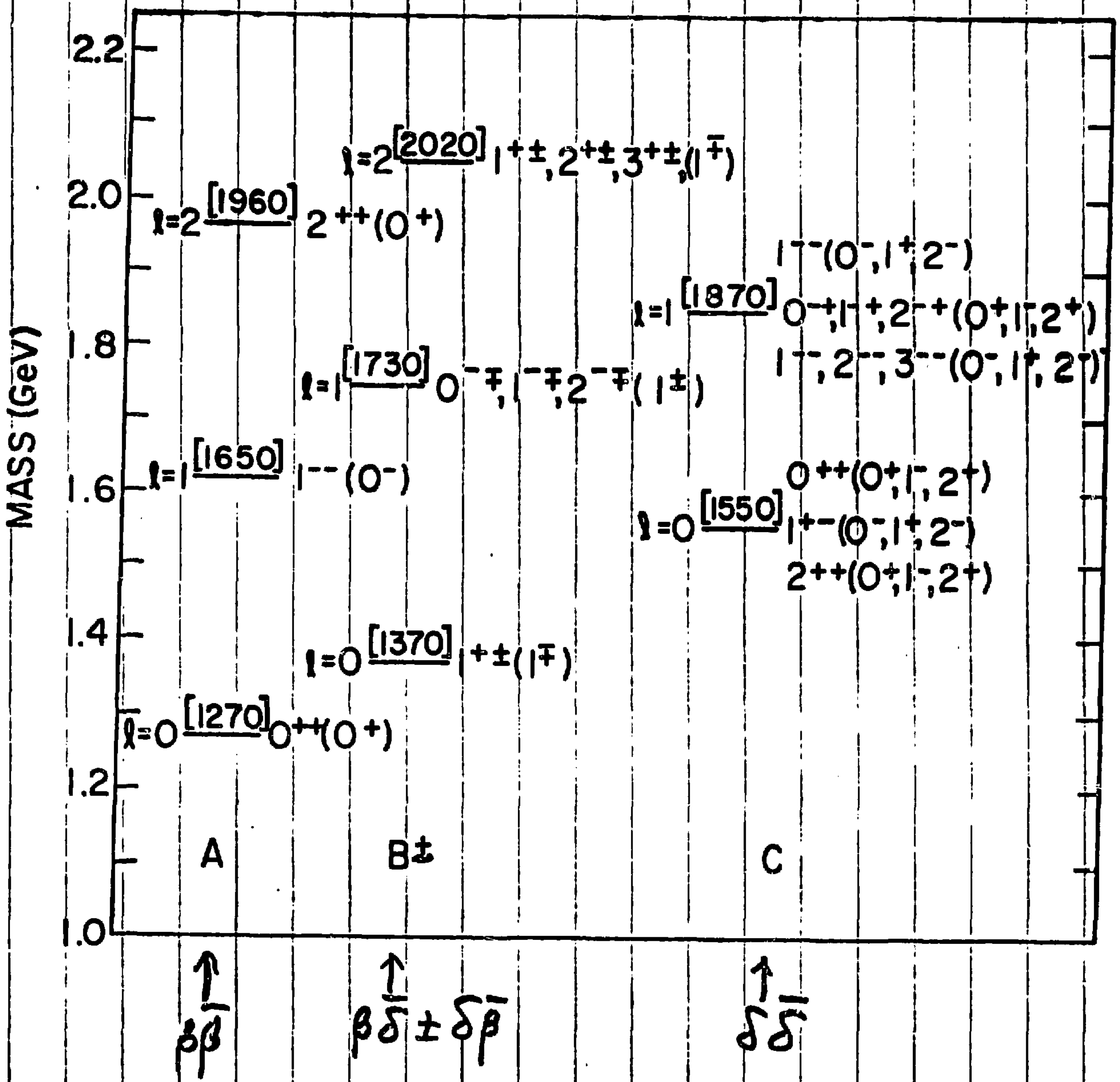
$$\psi_{color} = \begin{cases} \{\bar{3}\} \text{ antisymmetric } \left(\begin{smallmatrix}\square\\\square\end{smallmatrix}\right) \\ \{6\} \text{ symmetric } (\square\square) \end{cases}$$

$$\therefore \quad \psi_{spin} \otimes \psi_{isospin} = \begin{cases} \text{symmetric for } \{\bar{3}\}_c \\ \text{antisymmetric for } \{6\}_c \end{cases}$$

So allowed diquark configurations are

	Color SU(3)	Spin SU(2)	isospin SU(2)
α	$\{6\}$	0	1
β	$\{\bar{3}\}$	0	0
γ	$\{6\}$	1	0
δ	$\{\bar{3}\}$	1	1

SPECTRUM OF $Q^2\bar{Q}^2$ MESONS UP TO 2 GeV
$\{\bar{3}\} \times \{3\}$ of $SU(3)_c$

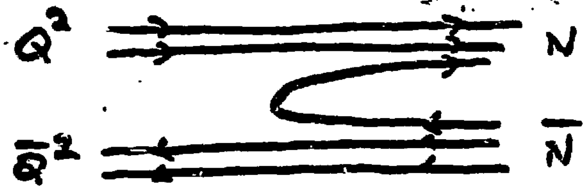


Possible mechanisms for narrow resonances

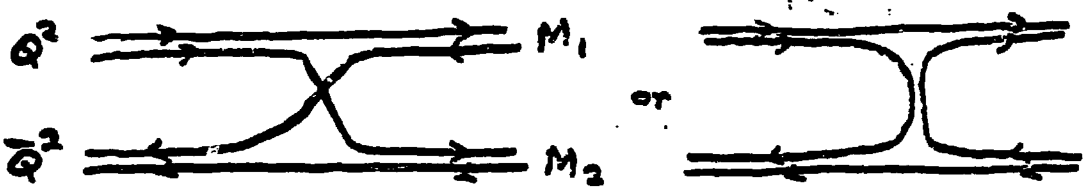
The $N\bar{N}$ potential model offers no obvious mechanism to suppress Γ_A (except centr. barrier

In the quark model, on the other hand, $Q^2\bar{Q}^2$ states prefer to couple to $B\bar{B}$ rather than to ordinary mesons, due to the

MODIFIED ZWEIG RULE: ($\varphi \to \bar{K}K$, not $\rho\pi$

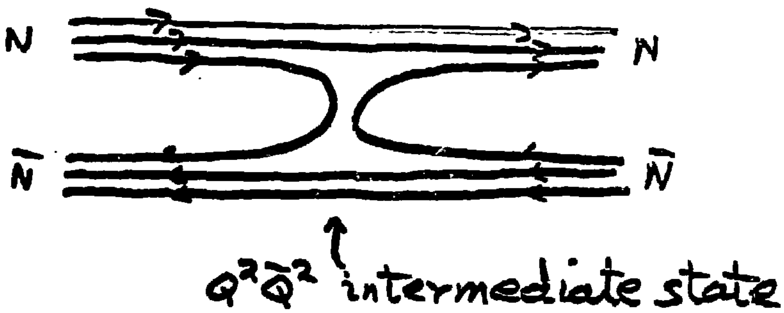


allowed



suppressed

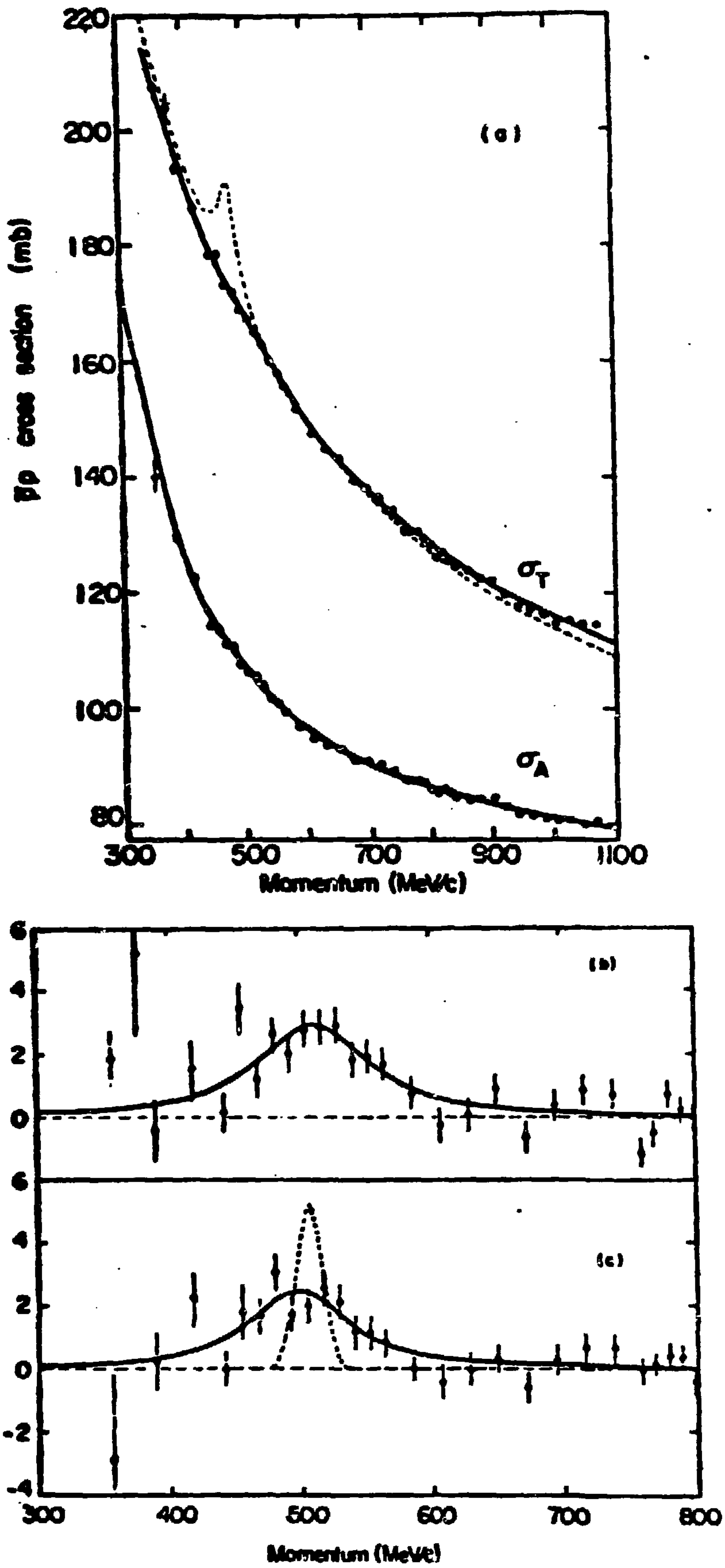
The situation is reminiscent of the appearance of narrow isobaric analog resonances in nucleon-nucleus elastic scattering [(p,n) + (n,p)
small W(r) in channel:



appreciable time delay in $Q^2\bar{Q}^2$ channel if $Q^2\bar{Q}^2 \leftrightarrow N\bar{N}$ coupling not too strong!

DISTINGUISHING FEATURES OF $\bar{N}N$ AND $Q^2\bar{Q}^2$ SPECTROSCOPY

$\bar{N}N$	$Q^2\bar{Q}^2$
1) coherent attraction for $I=0, S=1, L=J\pm1$ → $0^{++}, 1^{--}, 2^{++}, 3^{--}$ band lies lowest	1) $I=0, S=1, L=J\pm1$ band most strongly coupled to $\bar{N}N$
2) large isospin splittings for $S=1$	2) isospin degeneracy of leading trajectorie[s] $(I=0, 1, 2)$
3) no G-parity doublets for $\bar{N}N$	3) G-parity doublets ex. $2^{-+}(1^-), 2^{--}(1^+)$ $(\bar{\alpha}\beta, \alpha\bar{\beta})$
4) both parities near threshold	4) Negative Parity only near threshold (no P-states)



R. P. Hamilton et al, Physical Rev. Lett. 44, 1182(1

FORMATION EXPERIMENTS IN THE S-MESON REGION

Resonance	Experiment (Ref)	Type	RMS, Energy Resol. (MeV)	Precision mb/10MeV/c
I. PRE-BARR (1978)				
yes	CARROLL [1]	CTR	± 4.3	± 2.5
yes	CHALOUPKA [2]	BC σ_T,σ_A ...	1.5	2.2
yes	BRUCKNER [3]	CTR σ_A,σ_{EL}	1.0	0.7
yes	SAKAMOTO [4]	BC σ_T	1.5	4.3
yes	CLINE [11]	BC $\bar{p}p$ 180°	1.5	0.1 (mb/sr)
yes	D'ANDLAU [12]	BC $\bar{p}p$ 180°	1.5	0.1 (mb/sr)
no	ALSTON-GARNJOST [8]	CTR $\bar{p}p \to \bar{n}n$	5.5	0.2
II. 1979-1980				
no	ALSTON-GARNJOST [10]	CTR $\bar{p}p$ 180°	3.0	0.04 (mb/sr)
no	HAMILTON [9]	CTR $\bar{p}p \to \bar{n}n$	1.5	0.14
yes	DEFOIX [16]	BC $\bar{p}p \to 5\pi$	1.5	1.4
possible	HAMILTON [6]	CTR σ_T,σ_A	1.5	0.6
no	KAMAE [18]	CTR σ_T	1.5	2.7
no	JASTRZEMBSKI [19]	CTR σ_A	1.5	0.9
no	LOWENSTEIN [20]	CTR σ_A	2.0	0.9
no	CRESTI [21]	BC σ_T,σ_A ...	1.5	1.8
	HEIDELBERG-SACLAY running	CTR σ_T,σ_A		
	BNL . scheduled	CTR σ_T		

R. Tripp, Bressanone Conf. (1980)

MOMENTUM SPECTRUM
OF SPECTATOR p_s

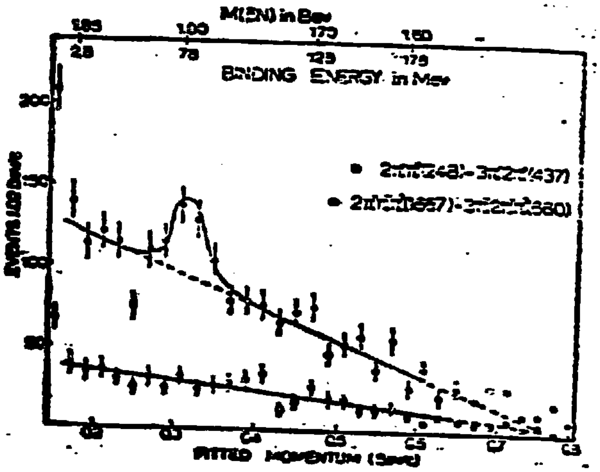
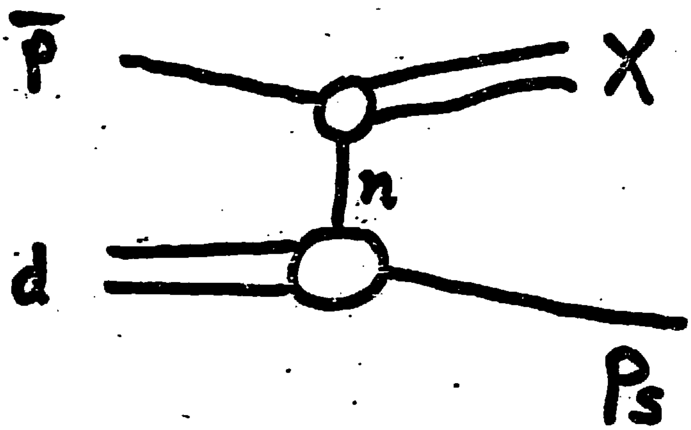


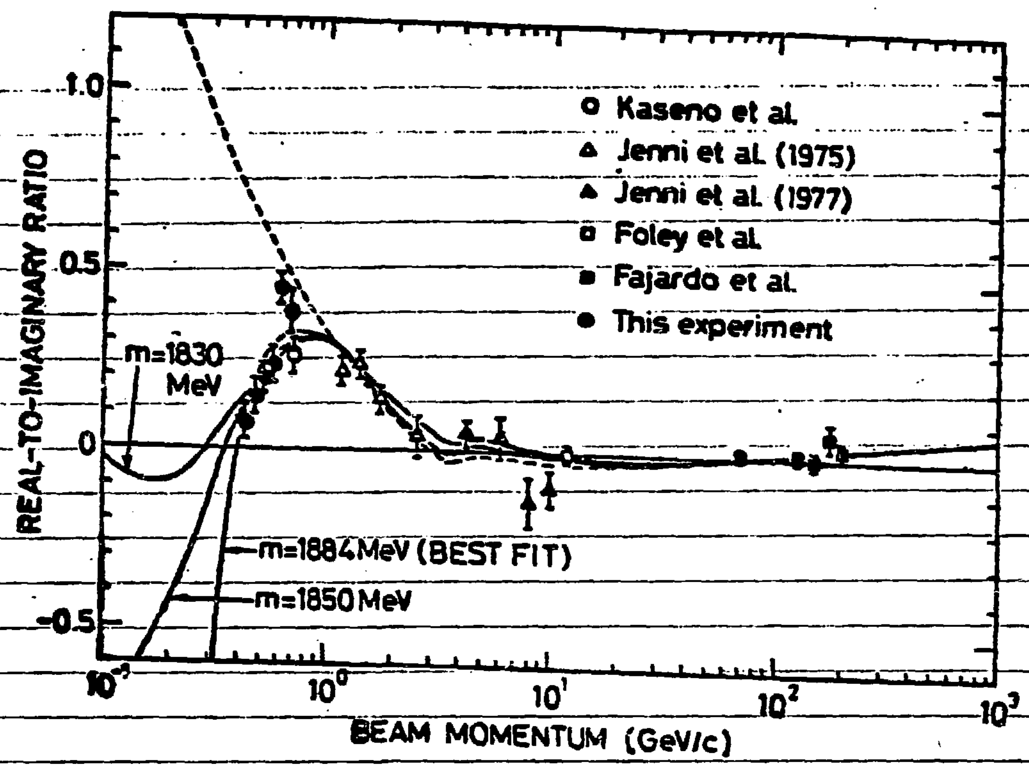
FIG. 2. Fitted momentum spectra

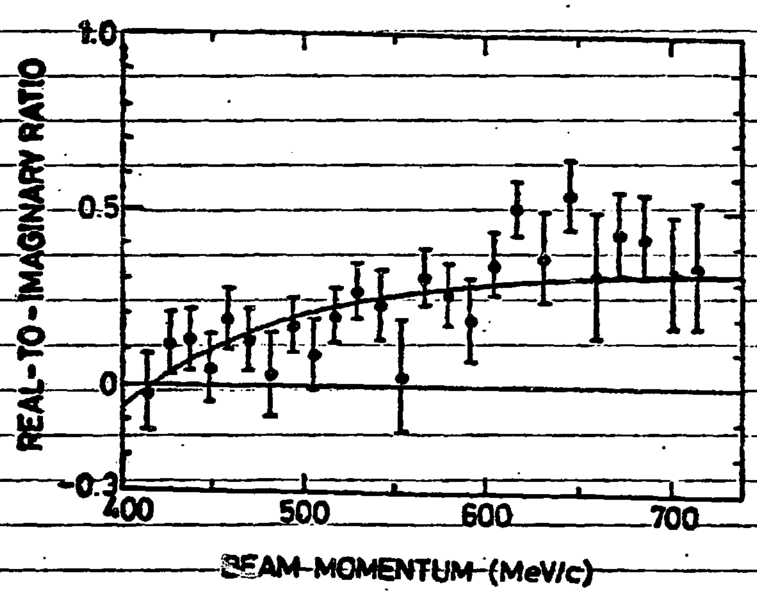
$$\bar{p} + d \rightarrow p_s + X$$



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

$\bar{p}p$ ELASTIC AMPLITUDE : REAL PART





H. Iwasaki et al, Phys. Lett. 103B, 157(1981)

1-681-82

Rates for $\bar{p}p \to M_i M_j$ at rest

(Baltay et al, Phys. Rev. Lett 15, 532 (1965))

$M_i M_j$	Rate
$\pi^+\pi^-$	3.2×10^{-3}
K^+K^-	1.1×10^{-3}
$K_1^0K_1^0 + K_2^0K_2^0$	0.9×10^{-5}
$K_1^0 K_2^0$	0.6×10^{-3}
$\pi^\pm \rho^\mp$	2.9×10^{-2}
$\pi^0 \rho^0$	1.4×10^{-2}
$\rho^0 \eta^0$	2.2×10^{-3}
$\rho^0 \omega^0$	7.0×10^{-3}
$\rho^0 \rho^0$	3.8×10^{-3}
$K^0 K^{0*}$	1.2×10^{-3}
$K^\pm K^{\mp *}$	0.9×10^{-3}
$K^{\pm *} K^{\mp *}$	1.3×10^{-3}
$K^{0*} \bar{K}^{0*}$	2.9×10^{-3}

TOTAL $\approx 6.3 \times 10^{-2}$ of annihilations

Selection Rules for $\bar{N}N \rightarrow M_i M_j$:

M_i = non-strange pseudoscalar meson

$\bar{N}N$: $P = (-)^{L+1}$ $\quad$ $M_i M_j$: $P = (-)^J$

$\underset{\sim}{J} = \underset{\sim}{L} + \underset{\sim}{S}$ $\quad$ $S = 0, J = L$

$G = (-)^{L+S+I}$ $\quad$ $G = G_i G_j$

1) conservation of parity P $\Rightarrow$ $J = L \pm 1$ for $\bar{N}N$

$\rightarrow$ $S = 1$ for $\bar{N}N$

2) cons. of G parity $\Rightarrow$ $(-)^{L+1+I} = G_i G_j$

$\rightarrow$ L+I odd for $\pi\pi$, $\eta\eta$; L+I even for $\pi\eta$

$\therefore$ $\bar{N}N \rightarrow \pi^+\pi^-$ from ${}^{13}P_{0,2}$, ${}^{33}S_1$, ${}^{33}D_{1,3}$ ....

$\bar{N}N \rightarrow \pi^0\pi^0, \eta^0\eta^0$ from ${}^{13}P_{0,2}$ ..... (I=0 only)

$\bar{N}N \rightarrow \pi^0\eta^0$ from ${}^{33}P_{0,2}$ .... (I=1 only)

DISCRETE γ-RAYS FROM $\overline{P}P$ ATOM

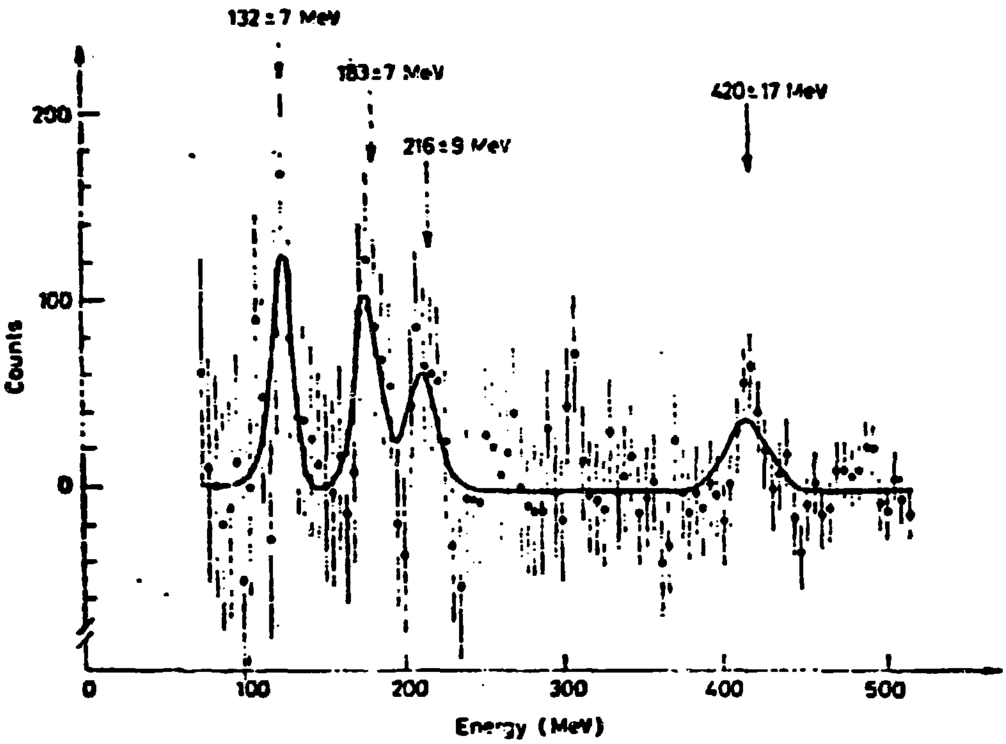


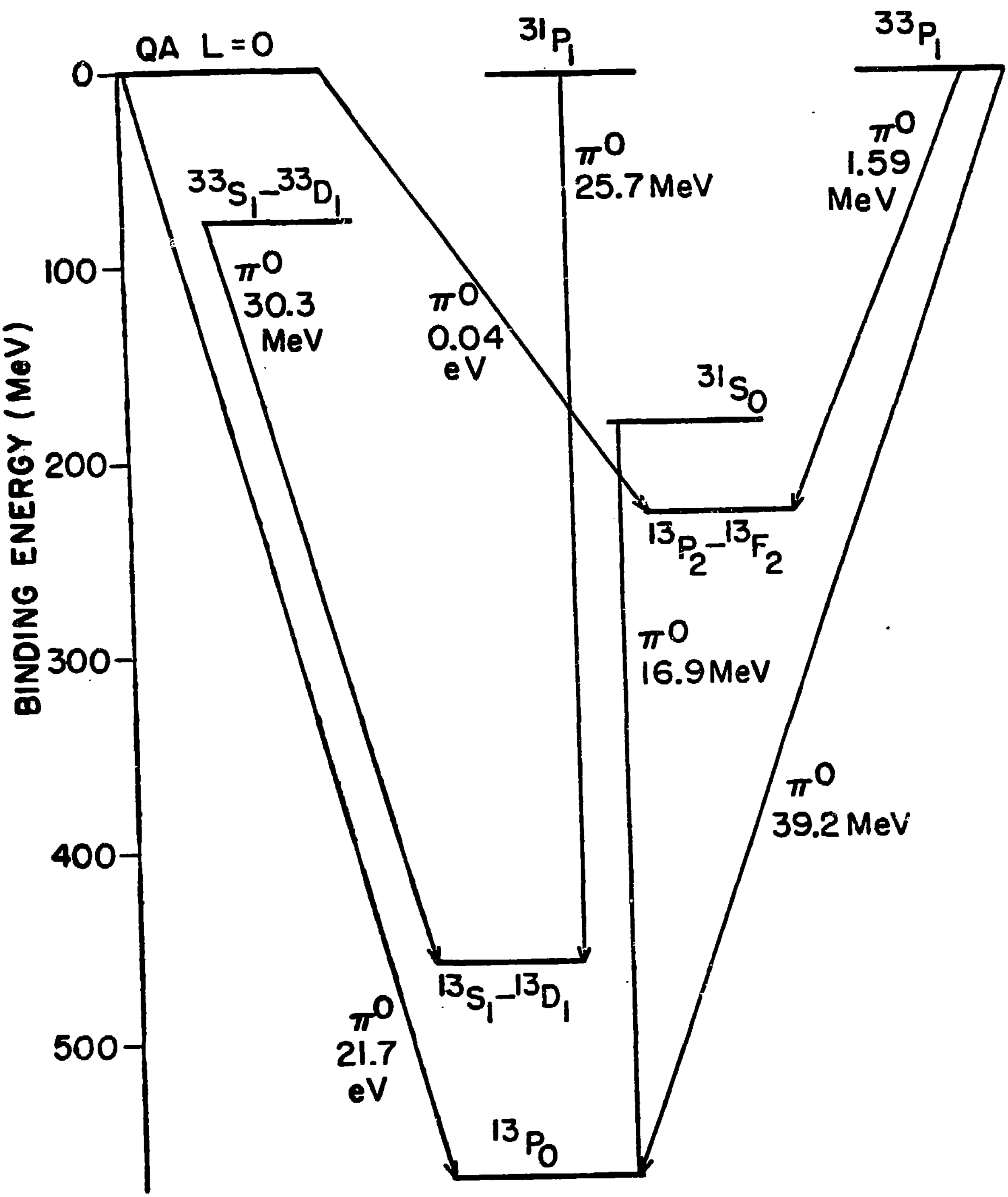
FIGURE 4 Gamma-ray spectrum as obtained after subtraction of a third order polynomial. The solid line corresponds to a computer fit to the peaks in the original spectrum.

TABLE I Results

Energy (MeV)	Instrumental line width (MeV)	Confidence level (%)	Yield per annihilation
132 ± 6	16	99.3	$(5.1 \pm 2.7) \times 10^{-3}$
183 ± 7	19	99.0	$(7.2 \pm 1.7) \times 10^{-3}$
216 ± 9	21	97.5	$(6.0 \pm 1.9) \times 10^{-3}$
420 ± 17	34	98.2	$(8.5 \pm 2.0) \times 10^{-3}$

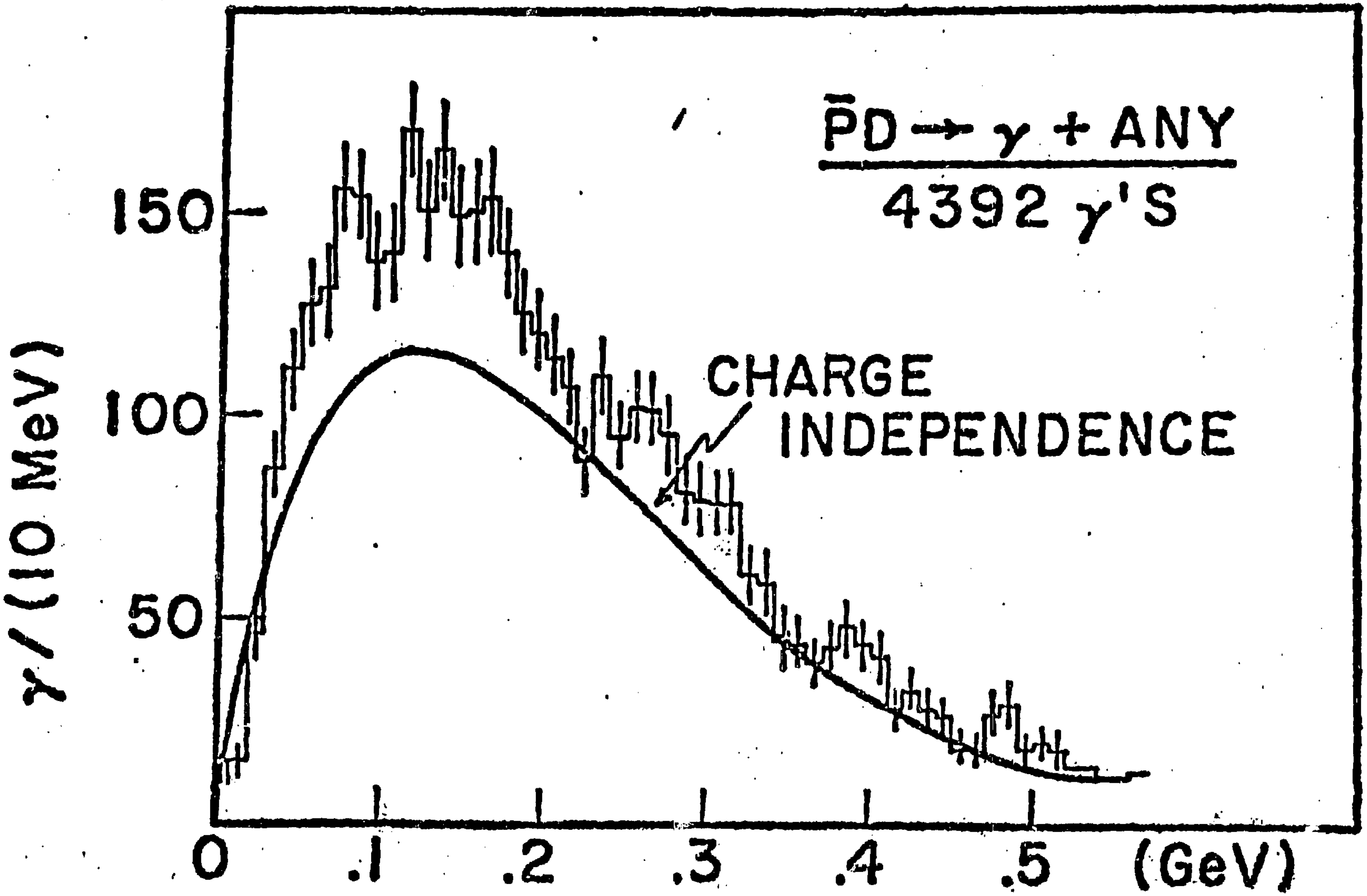
P. Pavlopoulos et al, Phys. Lett. B72, 415(19
(CERN)

π° Emission from p̄p system



Ann. Phys. 130, 70 (1980)

BNL NEG # 6-455-78



T. Kaloqeropoulos

ANL NEG# 10-236-75

PHYSICS WITH MULTI-GEV $\bar{p}$'s

1) $\bar{p}p \to e^+e^-$ timelike form factor of proton

4 nb at 1 GeV/c , 0.1 nb at 2.3 GeV/c

$\bar{p}d \to \bar{p}p + n$

$\quad \hookrightarrow e^+e^-$ look for 1^{--} states below $\bar{p}p$ threshold

$\bar{p}p \to V + \pi^0$

$\quad \hookrightarrow e^+e^-$

Problem: $\Gamma(\bar{p}p \to \ell^+\ell^- + \text{any}) / \Gamma(\bar{p}p \to h^+h^- + \text{any}) \doteq 10^{-9} - 10^{-8}$
must reject hadron pairs to 1 in 10^{10}

2) $\bar{p}p \to$ heavy quarks

$\bar{p}p \to \chi\ ({}^3P_{0,1,2})$ $\qquad \sigma \sim \mathcal{O}(1\,nb)$

$\to \eta_c, \eta_c'$ and ${}^1P_1$

$\to {}^1D_2, {}^3D_2, {}^3D_3$ $\bar{c}c$ states near $\bar{D}D^*$ threshol

$\to \bar{b}b$ states (rates 10^{-2} of $\bar{c}c$)

$\to H^0 \to \tau^+\tau^-$ if $m_{H_0} \doteq 10$ GeV

$\tau^+ \hookrightarrow e^+\nu\bar{\nu}$, $\tau^- \to e^-\nu\bar{\nu}$ $\quad (10^{-1} - 10^{-2}$ of $\bar{b}b)$

$\bar{p}$ - Nucleus Physics

a) Nuclear structure physics

anticipate strong <u>selectivity</u> in inelastic scattering → giant resonances

$\bar{p}$-scattering sensitive to $\rho_p(r)$, $\rho_n(r)$ in tail region

b) $\bar{p}$, $\bar{n}$ optical potential

real part very deep
absorption strong (?)
could be more transparent than expected!
(Pauli effect)

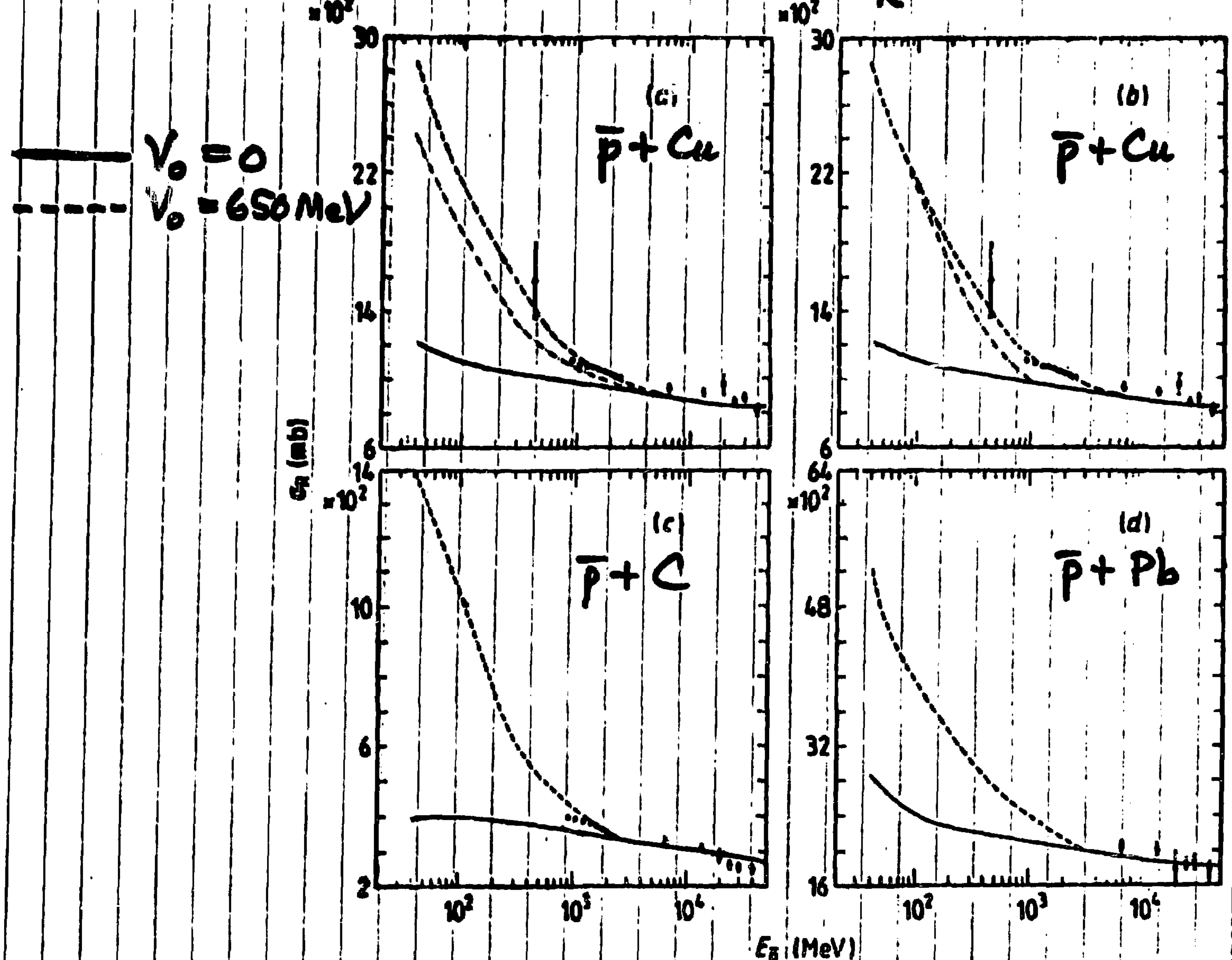
get V_0, W_0 from measuring σ_R or σ_{TOT}

could have radius difference $r_R - r_I$

single particle <u>spin-orbit</u> potential from <u>tensor</u> forces in 2nd order

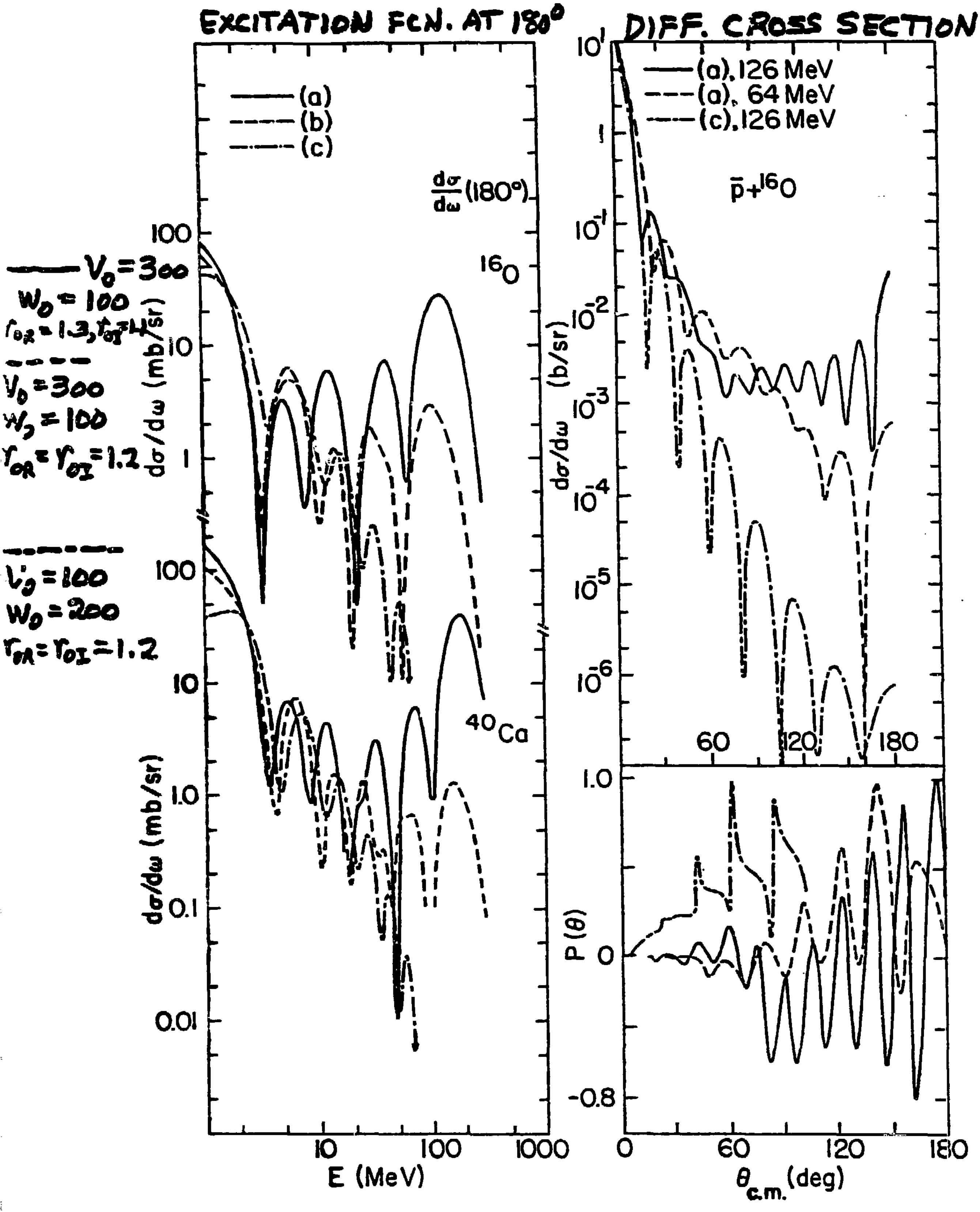
expect strong <u>isospin</u> <u>dependence</u> in both central and spin-orbit real well depths → do $(\bar{p},\bar{p})$, $(\bar{n},\bar{n})$, $(\bar{p},\bar{n})$ on nuclei

$\bar{p}$ - NUCLEUS TOTAL REACTION CROSS SECTION σ_R



N. DiGiacomo, J. Phys. G7, L169 (1981)

$\bar{p}$ – ^{16}O ELASTIC SCATTERING
^{40}Ca



E. Auerbach, CBD, S. Kahana, Phys. Rev. Lett. 46, 702 (1981)

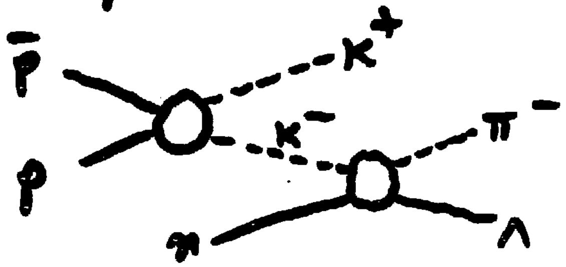
Interesting $\bar{p}$-induced reactions on nuclei

a) $(\bar{p}, p)$ with p at 0° and $\varepsilon_p \approx \varepsilon_{\bar{p}}$

$(\bar{p}, p\gamma)$ search for resonant $\bar{p} + (A-1)$ states and transitions between them

b) $\bar{p}$-induced fission of hypernuclei (Polikanov)

$\bar{p}$ + Pu or U



c) $(\bar{p}, X)$ X = heavy fragment $(d, \alpha \ldots)$