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Nuclear Physics with Antiprotons*

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Outline : $\boxed{\text{NUCLEAR PHYSICS WITH ANTIPROTONS}}$

1) salient features of <u>two-body $N\bar{N}$ interactions</u>

$N\bar{N} \overset{G}{\leftrightarrow} NN$

annihilation mechanisms (quark models)

optical model phenomenology

2) <u>$\bar{N}$ - nucleus interactions</u> (elastic, inelastic ....)

new cross section data (LEAR, BNL, KEK)

optical potentials

signatures of spin-isospin dependence of $N\bar{N}$ force

$(\bar{p}, p)$ reaction

3) <u>$\bar{N}$ - nucleus annihilation processes</u>

features of cascade or fluid dynamics calcs.

searches for baryonium and other exotica

meson interferometry

$(\bar{p}, NN)$ reactions

⋮

Features of the two-body $N\bar{N}$ Interaction

a) G-parity transformation for meson exchange

$$V_{NN} = \sum_i \quad = \sum_i V_i \quad \longrightarrow \quad V_{N\bar{N}} = \sum_i (-)^{G_i} V$$

where $G_i = C_i\,(-)^{I_i} = (-)^n$ for n pions

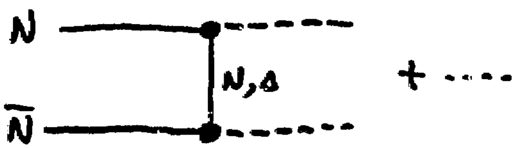
Consequences: π, ω change sign $\rightarrow$ strong attract

coherence in central and tens
forces $\rightarrow$ dramatic spin effect

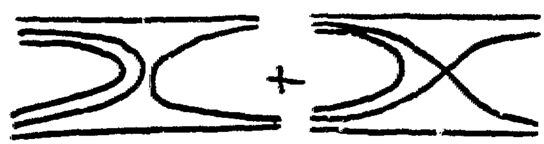
(ex. $\sigma_{\rightrightarrows} \approx 30\,\sigma_{\rightleftarrows}$ for $\bar{p}p \rightarrow \bar{n}n$)

b) strong annihilation for $N\bar{N}$ (absent for NN

baryon exchange picture:



Quark picture:



1) $\sigma_{TOT} \approx 250$ mb at 300 MeV/c ; $\boxed{\sigma_{Ann}/\sigma_{EL} \approx 2}$

$\sigma_{Ann} \approx \pi(R+\lambda\!\!\!^{-})^2 \longrightarrow R \approx 1.5\,\mathrm{fm}$

2) mean multiplicity of pions $\boxed{\langle N_\pi \rangle \approx 5}$ at E ≈

Phenomenological $N\bar{N}$ Optical Potentials:

$$\boxed{\mathcal{U}(r) = V_{meson}(r) + V_{Ann}(r) - i\,W(r)}$$

a) Absorption independent of spin S, isospin I, energy E

Dover-Richard, Phys. Rev. C21, 1466 (1980)

$$V_{ann}(r) - i\,W(r) = -(V_0 + i W_0)/(1 + e^{(r-R)/a})$$

$R = 0.8\,\text{fm}$, $a = 0.2\,\text{fm}$, $V_0 = W_0 = 500\,\text{MeV}$

b) Absorption strongly dependent on S, I, E

Coté et al, Phys. Rev. Lett. 48, 1319 (1982)

$$W(r) = \Big\{ g_c(1+f_c E) + g_{ss}(1+f_{ss}E)\,\underset{\sim}{\sigma_1}\cdot\underset{\sim}{\sigma_2} + g_T S_{12} + (g_{LS}/4M^2)\,\underset{\sim}{L}\cdot\underset{\sim}{S}\,\frac{1}{r}\frac{d}{dr}\Big\}\,\frac{K_0(2Mr)}{r} \quad \text{for } I = 0, 1$$

$\frac{1}{2M} = 0.1\,\text{fm}$

Features: $\boxed{W^{S=0} \gg W^{S=1}}$

$W^{00} : W^{10} : W^{01} : W^{11} = 1 : 0.81 : 0.11 : 0.07$ for $E \approx 0$

$W^{00}(200\,\text{MeV}) / W^{00}(100\,\text{MeV}) \approx 1.6$

c) coupled channel model (Nijmegen group)

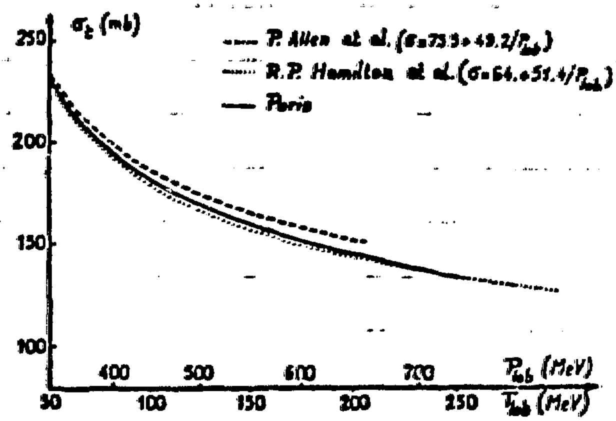
Timmers, van der Sanden + de Swart, Phys. Rev. D29, 1928 (198

Features: coupling potentials depend on I, not S or E

longer range (0.3–0.4 fm) than Coté et al

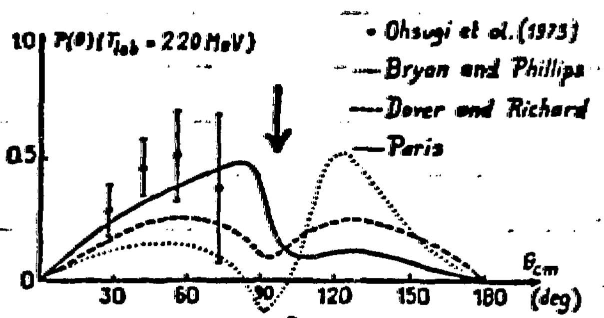
Sample fits to $N\bar{N}$ Data by Paris group

σ_{TOT}



TOTAL CROSS SECTION

P(θ)

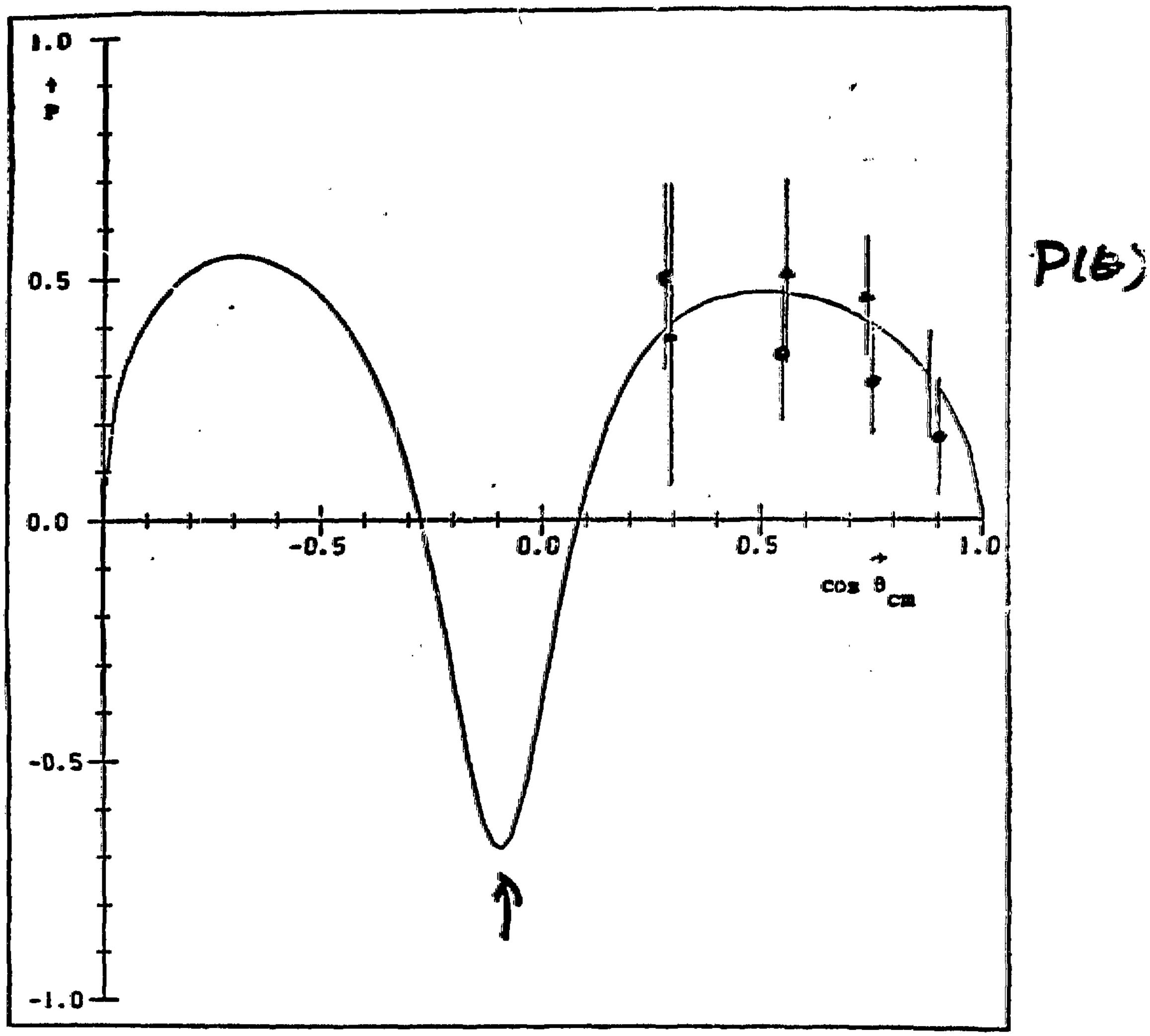


θ

POLARIZATI at E = 220 MeV

J. Coté et al, Phys. Rev. Lett. 48 (1982) 1319

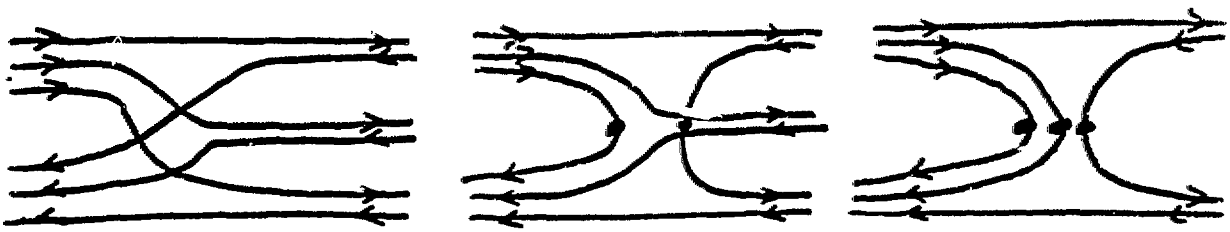
Sample fit to $N\bar{N}$ data by Nijmegen group



Elastic Polarization at E = 230 MeV

Guidance from the quark model:

Mechanisms:



"rearrangement" + ...

The "rearrangement" process gives rise to a separable annihilation potential (s-wave)

$$\boxed{V_{ann}(\underset{\sim}{r},\underset{\sim}{r}') = -\frac{\hbar^2}{M}\lambda\, I_{ann}(I,S,E)\, e^{-\frac{3}{4}\beta(r^2+r'^2)}}$$

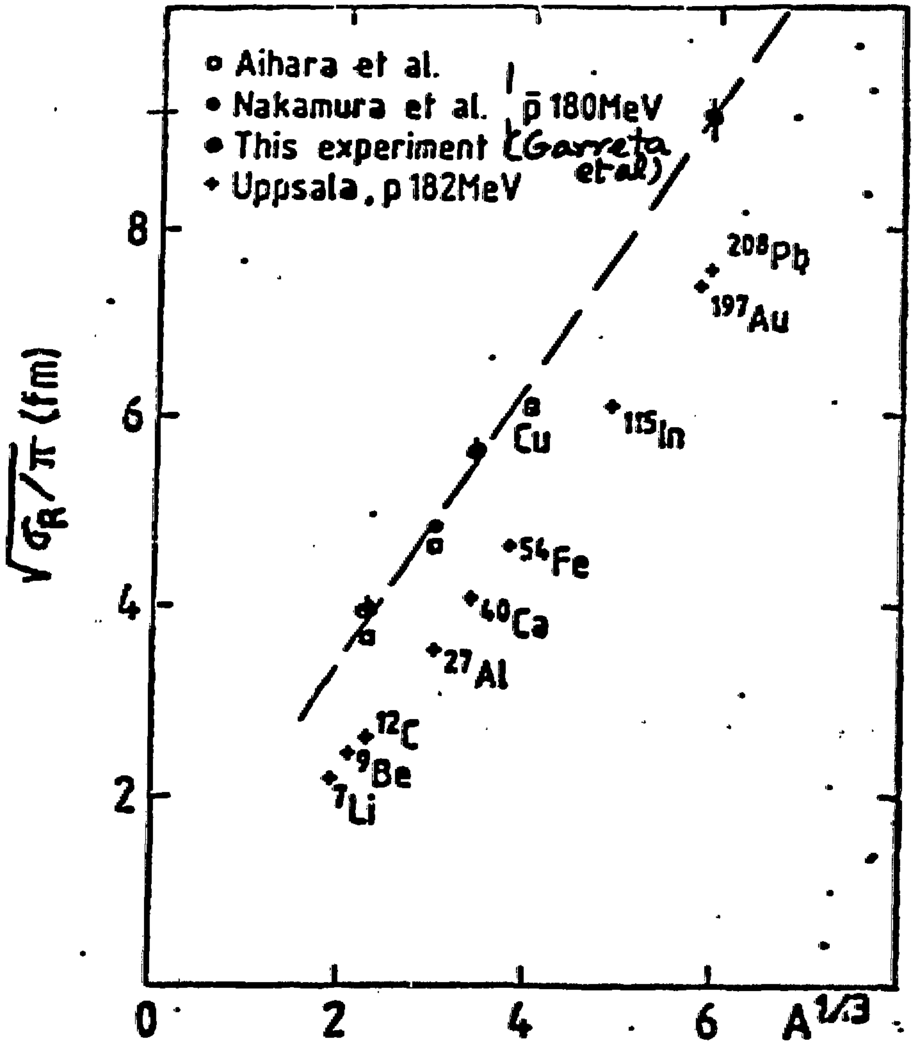
free parameter

oscillator wave fcns. for the quarks

This model is consistent with observed relative branching ratios for $\underline{N\bar{N} \to M_1 M_2 M_3}$ ($M_i = \pi, \eta, \rho, \omega$)

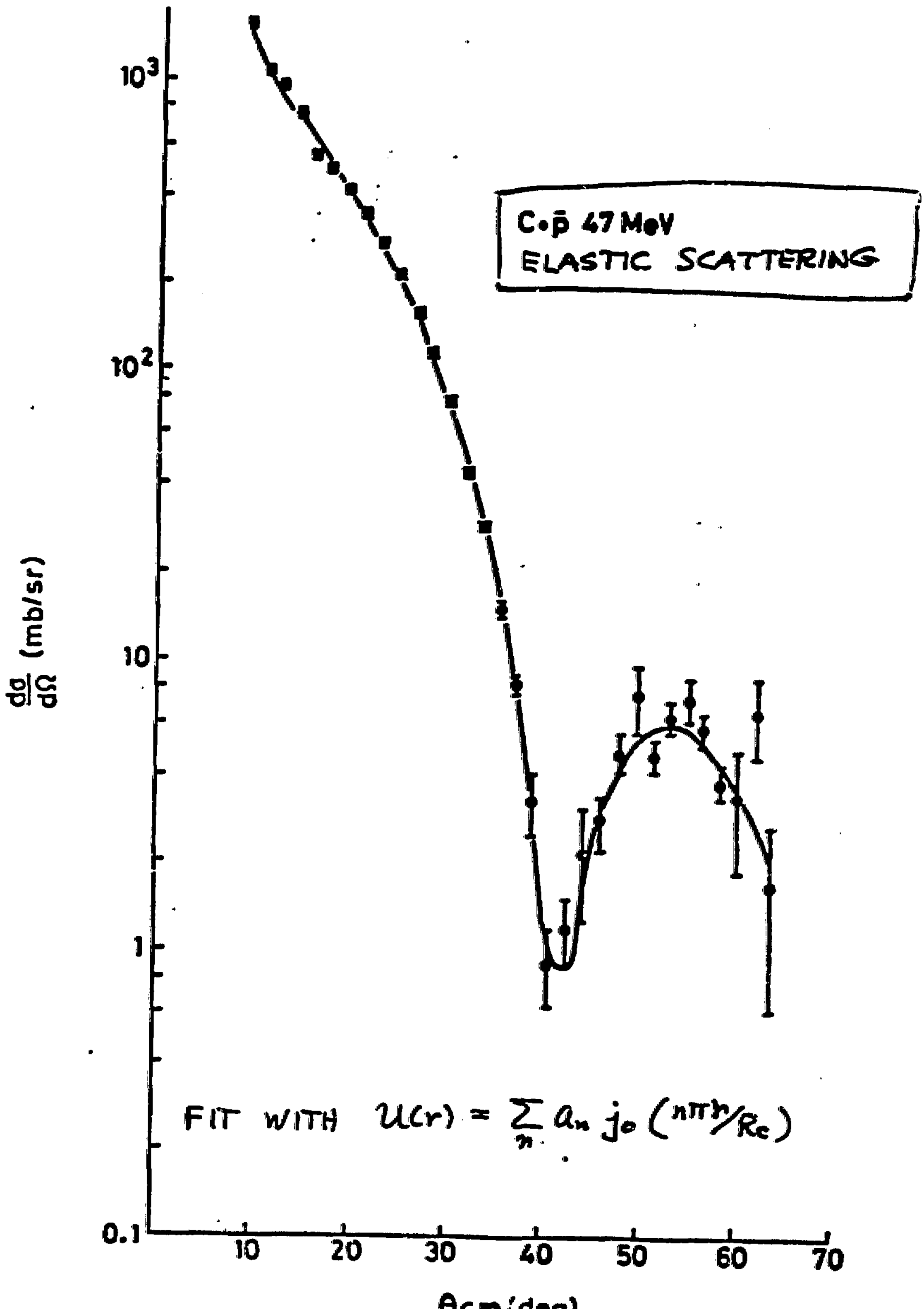
Refs: M. Maruyama + T. Ueda, Nucl. Phys. A364, 297 (1981);
Prog. Theor. Phys. 69, 937 (1983)
preprints OUAM 84-3-1 and 84-6-2
A. M. Green and J. Niskanen, Nucl. Phys. A412, 448 (1984)
Helsinki preprint HU-TFT-84-19
HU-TFT-84-33

$\bar{p}$ - nucleus reaction cross sections



— — $\boxed{\begin{array}{l}\sigma_R(\bar{p}A) = \pi(a + r_0 A^{1/3})^2 \\ a \approx 0.65 \text{ fm} \\ r_0 \approx 1.45 \text{ fm}\end{array}}$

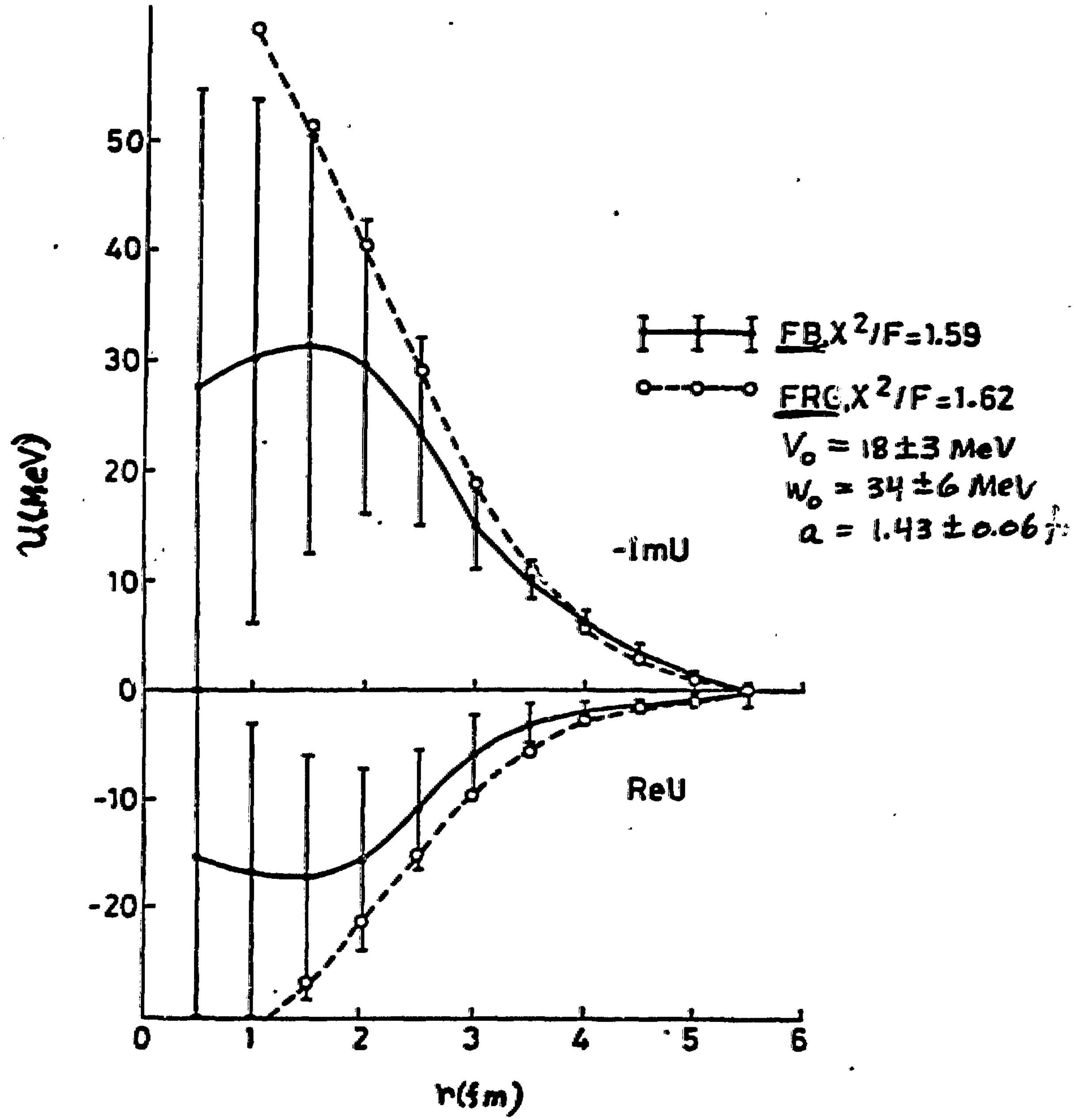
$+ = \sigma_R(pA)$ at 182 MeV



BATTY, FRIEDMAN + LICHTENSTADT. Phys. Lett. 142B, 241 (1984) + preprint

$\bar{p}+{}^{12}C$ OPTICAL POTENTIAL $\mathcal{U}(r)$ AT 47 MeV

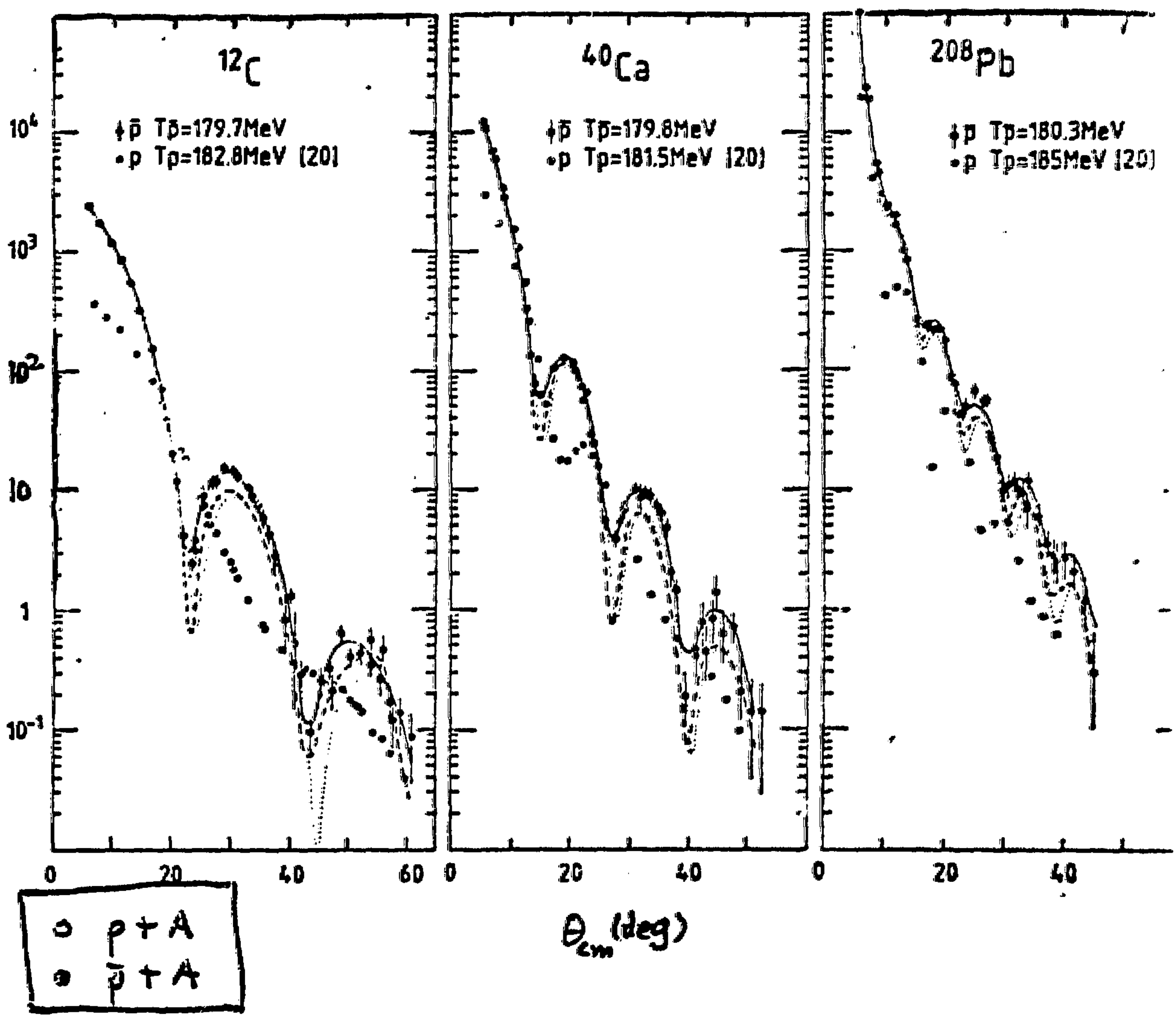
(FOURIER–BESSEL (FB) AND FINITE–RANGE GAUSSIAN (FRG) MODELS)



FB: $\mathcal{U}(r) = \sum_n a_n j_0(n\pi r/R_c)$

FRG: $\mathcal{U}(r) = -(V_0+iW_0)\int d^3\underset{\sim}{r}'\,\rho(\underset{\sim}{r}')\, e^{-(\underset{\sim}{r}-\underset{\sim}{r}')^2/a^2}$

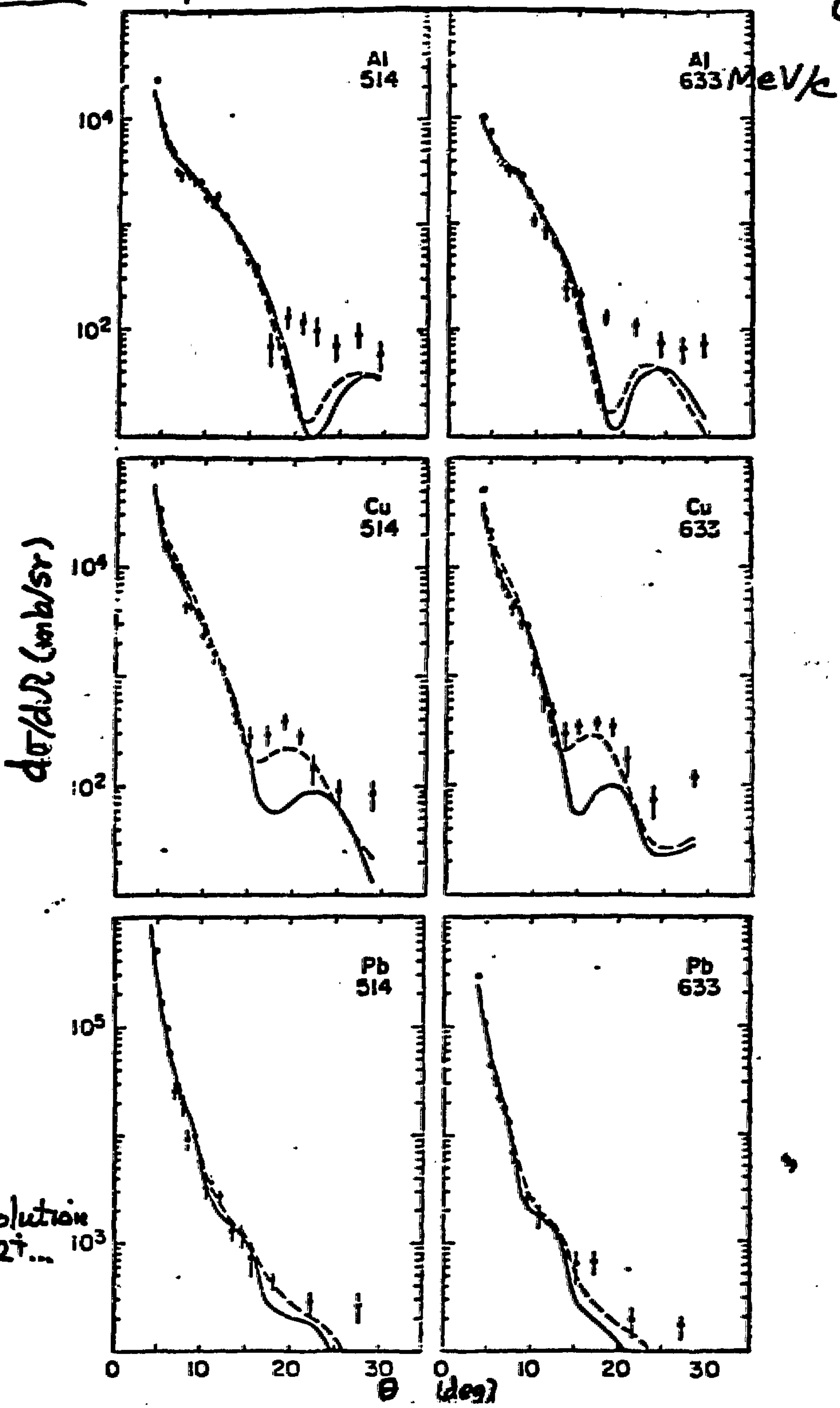
ANGULAR DISTRIBUTIONS FOR $\bar{p}$ – NUCLEUS ELASTIC SCATTERING



D. Garreta et al, CERN-EP/84-114 (September, 1984)

(Saclay – Grenoble – Strasbourg – Tel Aviv collab.)

BNL data on $\bar{p}$+Al, Cu, Pb : Ashford et al, Phys. Rev. C (1984)



coarse resolution → includes 2^+...

Phenomenological $\bar{p}$ Optical Potentials (Garreta et al)

$$\mathcal{U}(r) = -(V_0 + iW_0)\,\rho(r)/\rho(0) = V(r) + iW(r)$$

$V(r)$ and $W(r)$ determined near the strong absorption radius

$$R = \frac{1}{k}\left(\eta + \left(\eta^2 + \ell_{1/2}(\ell_{1/2}+1)\right)^{1/2}\right)$$

Target	P_{lab} (MeV/c)	R (fm)	V(R)	W(R)	V_0	W_0
^{12}C	300	3.7	−3.5	−8.5	35	77
^{12}C	600	3.3	−7.8	−19.6	44	96
^{40}Ca	600	4.9	−6.2	−13.3	43	119
^{208}Pb	600	8.2	−5.4	−10.8	60	152

$\underbrace{V(R),\ W(R),\ V_0,\ W_0}_{\text{in MeV}}$

1) <u>shallow real part</u> preferred : $\boxed{W(R)/V(R) \approx 2}$

2) fits with deep real part and shallow absorption not consistent with a global analysis of $\bar{p}$-atom + $\bar{p}$ elastic and inelastic data (Batty et al)

Estimates of the $\bar{N}$-nucleus optical potential:

a) simplest mean field theory (Bogута, Phys. Lett. 106B, 245 (1981));
(Bouyssy + Marcos, Phys. L. 114B, 397 (1982));
(Di Giacomo, J. Phys. G7, L169 (1981))

$$\mathcal{U}(r) = \int d^3\underset{\sim}{r}' \, \rho(\underset{\sim}{r}') \, \mathcal{V}_{N\bar{N}}(\underset{\sim}{r}-\underset{\sim}{r}')$$

→ extremely deep real part $(\sigma+\omega)$, $V_0 > 600$ MeV

$\boxed{\text{ruled out}}$ by the data on $\bar{p}$ elastic scattering

b) folding with free t-matrix (von Geramb et al, preprint (198
→ corrected for Pauli princi...

$$\mathcal{U}(r) = \int d^3\underset{\sim}{r}' \, \rho(\underset{\sim}{r}') \, t^{free}_{N\bar{N}}(\underset{\sim}{r}-\underset{\sim}{r}')$$

→ gives repulsion in nuclear interior, weak attraction in tail region (if Paris $N\bar{N}$ potential used)

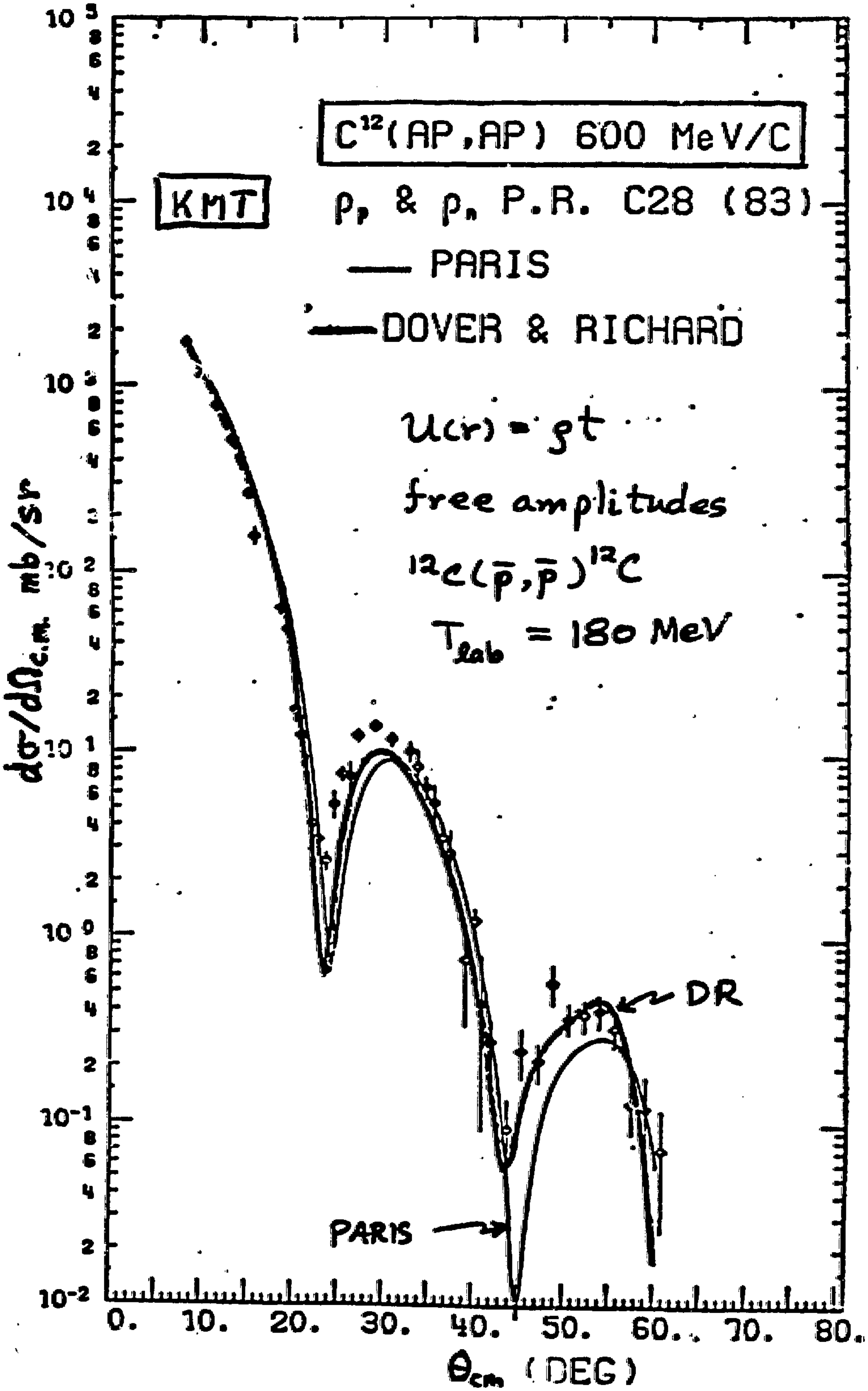
sign of $\mathrm{Re}\,\mathcal{U}(r)$ for large r related to number of bound states in $N\bar{N}$ potential

c) folding with self-consistent t in the nuclear medium

Green + Wycech, Nucl. Phys. A377, 441 (1982)
Niskanen + Green, Nucl. Phys. A404, 495 (1983)
Kronenfeld, Gal + Eisenberg, Nucl. Phys.

→ due to large absorption, self consistency important
→ $\boxed{\text{changes sign of real part in interior}}$

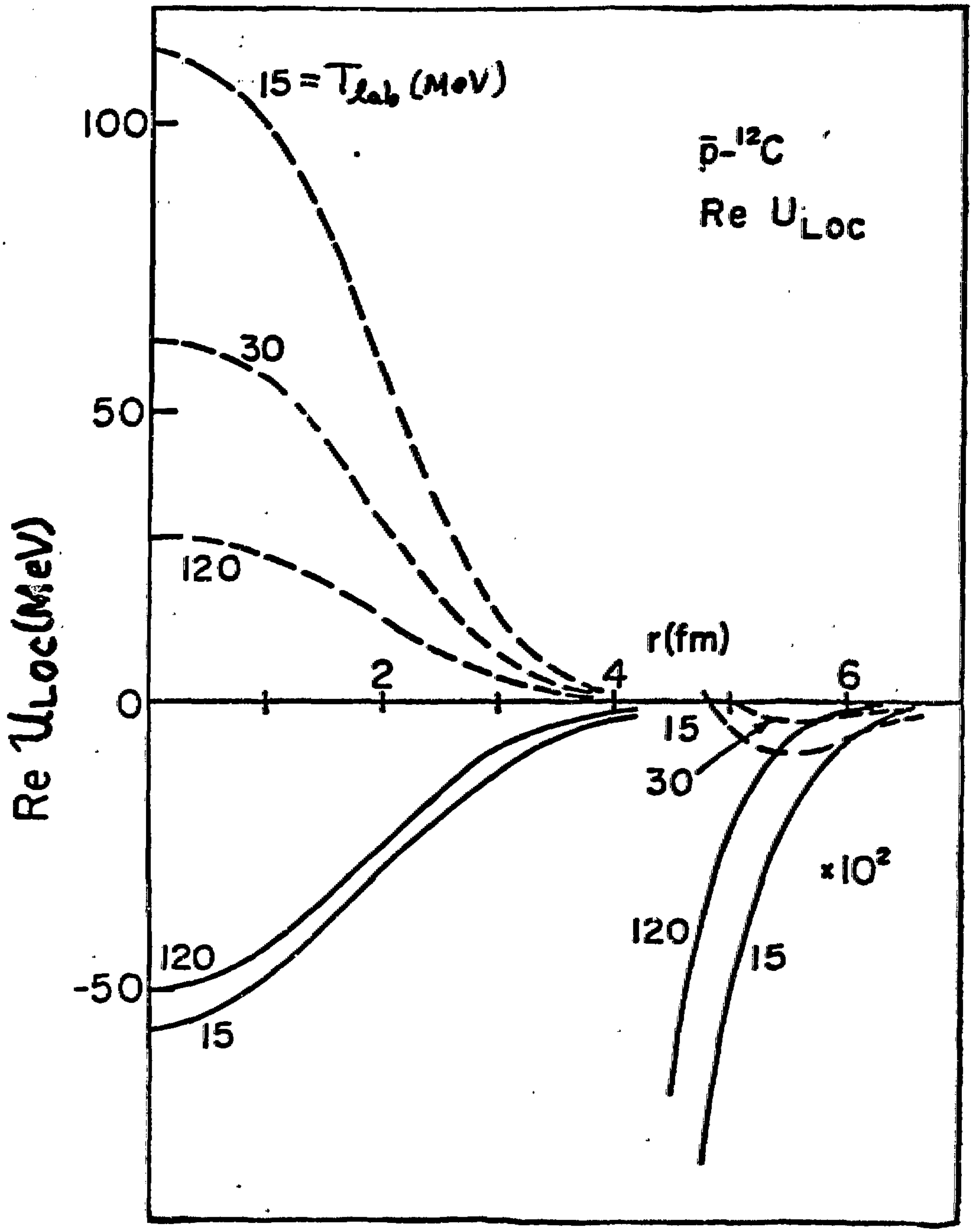
A. Chaumeaux



C¹²(AP,AP) 600 MeV/C
KMT
ρp & ρn P.R. C28 (83)
PARIS
DOVER & RICHARD
U(r) = ρt
free amplitudes
¹²C(p̄,p̄)¹²C
Tlab = 180 MeV
DR
PARIS
dσ/dΩc.m. mb/sr
θcm (DEG)

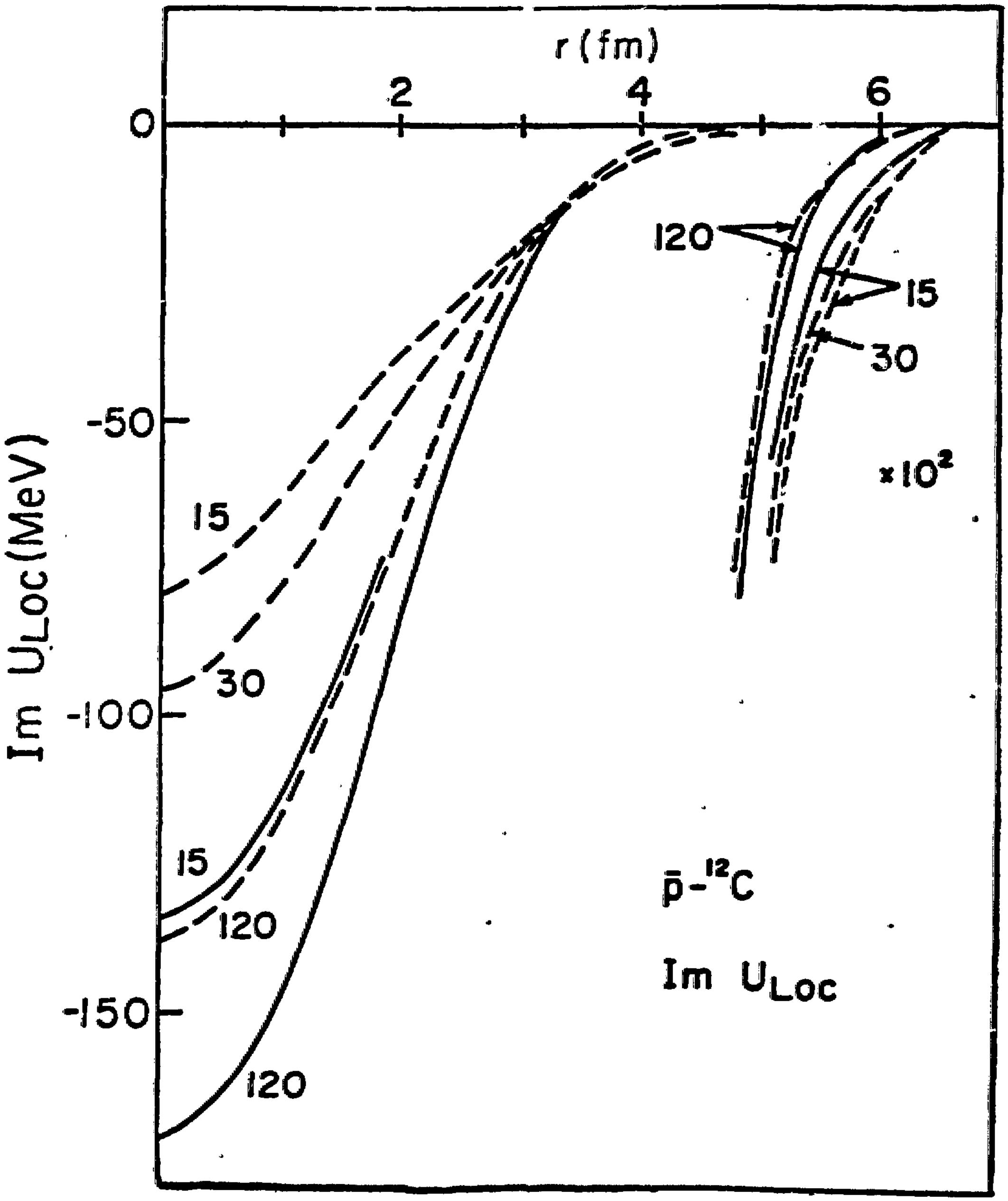
Kronenfeld, Gal & Eisenberg (1984)

Local Equivalent $\bar{p}$ Optical Potential $\mathcal{U}_1$

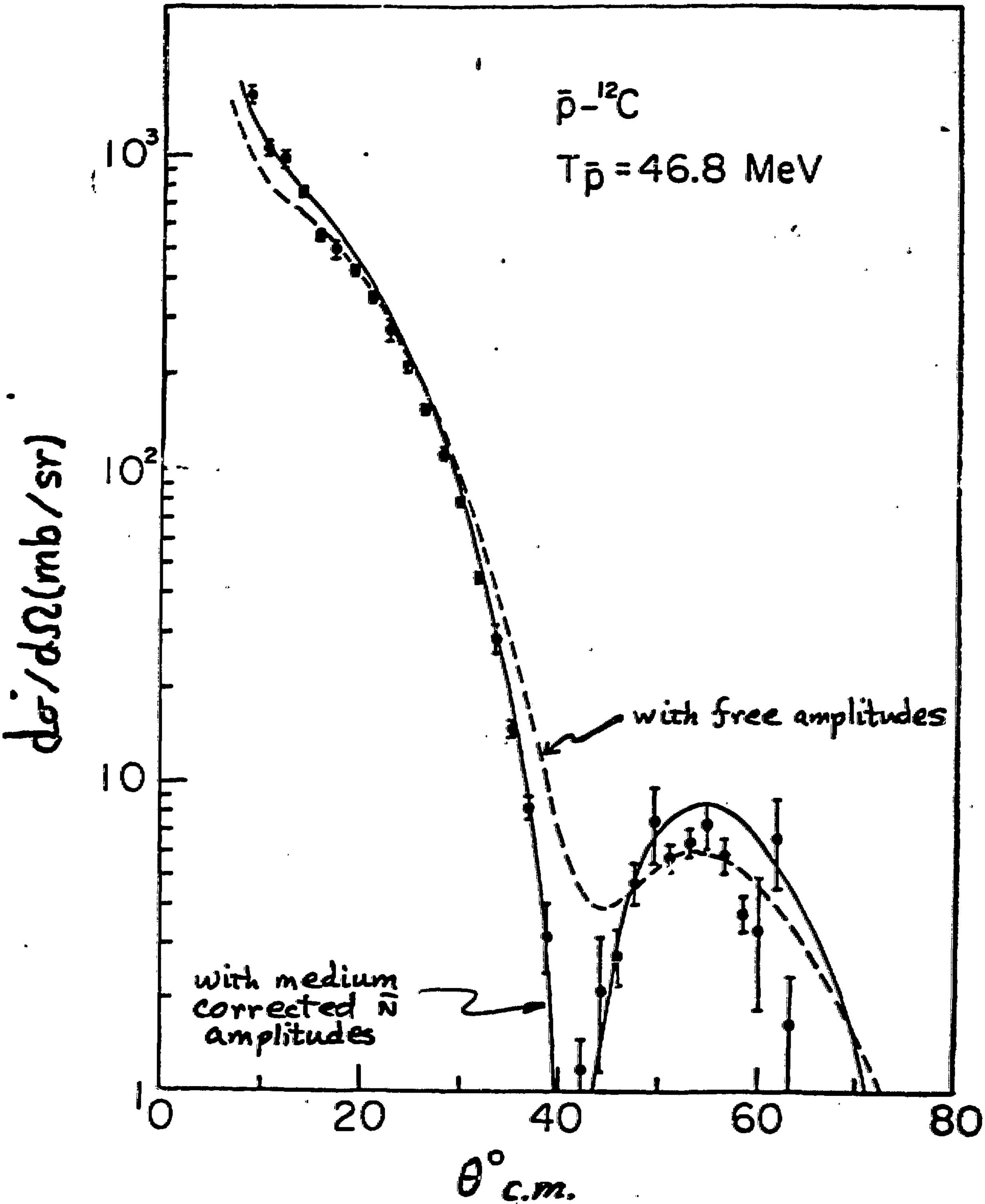


dashed curves: "$t\rho$" approximation
solid curves: with medium corrections

Kronenfeld, Gal & Eisenberg (1984)



Kronenfeld, Gal + Eisenberg (1984)



$\bar{P}$ INELASTIC SCATTERING ON ^{12}C

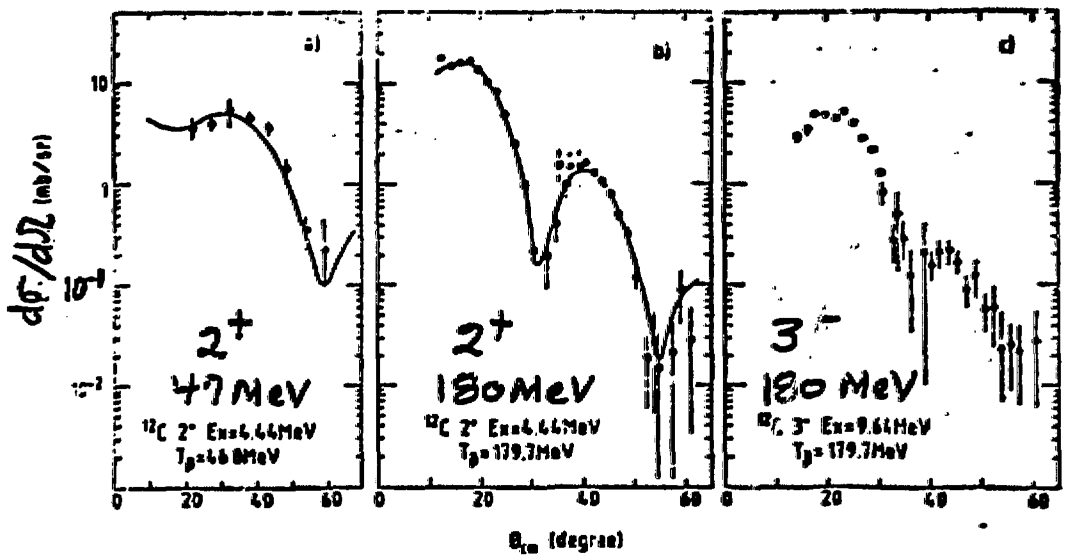


Fig. 5 Differential cross-section for $\bar{p}$ + ^{12}C inelastic scattering. In (a) each point corresponds to a measurement integrated over an angular range of 7.2°. In (b) and (c) the angular resolution is the same as for elastic scattering (see text). The solid curves result from a coupled channel fit to the data with the following parameters: (a) the optical-potential parameter are those of Fig. 3 and the deformation length $\beta_2 R$ = − 1.6 fm; (b) $(V_0, W_0, r_{0V}, a_V, r_{0W}, a_W)$ = (41; 176 MeV, 1.116 fm, 0.522 fm, 1 fm, 0.487 fm) and βR = − 1.71 fm.

D. Garreta et al, CERN-EP/84-114 (1984)

ANTINUCLEON - NUCLEUS ELASTIC AND INELASTIC SCATTERING:

1) good signatures of spin and isospin dependence of two-body $\bar{N}N$ force:

a) ratios of inelastic cross sections to final states with $\Delta S = 1$, $\Delta T = 0, 1$

example: $1^+(12.7, T=0)$ and $1^+(15.1, T=1)$ in ${}^{12}C(\bar{p}, \bar{p}')^{12}C^*$

should use Dirac approach here

b) P-A can be large for $\Delta S = 1$ transiti[tion] (polarization - asymmetry)

c) elastic and charge exchange $(\bar{p}, \bar{n})$ polarizations

2) Quantities which are relatively insensitive to S, I dependence of $\bar{N}N$ force:

a) σ_R

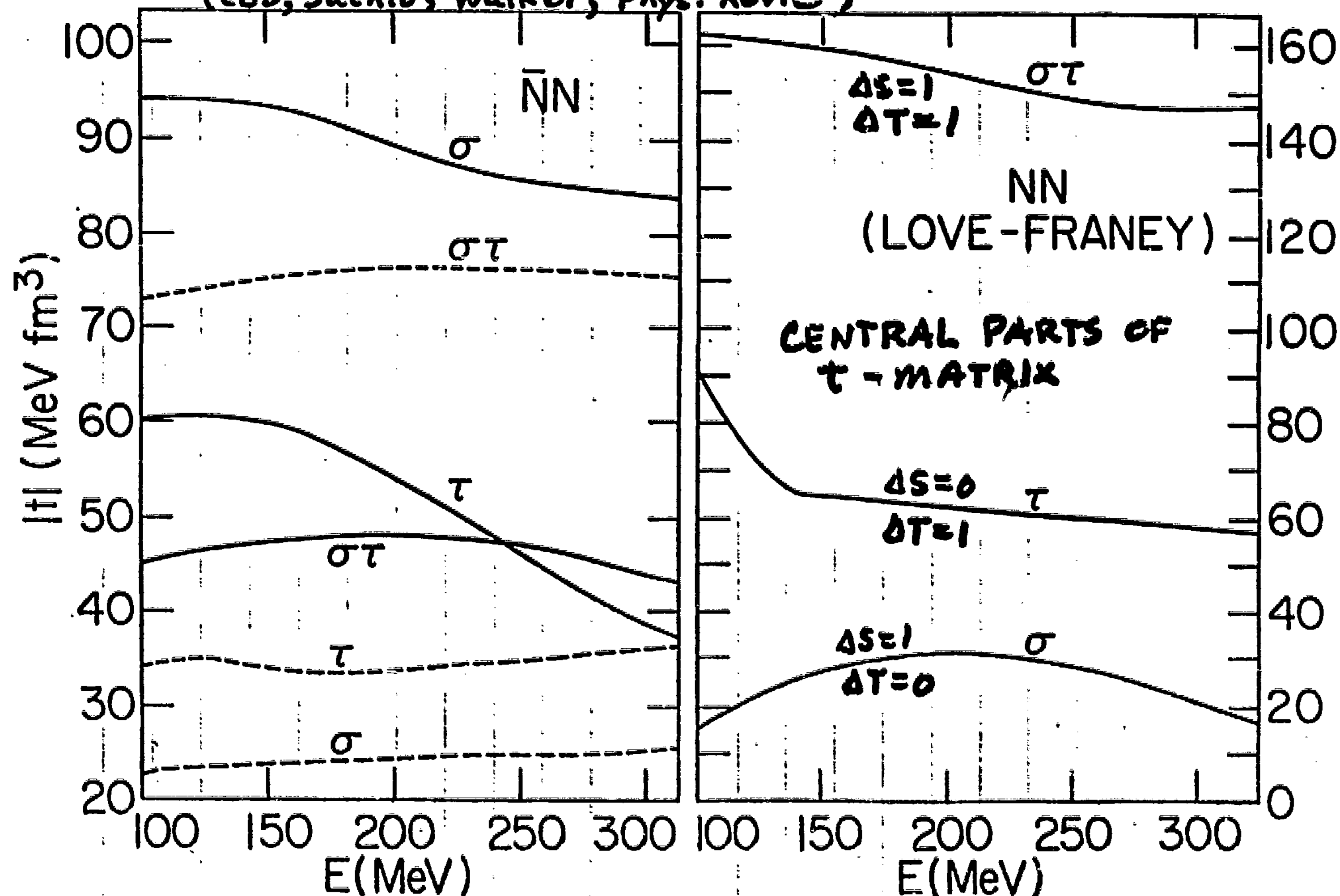
b) σ_{EL}, $d\sigma_{EL}/d\Omega$

c) $d\sigma_{inel}/d\Omega$ to states excited by $\Delta S = \Delta T = 0$ part of $N\bar{N}$ force

here, detailed fits to data give us R_{abs}, $\left.\frac{V(r)}{W(r)}\right|_{R_{abs}}$

→ need guidance from theory for geometrical aspects (folding model with range of $t_{N\bar{N}}$ included

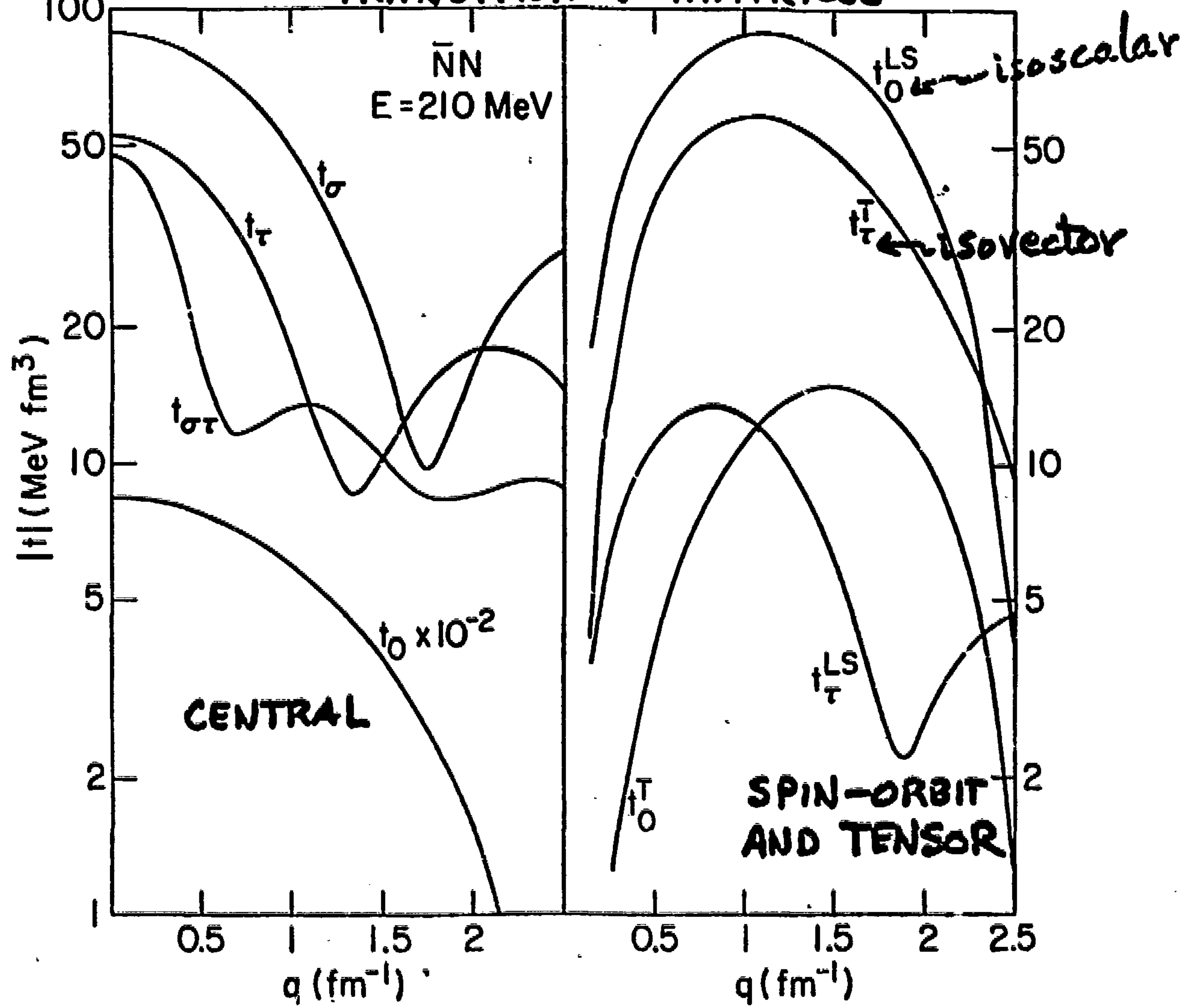
TRANSITION t-MATRICES FOR $\bar{N}$ AND N INELASTIC SCATTERING ON S=0 I=0 NUCLEI
(CBD, Sainio, Walker, Phys. Rev. C)



——— Coté et al

- - - - Dover-Richard (spin-isospin independent W(r))

$\bar{N}$ INELASTIC SCATTERING ON NUCLEI
TRANSITION t-MATRICES



CBD, Sainio, Walker, ~~BNL preprint~~ Phys. Rev. C28, 2368 (1983)

RESULTS FOR $^{12}C(\bar{p},\bar{p}')^{12}C^*$ [Franey, Sainio, Love Walker, CBD]

Define $R = [d\sigma/d\Omega(1^+, 12.7, I=0)] / [\frac{d\sigma}{d\Omega}(1^+, 15.1, I=$

At $E = 175$ MeV ($p_{lab} = 600$ MeV/c), we find

θ_{cm}	R(Paris)	R(DR)	Paris $d\sigma/d\Omega$ (15.1)	DR $d\sigma/d\Omega$ (15.
0°	$\boxed{0.44}$	$\boxed{0.05}$	0.33 mb/sr	0.45 mb/
5°	0.60	0.11	0.20	0.26
10°	0.38	0.15	0.20	0.20
15°	0.30	0.16	0.14	0.14

Conclusions:

1) best test of P vs DR models at 0°
→ order of magnitude difference in R !
→ reflects large difference in t_σ
(i.e. $\Delta S=1$, $\Delta T=0$ to 12.7 state)

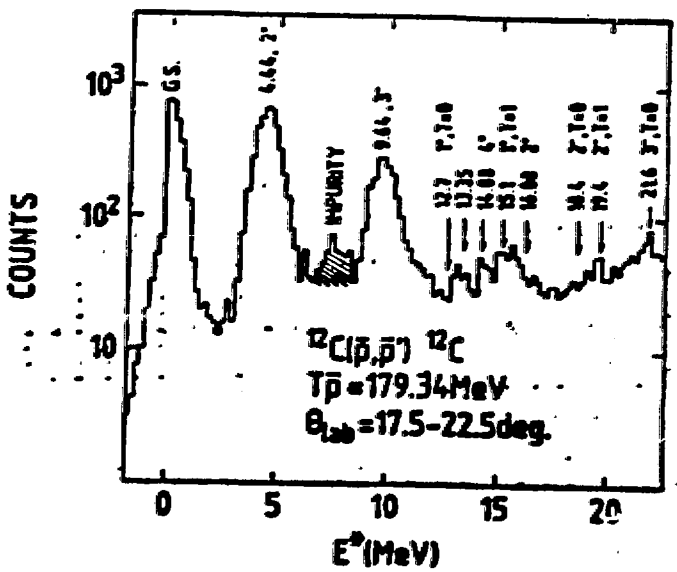
2) for larger angles, V_{LS}, V_T, V_{TQ} operators become important (spin-orbit and tensor for higher q). These contributions do not differ qualitatively for P vs DR

example: 1^+(15.1) cross sections

θ	V_c only (central)	$V_c + V_{LS}$	$V_c + V_{LS} + V_T + V_{TQ}$
0°	0.21 mb/sr	0.21	0.33
10°	0.0014	0.0028	0.20

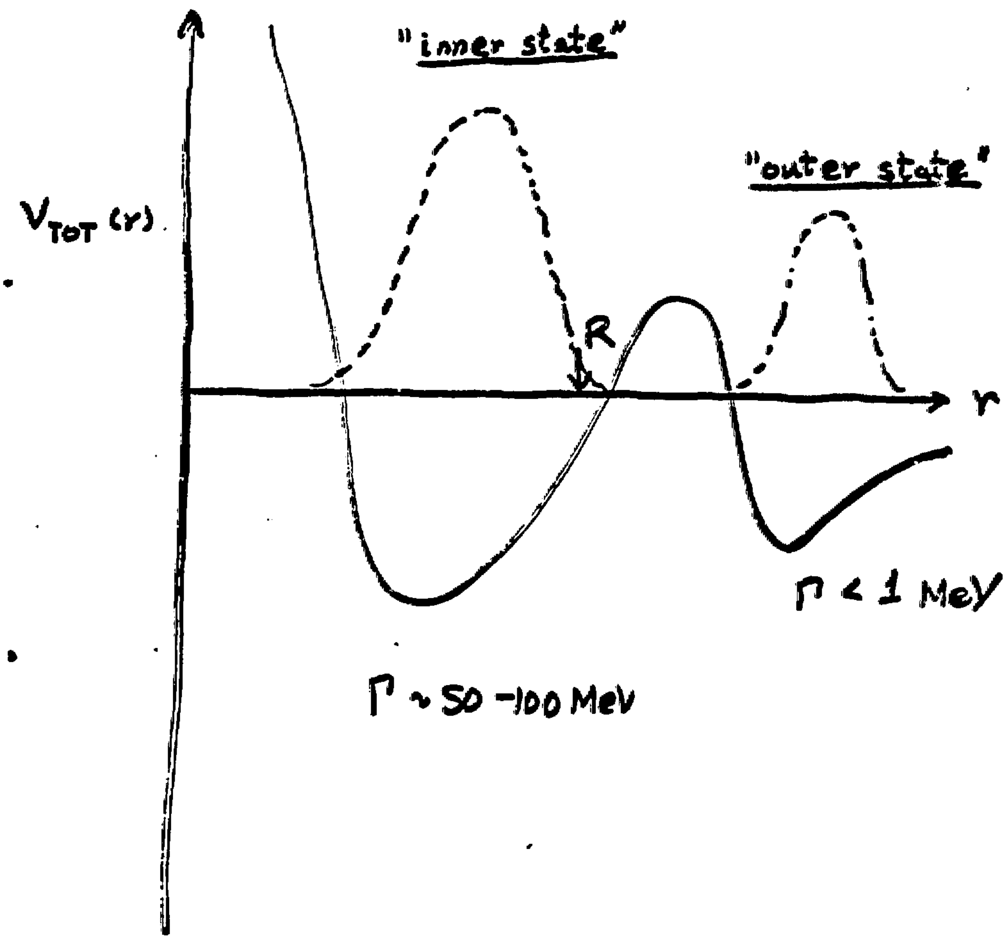
EXCITATION FUNCTION FOR $^{12}C(\bar{p},\bar{p}')^{12}C^*$

INELASTIC SCATTERING AT 180 MeV



D. Garreta et al, LEAR experiment (preliminary)

Two classes of $\bar{p}$ states:



<u>How to produce these states</u>?

$(\bar{p}, p)$, $(\bar{p}, \pi)$ .... $(\bar{p}, \alpha)$

NOTE: the γ cascade through $\bar{p}$-atomic states terminates at 3d state in $\bar{p} + {}^{16}O$, but "outer" p, s states exist.

PROTON SPECTRA FROM $A(\bar{p},p)X$ REACTION

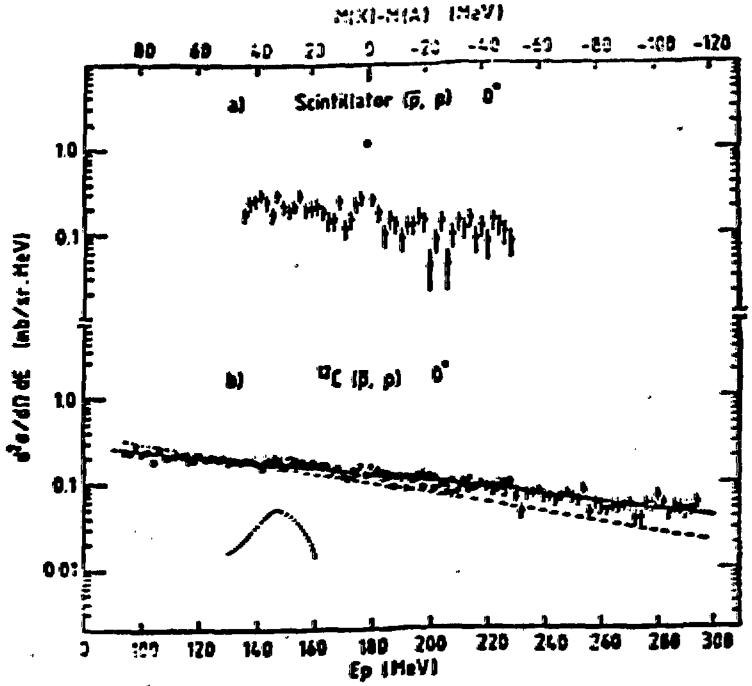
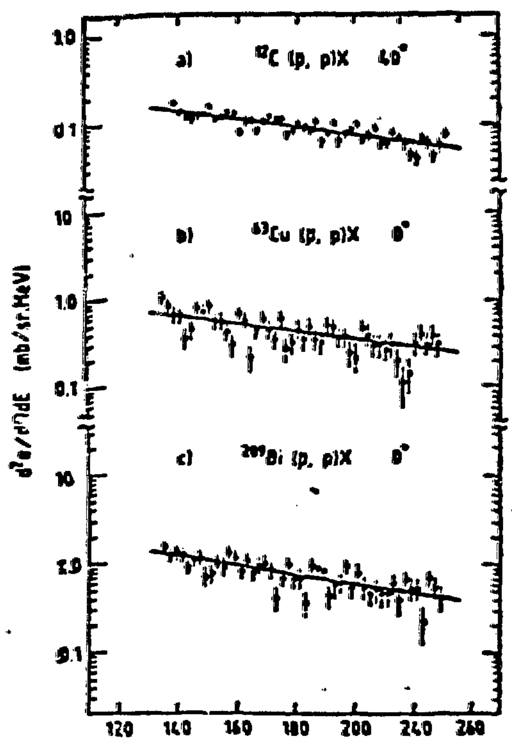


Fig. 6 Proton spectra for the $A(\bar{p},p)X$ reaction at $T_{\bar{p}} = 180$ MeV and 0° (a) for scintillator and (b) for carbon targets. The double differential cross-section is plotted versus the proton kinetic energy and the mass difference [M(X) − M(A)]. The sharp peak near 180 MeV in (a) corresponds to elastic scattering from hydrogen. Also shown are an INC calculation (dashed line) and a Maxwellian distribution best fit (solid line). A calculation for the quasi-free cross-section is indicated by the dotted curves.

$$\frac{d^2\sigma}{d\Omega dE}$$



D. Garreta et al
CERN-EP/84-9.
(July, 1984)

Fig. 7 The $(\bar{p},p)$ spectra from ^{12}C at 40°, and from ^{63}Cu and ^{209}Bi at 0°. The solid curves are best fits assuming a Maxwellian distribution.

also diGiacomo et al: $^{28}Si\,(\bar{p},p)$

FIT TO PROTON SPECTRUM FROM $(\bar{p}, p)$ REACTION

$$\boxed{\frac{d^2\sigma}{d\Omega dE} \approx C\sqrt{E}\, e^{-E/T}}$$

$$C \sim A^{0.63}$$

Parameters resulting from fits to p spectra with the expression $d^2\sigma/d\Omega dE = C\sqrt{E}\exp(-E/T)$

Target	θ_{lab} (degrees)	T (MeV)	C (μb/sr · MeV$^{3/2}$)
^{12}C	0	86 ± 1.5	80
^{12}C	40	77 ± 6	75
^{63}Cu	0	69 ± 10	405
^{209}Bi	0	69 ± 7	770

from Garreta et al, CERN-EP/84-92 (July, 1984)

(similar results for $^{28}Si(\bar{p}, p)$ from N. diGiacomo et al

for ^{31}P, estimate $d^2\sigma/d\Omega dE \approx 200$ μb/sr/MeV

at $E = 175$ MeV

Cross section estimates for $(\bar{p}, p)$ reaction:

a) "inner states"   ex. 1S bound by 2 MeV with $\Gamma \approx 95$ MeV in $\mathcal{U}(r)$ of Garreta et al ($\bar{p}+{}^{12}C$)

typical $d\sigma/d\Omega \sim 0.5$ mb/sr spread over 100 MeV

$\therefore$ $d^2\sigma/d\Omega dE \sim 5 \mu b/sr/MeV$

measured background $\sim 200 \mu b/sr/MeV$

$\rightarrow$ $\boxed{\text{signal/noise} \sim 1/40}$

Baltz, CBD, Sainio, Gal, Toker, BNL preprint

b) "outer states"

typical $d\sigma/d\Omega \sim 0.5 \mu b/sr$ spread over 100 keV

$\therefore$ $d^2\sigma/d\Omega dE \sim 5 \mu b/sr/MeV$

again, signal/noise $\sim 1/40$

Exception: ${}^{31}P(\bar{p}, p)({}^{30}Si + \bar{p})_{2S\ \text{atom}}$

Gibbs + Kaufman Phys. Lett.

has good wave function overlap
+ large spectroscopic factor for $\Delta L = 0$ transition

here $d^2\sigma/d\Omega dE \approx 80 \mu b/sr/MeV$

so signal/noise ~ 0.4

$\rightarrow$ may be measurable

$\bar{p}$ INDUCED REACTIONS IN NUCLEI :

1) investigate formation of isomers far from the valley of stability in $\bar{N}$ annihilation

use isospin transfer degree of freedom (pions take out isospin) and nucleon evaporation

- perhaps use radiochemical techniques to identify isomer (β-decay)

2) look for narrow states in light $\bar{p}$ + core systems

Idea: π contributes to real potential if core is spin-isospin unsaturated ; two body $\bar{N}N$ absorption minimum in $I=1, S=1$ channel

Examples: $\bar{p} + d\Big|_{\substack{S=1\\T=0}} \rightarrow p\,(0^\circ) + (\bar{p}n)_{S=T=1}$

$\bar{p} + {}^3He \rightarrow p + (\bar{p}pn)$ or $\pi^+ + (\bar{n}nnn)$
$(\bar{p}pnn)$

$\bar{p} + {}^4He \rightarrow \pi^+\pi^+\ (\bar{p}nnnn)$

$\bar{p} + {}^6Li \rightarrow \pi^+\pi^+\ (\bar{n}nnnnnn)$

Can $\bar{p}$ stabilize a system of neutrons ?

Gross features of $\bar{N}$ - nucleus annihilation

1) Energy spectrum of pions does not differ substantially from $\bar{N}N$ two-body annihilation

2) Pion angular distribution not isotropic
→ "pion backsplash"

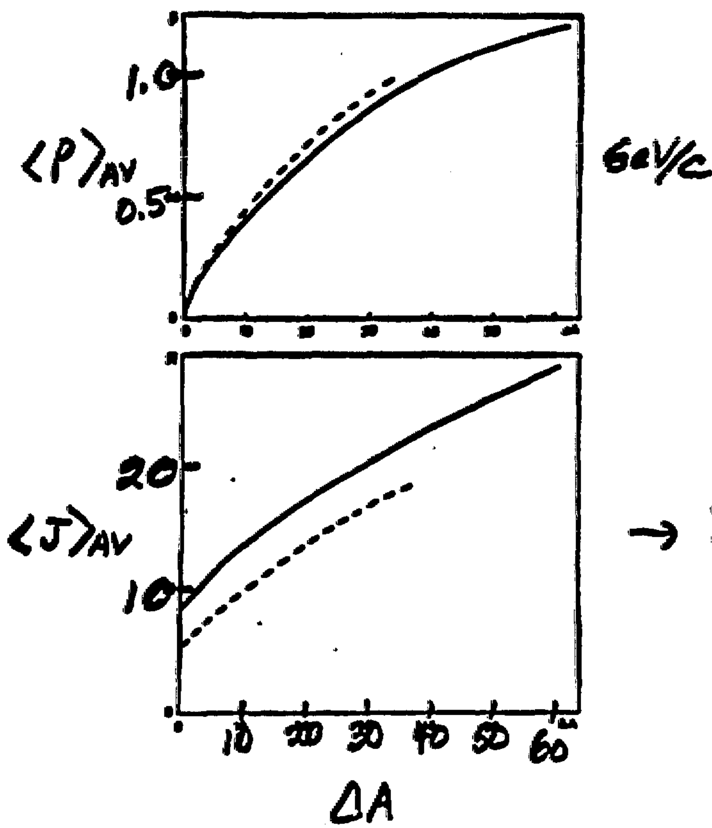
3) very strong spallation of the nucleus
→ several tens of nucleons emitted typically (up to 50 - 70)

→ results from very high energy deposition of pions ; strongly heated nuclear matter with $E^* \sim m_N$ rather than $E^* \sim m_\pi$ as for π a

4) high spin residual nuclei formed ($J > 20$)
large recoil momentum

5) could possibly see η or ω + (NN) → (NN)
→ probe of short range correlations at 0.2–0.3 fm

MEAN VALUES OF LINEAR MOMENTUM ⟨P⟩, AND ANGULAR MOMENTUM $\langle J \rangle_{AV}$ CARRIED BY RESIDUAL NUCLEUS AFTER $\bar{p}$ ABSORPTION AT REST



→ high spins!

ΔA = number of nucleons evaporated from target nucleus

from Iljinov et al, Nucl. Phys. A382 (1982) 378

Other aspects of $\bar{p}$ Annihilation in nuclei :

1) <u>fluid dynamics approach</u> (D. Strottman, Phys. L. 119B, 39 (198
Gibbs + Strottman, preprin

$\bar{p}$ produces a sound wave, not a shock wave

sensitivity to nuclear eqn. of state for low T, $\rho < 2\rho_0$

<u>signature</u>: high energy peak (100–150 MeV) at 180° in $d^2\sigma/d\Omega dE$ for proton emission ($\bar{p}$ at res

2) <u>statistical mechanics approach</u> (Rafelski et al)

$\bar{p}$ absorption in center of nucleus may produce large quark bags

<u>signature</u>: enhanced strange particle production relative to $N\bar{N}$

3) <u>pion interferometry</u>: $(\bar{p}, \pi\pi)$

already done for $p\bar{p}$ system

4) study <u>three body correlations</u> via $(\bar{p}, pp)$

ex. $\bar{p} + NNN \rightarrow NN + 0 \text{ or } 1 \text{ pion}$

~2GeV energy

or other rare modes such as $\bar{p} + {}^6Li \rightarrow \alpha + n$ etc.

more exotic aspects of $\bar N$-nucleus physics:

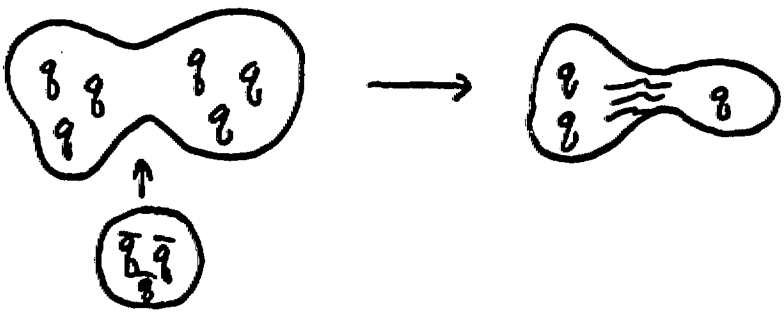
a) search for $N\bar N$ "baryonia" with nuclear targets

ex. $\bar p + {}^4He \to (\bar p n) + {}^3He$

$\bar p + {}^{6,7}Li \to {}^{3,4}_{\bar p}H + \alpha$

→ detect nuclear recoil

b) annihilate on spatially correlated NN pair to produce extended objects in QCD (Kahana)

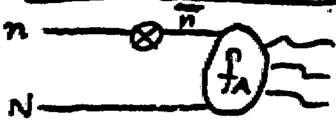


c) information on $\bar p - {}^4He$ annihilation may impose stringent limits on amount of antimatter in the early universe → restrict some GUT + SUSY models

$$\frac{n_{\bar p}}{n_p} \le \frac{4}{3}\,\frac{X_{^3He}}{X_{^4He}\, f_{^3He}} \sim 10^{-3}$$ if $\bar p + {}^4He \to {}^3He + X$ as probable as other channels

Falomkin et al, Nuovo Cim. 79A, 1
(198

d) limits on nuclear stability → limits on $n \to \bar n$ oscillat



$T > 2.4 \times 10^{31}$ yrs ⇒ $\boxed{\tau_{n\bar n} > (1 \pm 0.3) \times 10^{8}}$

(CBD, Gal, Richard)