

# Low-Energy Antinucleon-Nucleus Interaction Revisited

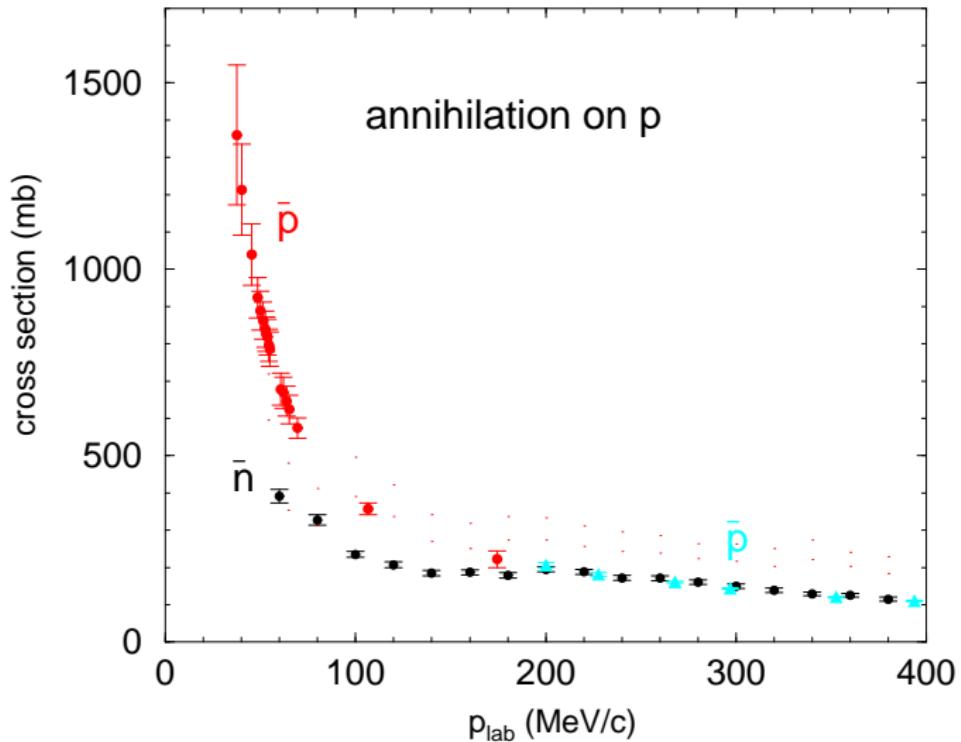
E. Friedman

Racah Institute of Physics,  
Hebrew University, Jerusalem

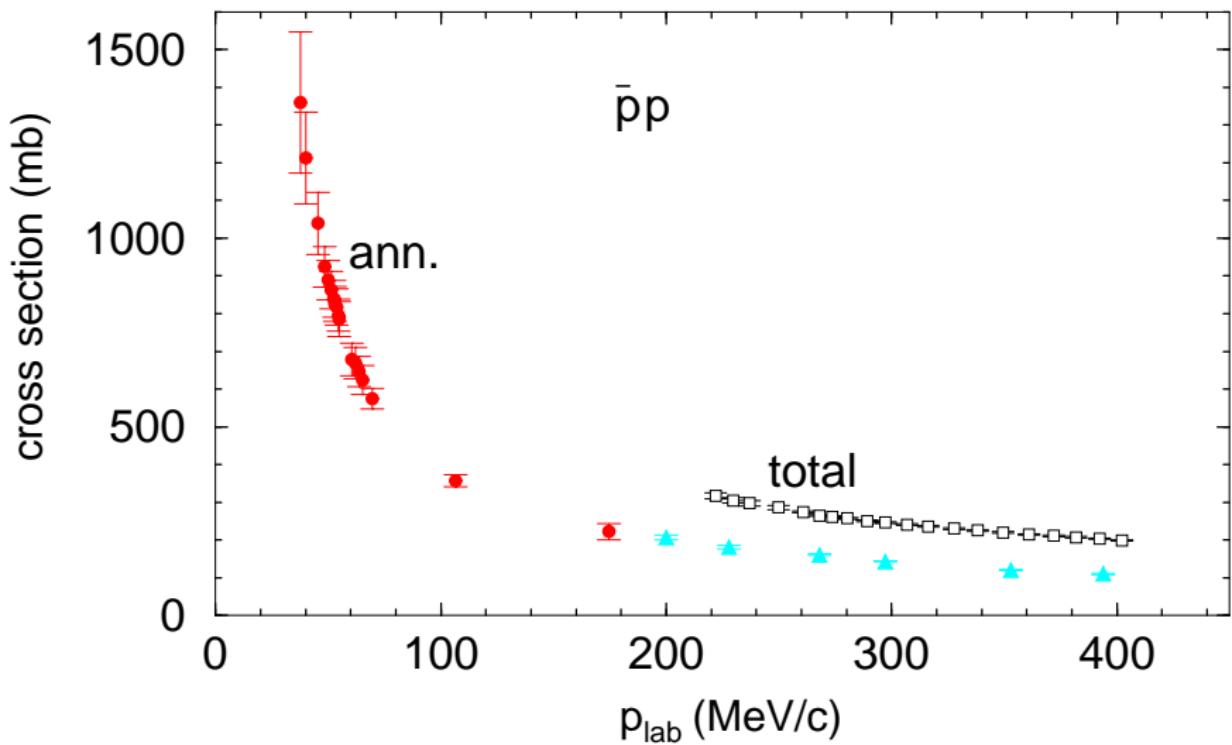
EXA2014 Vienna, Sept. 2014

## Outline

- Data to data comparisons  $\bar{p}p$  to  $\bar{n}p$  and 'Coulomb focusing'
- The world's data and the need to interpolate
- $\bar{p}$  atoms
- $\bar{p}$ -nucleus elastic scattering up to 600 MeV/c
- $\bar{p}$  annihilation on nuclei
- $\bar{n}$  annihilation on nuclei
- A puzzle and what to do next



$\bar{p}$  and  $\bar{n}$  from OBELIX,  $\bar{p}$  from Z. Phys. A 335 (1990) 217.



Total cross sections from PLB 194 (1987) 563.

Large cross sections beyond ' $1/v$ ' result from Coulomb focusing:

Classical derivation:

$\sigma_R = \pi R^2$  for uncharged particles,  
but for charged particles

$\sigma_R = \pi b_0^2$  where  $b_0$  is the impact parameter for  
which the distance of closest approach is  $R$ .

$$b_0^2 = R^2 \left[ 1 + \frac{m+M}{M} \frac{Ze^2}{RE_{lab}} \right]$$

For Coulomb attraction  $b_0 > R$ .

$$b_0^2 = R^2 \left[ 1 + \frac{m+M}{M} \frac{Ze^2}{RE_{lab}} \right]$$

For Coulomb attraction  $b_0 > R$ .

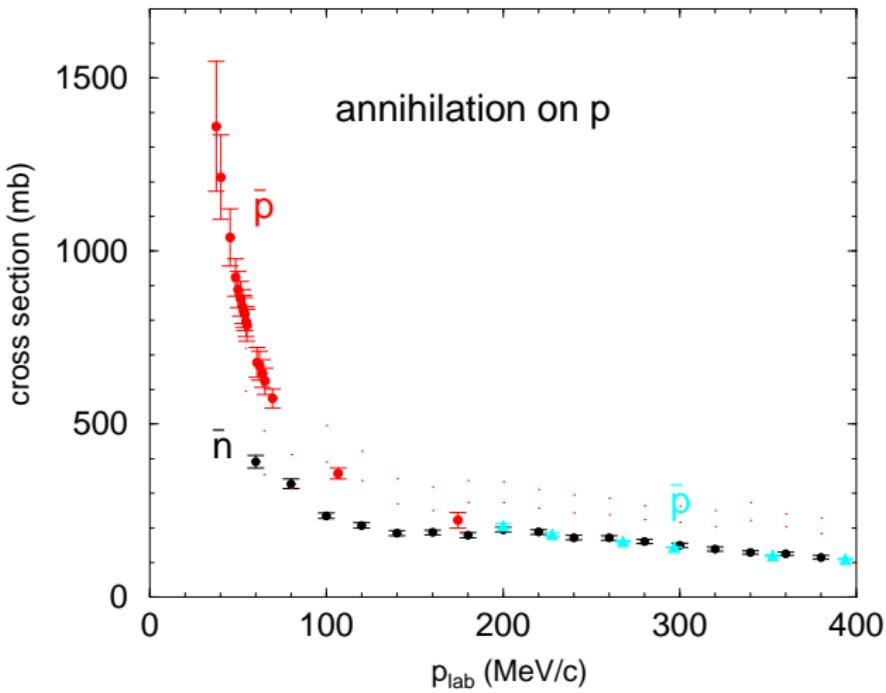
Same result obtained quantum-mechanically.

At very low energies  $\sigma_R \approx ZR \approx ZA^{1/3}$  in agreement with experiment,  $R = 1.84 + 1.12A^{1/3}$  fm.

(C.J Batty, E.Friedman, A. Gal, NPA 689 (2001)  
721.)

Coulomb focusing: where the enhancement factor = 2.

	R(fm)	$E_L$ (MeV)	$p_L$ (MeV/c)
p	3.0	1.0	43.
C	4.4	2.1	63.
Cu	6.3	6.6	112.
Sn	7.4	9.8	136.
Pb	8.5	14.	162.



Differences consistent with ONLY Coulomb focusing.  
No difference between  $(I = 1)$  and  $1/4(I = 0) + 3/4(I = 1)$ ,  
in agreement with PRD 38 (1988) 742 (AGS experiment).

### Experiments at low energies

target	$\bar{p}$ atoms	$\bar{p}$ ann.	$\bar{p}$ scatt.	$\bar{n}$ ann.
C	+		+	+
O	+*			
Ne		+		
Al				+
Ca	+		+	
Fe	+			
Ni	+	+		
Cu				+
Zr	+			
Ag				+
Cd	+			
Sn	+	+		+
Te	+			
Pt		+		
Pb	+		+	+
data	90	7	88	6

\*pre-LEAR data.

Interpolations are required!

## When interpolation is impossible

TABLE I

Best-fit parameters and reaction cross sections obtained for an optical potential having Woods-Saxon geometry

Target	Energy [MeV]	$V_0$ [MeV]	$r_{0V}$ [fm]	$W_0$ [MeV]	$r_{0W}$ [fm]	$a_V = a_W$ [fm]	$\lambda$	$\chi^2/NF$	$\sigma_R$ [mb]
$^{12}\text{C}$	46.8	25	1.22	61	1.17	0.56	1.0	0.70	616
$^{40}\text{Ca}$	47.8	9	1.4	143	1.03	0.63	1.0	0.68	1243
$^{208}\text{Pb}$	48.3	0.0		22	1.38	0.50	1.0	0.58	3458
$^{12}\text{C}$	179.7	44	1.05	184	0.935	0.56	1.0	0.86	510
$^{16}\text{O}$	178.4	35	1.2	79	1.20	0.52	0.92	0.71	581
		(31.5)		(75)	(1.21)		(1)	(1.08)	
$^{18}\text{O}$	178.4	38.5	1.05	150	0.98	0.62	0.99	0.89	660
$^{40}\text{Ca}$	179.8	40.5	1.1	111	1.1	0.63	1.05	0.63	1035
$^{208}\text{Pb}$	180.3	60	1.097	105	1.13	0.70	1.0	1.07	2710

From NPA 451 (1986) 541.

Must consider some physics in addition to  $\chi^2/\text{df}$ .

To enable interpolations between targets use the simplest possible optical potential whose geometry is determined mainly by the nuclear density, (with possible finite-range folding).

The simplest form of a ' $t\rho$ ' potential:

$$2\mu V_{\text{opt}}(r) = -4\pi \left(1 + \frac{\mu}{M} \frac{A-1}{A}\right) [b_0(\rho_n + \rho_p) + b_1(\rho_n - \rho_p)] .$$

In the impulse approximation  $b_0$  and  $b_1$  are minus the isoscalar and isovector scattering lengths, respectively.

Adopting two-parameter Fermi distributions for the nuclear densities:

$$\rho_{n,p}(r) = \frac{\rho_{0n,0p}}{1 + \exp((r - R_{n,p})/a_{n,p})}.$$

For a 'halo' form  $R_n = R_p$ , and values of  $r_n - r_p$  determine  $a_n$ .

An accepted parameterization is:

$$r_n - r_p = \gamma \frac{N-Z}{A} + \delta, \quad \gamma \approx 1.0 \text{ fm}, \quad \delta \approx 0 \text{ fm},$$

E.Friedman, A. Gal, J. Mareš, NPA 761 (2005) 283.

( also PRL 112 (2014) 242502 for  $^{208}\text{Pb}$ .)

Antiprotonic atoms: most extensive data base,  
several isotopic chains, good accuracy. Use 90 data  
points in global analyses.

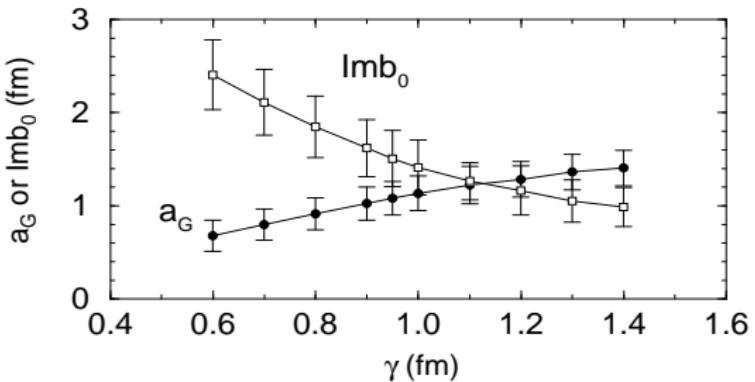
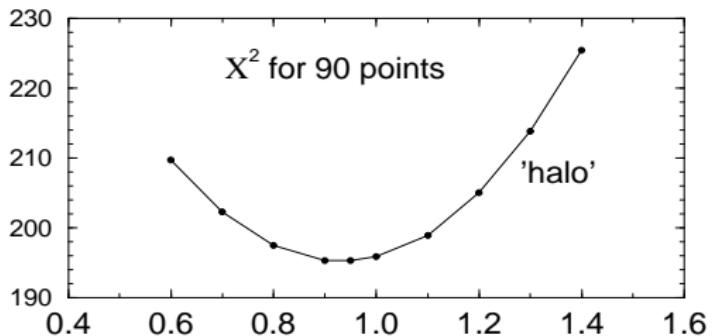
The KG equation (yielding the j-averages of Dirac  
equation):

$$[\nabla^2 - 2\mu(B + V_{\text{opt}} + V_c) + (V_c + B)^2]\psi = 0. \quad (\hbar = c = 1)$$

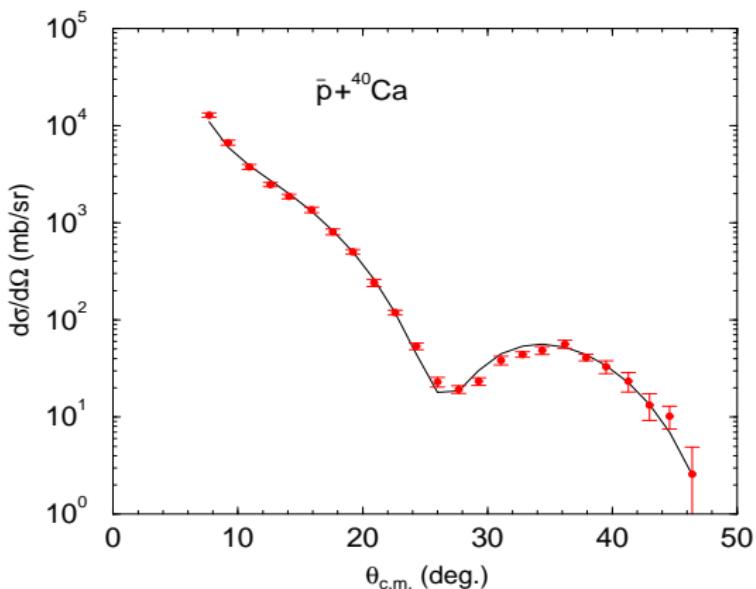
where  $B = BE + i\frac{\Gamma}{2}$ .

Need FR folding, no evidence for isovector term.

E.Friedman, A. Gal, J. Mareš, NPA 761 (2005) 283.



Global fits to  $\bar{p}$  atoms as function of the neutron density parameter  $\gamma$ . Top:  $\chi^2$  values for 90 data points, bottom: resulting parameters  $\text{Im } b_0$  and  $a_G$ , the range of Gaussian folding.



Fit to  $^{12}\text{C}$  and  $^{40}\text{Ca}$  together:  $\chi^2/\text{df}=1.9$ ,  
 Re  $b_0 = (0.40 \pm 0.04)$  fm, Im  $b_0 = (1.25 \pm 0.05)$  fm,  
 $a_G = (1.34 \pm 0.05)$  fm. Same parameters when  $^{208}\text{Pb}$  is included.  
 Interpolations are based on this potential.

Comparing with  $\bar{p}$  annihilation cross sections on Ne:

$p_{lab}$ (MeV/c)	57	192.8	306.2	607.9
$\sigma_{exp}$ (mb)	$2210 \pm 1105$	$956 \pm 47$	$771 \pm 28$	$623 \pm 21$
$\sigma_{calc}$ (mb)	2760	1040	865	676

Experimental results are lower limits as they exclude inelastic scattering.

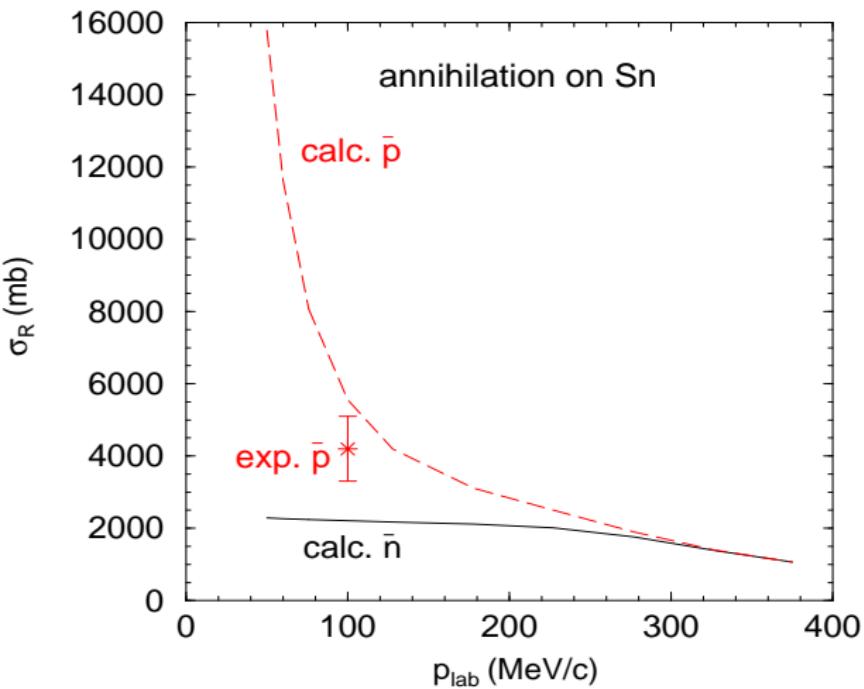
Experiments: NPA 452 (1986), PLB 481 (2000)  
194.

Comparing with  $\bar{p}$  annihilation cross sections at 100 MeV/c.

target	Ni	Sn	Pt
$\sigma_{exp}(\text{mb})$	$3300 \pm 1500$	$4200 \pm 900$	$8600 \pm 4100$
$\sigma_{calc}(\text{mb})$	3170	5560	8620

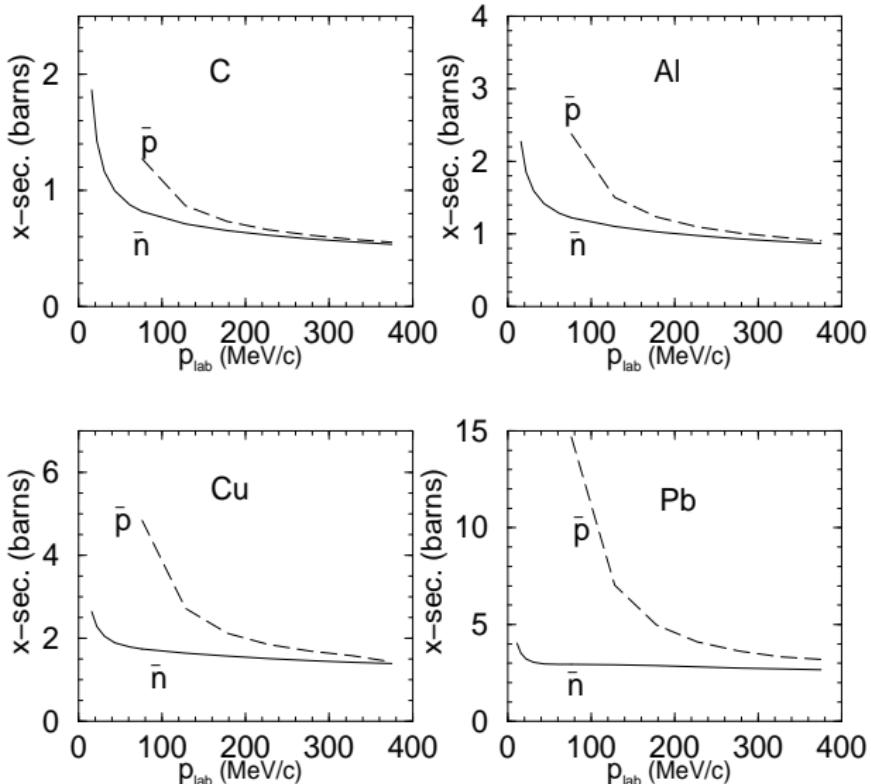
Experiments: PLB 704 (2011) 461; (5.3 MeV from the AD).

- $\bar{p}$ -nucleus interaction across threshold described well by a simple isoscalar optical potential (up to 600 MeV/c).
- Comparing  $\bar{p}p$  to  $\bar{n}p$  annihilation cross sections (**data vs. data**) suggest that the major difference is the Coulomb interaction.
- No evidence for an isovector term in  $\bar{p}$ -nucleus potentials.
- Use the above  $\bar{p}$ -nucleus potential also for  $\bar{n}$ -nucleus interaction (?)

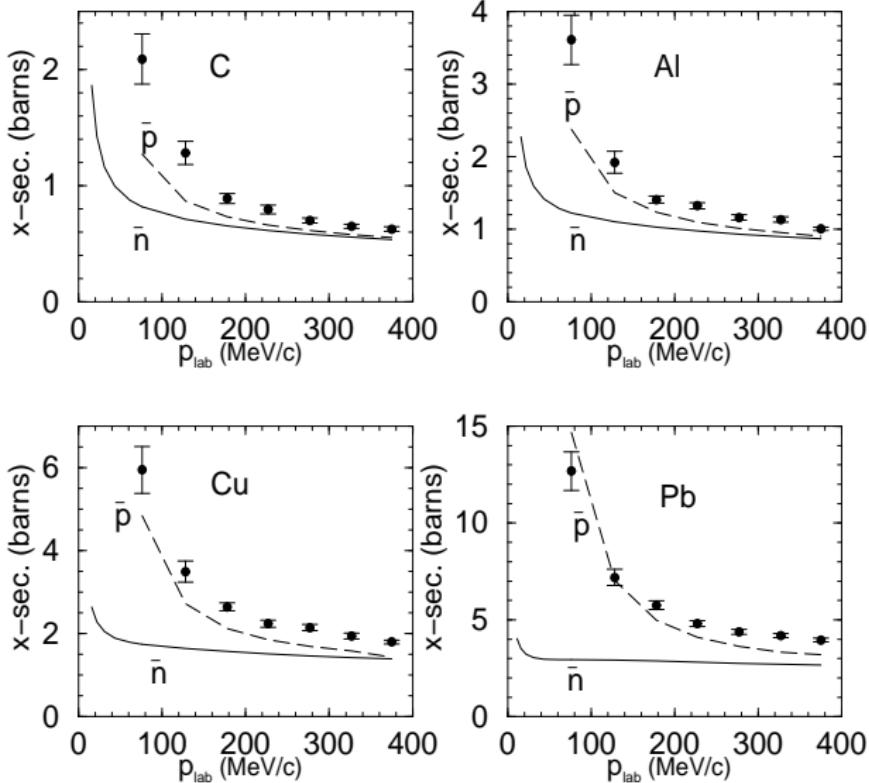


Coulomb focusing: where the enhancement factor = 2.

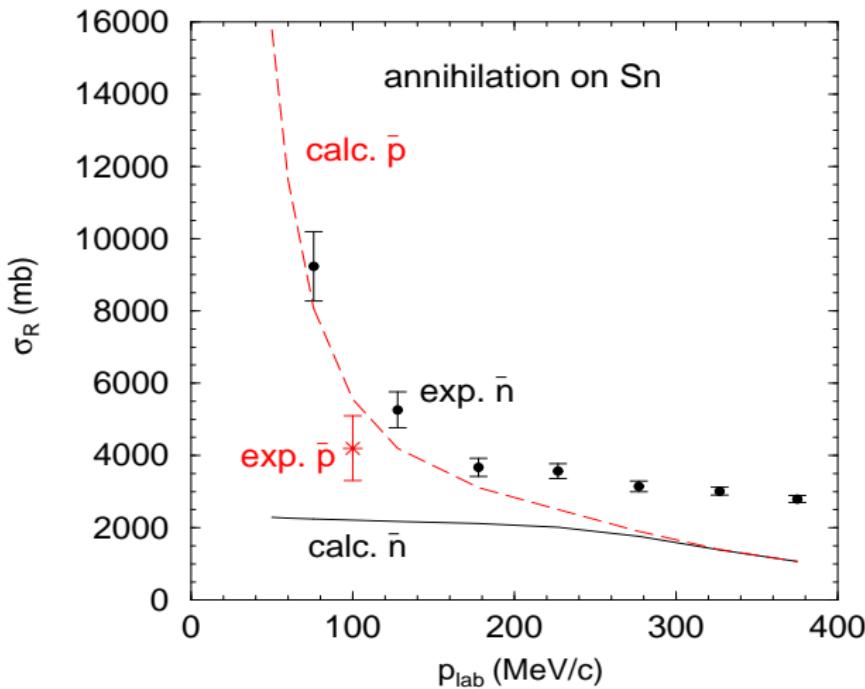
	R(fm)	$E_L$ (MeV)	$p_L$ (MeV/c)
p	3.0	1.0	43.
C	4.4	2.1	63.
Cu	6.3	6.6	112.
Sn	7.4	9.8	136.
Pb	8.5	14.	162.



Calculations based on the full optical potential.



$\bar{n}$  data from Astrua et al., NPA 697 (2002) 209.



Experimental  $\bar{n}$  to  $\bar{p}$  comparisons disagree with Coulomb focusing.

- Comparisons of experimental annihilation cross sections of  $\bar{n}$  and  $\bar{p}$  on  $p$  show the expected Coulomb focusing.
- Experimental annihilation cross sections of  $\bar{n}$  on nuclei increase at low energies much sharper than  $\bar{n}p$  cross sections.
- Direct comparison of cross sections on Sn indicate a reversed  $\bar{n}$  to  $\bar{p}$  behavior.
- $\bar{p}$  atoms and  $\bar{p}$ -nucleus annihilation and scattering are described very well by an *isoscalar* optical potential. The potential is used to predict annihilation cross sections for targets and energies where  $\bar{n}$  results exist.
- $\bar{n}$ -nucleus results exhibit features of Coulomb effects???

What can be done within reasonable time and resources to clarify the puzzle? (except finding an explanation!)

Measure (to 5-10%) total annihilation cross sections for antiprotons on the six targets measured for antineutrons and some of the same energies near 100-200 MeV/c.

This will enable direct data-to-data comparisons.

### Experiments at low energies

target	$\bar{p}$ atoms	$\bar{p}$ ann.	$\bar{p}$ scatt.	$\bar{n}$ ann.
C	+		+	+
O	+	*		
Ne		+		
Al				+
Ca	+		+	
Fe	+			
Ni	+	+		
Cu				+
Zr	+			
Ag				+
Cd	+			
Sn	+	+		+
Te	+			
Pt		+		
Pb	+		+	+
data	90	7	88	6

\*pre-LEAR data.

Fill the gaps! [NPA 925 (2014) 141]

## Acknowledgments

I wish to thank Tullio Bressani for providing  $\bar{n}p$  cross sections in tabulated form.

Thanks are also to Avraham Gal for many discussions.