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ANTIPROTON - NUCLEUS INTERACTIONS

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INTRODUCTION

As many speakers at this workshop have indicated LEAR represents a significant technical advance on any previous facility used to produce beams of antiprotons. This is especially true for low momentum $\bar{p}$ in the range $\leq$ 400 MeV/c. The opportunities for investigating $\bar{N}N$ physics are legion and have been discussed in detail in other contributions to this meeting. The beams from LEAR are also a means for uncovering a hopefully fertile source of physics in the interactions of antiparticles with nuclei. Bound or resonant states have been searched for in the $\bar{N}N$ system and perhaps one candidate found[1]. Resonances in the $\bar{N}$-A system may have an independent origin[2], unrelated to isolated states in the two-body system but nevertheless very revealing of the essential nature of the two-body forces.

The use of antiproton projectiles to study conventional, and occasionally exotic nuclear structure warrants some attention because of the extreme peripherality of many $\bar{p}$-induced reactions and the expected strong iso-spin selectivity for inelastic excitation of say giant resonances. The annihilation channels which generate strong absorption in the nuclear interior, localize direct reactions in the nuclear surface. In this fashion $\bar{p}$'s ressemble heavy-ion projectiles but possess the virtue of being a rather more elementary probe and it should be possible to calculate the average $\bar{p}$-A interaction (optical potential) from something closer to first

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principles. The long standing desire to disentangle neutron and proton distributions in the nuclear surface thus may be well served. Details of the real part of this optical potential will arise from particular components of the two-body $\bar{N}N$ force : for example a measurement of polarisations in elastic scattering directly determines the spin-orbit force and hence as indicated below confirms or negates predictions for the two-body spin-orbit interaction (small) and tensor force (large). A variety of unusual $\bar{p}$-induced reactions present themselves for consideration : most annihilation channels are unique in the $\bar{N}$-A as opposed to N-A system with ($\bar{p}$,p) at forward angles as an example. Also interesting will be $\bar{p}$-induced fragmentation or fission of normal-and hyper-nuclei.

Perhaps the most fundamental reason for using antinucleons is as carriers, into the target, of antiquarks. It is not at all clear that the sea quarks in a hadron, i.e. in the form of quark-antiquark pairs, exist on an equal footing with valence quarks. The production of $c\bar{c}$ states (and even of $s\bar{s}$) appears highly suppressed in nucleon-nucleon collisions. This suppression must be taken into account in establishing the relative merits of pp or $p\bar{p}$ colliders in producing say the W-meson. By introducing antiquarks directly via $\bar{N}N$ and $\bar{N}$-A one should surely obtain more definite information about $q\bar{q}$ interactions with LEAR, at the low momenta presumably crucial for hadron structure. Again much of this information will come from a study of the two-body system but additional unobtainable knowledge will result if $\bar{N}$-A states of reasonable width exist, the interaction time for $q\bar{q}$ being effectively lengthened.

In any case the comparison of the two and many body data will be of considerable interest. Should the two-body resonant states prove to be experimentally ephemeral, i.e. to exist only in theorists calculations, while at the same time interesting structures appear in $\bar{N}$-A scattering then one will have extracted vital spatial information about the $\bar{N}N$ real and imaginary potentials, and by inference about $q\bar{q}$ interaction.

$\bar{p}$+A "SHELL MODEL" STATES : ORBITING

Probably the most interesting question to be asked about the macroscopic behaviour of the $\bar{p}$-A interaction is whether or not a mean field develops in which antinucleons move in more or less well defined single particle states. It is highly unlikely that low angular momentum states survive the hostile interior of the nucleus. The $\bar{p}$ mean free path for a conservative choice of absorption strength is between .5 fm and 1 fm for momenta .01 mc < p_L < .1 mc and probably not much larger for even GeV antiprotons. Clearly then it is advantageous to look for $\bar{p}$-A states amongst lighter nuclei. I indicate below that the $\bar{p}$+A scattering is highly analogous to the interaction of complex nuclei, with relatively high ℓ or surface states being produced and observed as anomalies in the backward hemisphere angular distributions and excitation functions. Unusual angular distributions may extend for the heavier nuclei considered to angles as far forward as 30°-40°.

The "Elementary" Two-Body System

The inability of experiments to observe sharp $N\bar{N}$ states may be an indication of annihilation dominance. Analyses of σ_{TOT} and $\sigma_{elastic}$ first by Bryan and Philips[3] and more recently by Dover and Richard[4] suggest this might be the correct explanation. The two-body data is well described by[4]

$$\sigma_{elastic} = (28 + \frac{17}{p_L})\ \text{mb}$$

$$\sigma_{annih.} = (38 + \frac{35}{p_L})\ \text{mb}$$

and $$\sigma_{c.e} = \left(18 \quad 1 - (\frac{-1}{p_L})^2 \right)^{1/2} \Big/ \left(1 - \frac{p_L}{2} + 2.4\, p_L^2\right)\ \text{mb}$$

These in turn yiels an $\bar{N}N$ optical potential

$$V_{p\bar{p}}(r) = V_{\text{Meson ex.}}(r) + V_{AN}(r)$$

In particular a good fit is obtained for

$$V_{AN}(r) = -(V_o+iW_o)(1 + \exp(r-R)/a)^{-1}$$

with $R=0$, $a = \frac{1}{5}$ fm and $V_o \quad W_o \quad 20$ GeV.
One finds this admittedly short ranged but deep absorption implies

$$\text{Im}\ V_{AN} \approx \text{Re}\ V_{AN} \approx V_{\text{Meson ex.}} \approx 150\ \text{MeV} \quad \text{at} \quad r = 1\ \text{fm}$$

and naive estimates of the bound state width

$$\Gamma = \int \phi_\ell^2(r)\, W(r)\, d^3r$$

$$\approx -2\ \text{Im}\ V_{AN}(\bar{R}) = 300\ \text{MeV}$$

This width decreases of course with orbital angular momentum ℓ but most $\bar{N}N$ bound and resonant states are destroyed. A more recent analysis of the $\bar{p}p$ data has been made by Vinh Mau and collaborators[5] confirming a fit to the above data is possible with a very short ranged but perhaps weaker absorption.

For my purposes the range of the annihilation is pivotal. This range is indeed $1/2m_p \sim .1$ fm in a field theory treating nucleons and mesons as elementary but could be considerably larger if $q^2\bar{q}^2$

baryonium states exist. In this latter case a complete overlap of nucleon and antinucleon is not necessary to effectuate annihilation and a long range annihilation approximately of the size of the nucleon bag would arise. The annihilation would proceed through

$$B\bar{B} \rightarrow q^2\bar{q}^2 + \text{mesons}$$

Such an extended absorption might sound a death knell for $\bar{B}B$ states and if sufficiently strong might also eliminate the $\bar{N}$-A states I wish to discuss. But the existence of narrow $q^2\bar{q}^2$ states is of course highly interesting. The experimental evidence on the S-meson at or near 1930 MeV is still ambivalent[1] with a CERN re-experiment perhaps positive, a recent BNL experiment negative and the most recent BNL experiment as yet not completely analysed.

Optical Potential for $\bar{p}$-Nucleus

A reasonable description of the real part of the $\bar{p}$-nucleus optical potential can be obtained from a knowledge of both the $\bar{N}N$ meson-exchange interaction and of the nuclear density distribution. Only the surface real potential is important since annihilation will render the interior black. It is likely that only the long ranged parts of the meson exchange is required. To short circuit this direct derivation of a $\bar{p}$-A potential, my collaborators, C.B. Dover and E.H. Auerbach[2], and I employed a phenomenological optical potential submitted to the constraints of existing $\bar{p}$-atomic analyses. A favourable situation is shown in Figure 1. We imagine that the two-body annihilation is indeed short ranged $\sim .1$ fm and the $\bar{N}N$ real range considerably longer $\sim .7$ fm . A good candidate for producing this attractive real force is the strong pion tensor force acting in second order.

A semi-quantitative picture of the differences between real and imaginary optical potentials[2]

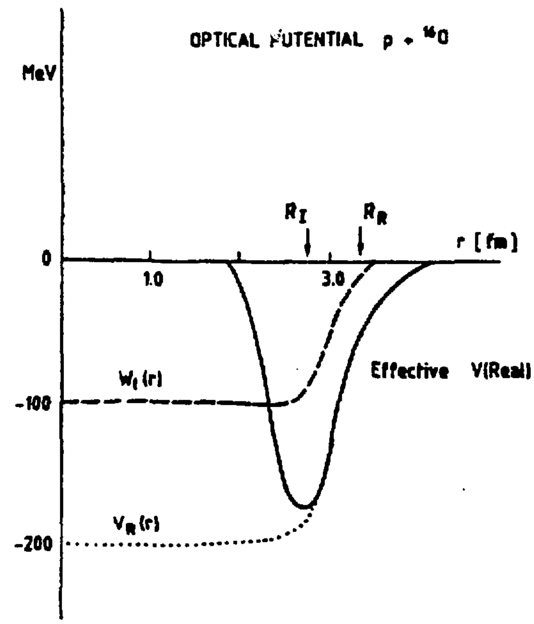
$$V_{\bar{N}}(r) = V(r) + i\,W(r)$$

results from the choices

$$W(r) = -W_o \frac{\rho(r)}{\rho(0)}$$

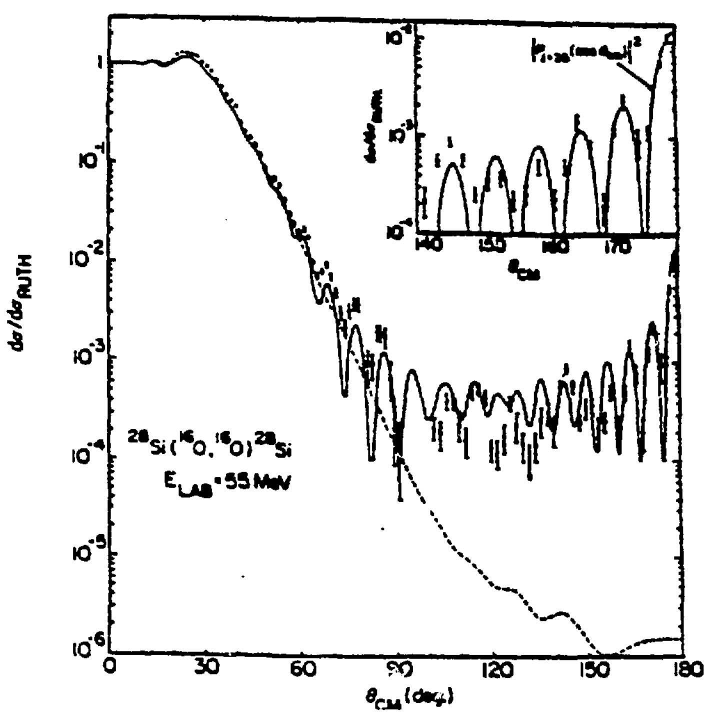
and $$V(r) = \int d^3r' \; V_{N\bar{N}}(r'-r) \; \rho(r')$$

Here we expect the absorptive part to follow the nuclear density $\rho(r)$ and the real part to arise, for large $\bar{p}$A separation, from folding with an effective two-body interaction. For a Yukawa choice of the latter two-body force for both real and imaginary parts, i.e. $V_{N\bar{N}} = (e^{-\mu r}/\mu r)$ we get as effective ranges for the optical potential



OPTICAL POTENTIAL p + 16O
MeV
0
-100
-200
1.0
3.0
r [fm]
Effective V(Real)

Fig.1



28Si(16O,16O)28Si
ELAB = 55 MeV
θCM (deg)
0
30
60
90
120
150
180
140
150
160
170

Fig.2

$$\mathcal{R}_{R,I} = \left(\frac{5}{3} \langle r^2 \rangle_A + 6\, \mu_{R,I} \right)^{1/2}$$

If we write $R = r^o A^{1/3}$ and $r^o_R = r^o_I + \delta$ then for $\mu_R^{-1} \approx (1/2m_\pi) \approx .7$ fm and $\mu_I^{-1} = (1/2m_N) = .1$ fm we find $\delta = .3$ fm for ^{16}O and $\delta = .1$ fm for ^{27}Al . We have then used $r_{oI} = 1.3$ fm . $r_{oI} = 1.1$ fm in the actual calculations.

Orbiting for $\bar{p}$-A : Analogy with Heavy Ions

The end result is a $\bar{N}$-nucleus real potential which extends beyond an absorptive, black core. This situation is reminiscent of the interaction between complex nuclei, with heavy-ion projectile comparably strongly absorbed and with a real attraction extending considerably beyond the point at which nuclear surfaces touch. In the heavy ion case one observes[6,7] classical orbiting of the projectile and target tantamount to the presence of high ℓ or surface resonances. An example is shown in Figure 2 of the angular distribution for $^{16}O + {}^{28}Si$ elastic scattering at 55 MeV, highlighting the strong rise in ratio to Rutherford in the backward directions. The experimental excitation function $\frac{d\sigma}{d\Omega}(180°)$ exhibits marked resonance structures. The $\bar{p}$-A system should exhibit similar behaviour, and over an effectively larger energy range since the character of the annihilative absorption is virtually independent of energy for $p_{\bar{N}} \lesssim 1$ GeV/c .

In practice we employed a phenomenological Saxon-Woods form.

$$V_{\bar{N}} = -i\, W_o\, f(r, a_I, r_{oI}) - V_o\, f(r, a_R, r_{oR})$$

with separate real and imaginary geometry (a, r_o) . The constraints of $\bar{p}$-atomic scattering can be imposed directly on V_o and W_o . Two analyses of this data with similar geometry differ considerably with $(V_o, W_o) = (240, 120)$ MeV for Barnes et al.[8] and (70,210) MeV for Roberson et al.[9]. By contrast two direct folding calculations yield $(V_o, W_o) = (1$ GeV , 700 MeV) for a meson exchange + annihilation potential and (-70 MeV , 65 MeV) for a free $\bar{N}N$ t-matrix as effective two-body input. One notes that a strong absorption produces a repulsive dispersive contribution to the real potential. A very strong modification of the folding model is indicated and hence our phenomenological analysis is in the first instance necessary.

Results

A summary of our calculations for $\bar{p}$-A with A = 16,40 is shown in Figure 3. The excitation function $\frac{d\sigma}{d\Omega}$ (180°) shows resonant structures for $\bar{p}$ laboratory energies between 10 and 200 MeV while the differential cross-section contains strong backward peaking at the energies of these resonances. The geometrical parameters must satisfy $r_{oR} > r_{oI}$ (or the equivalent for diffusivities) if the orbiting phenomenon is to exist. Further if the absolute absorption is too strong the resonances are considerably damped, despite favourable geometry. The departure from a "normal" or non-resonant angular distribution occurs furthest forward in angle for the heavier targets. Thus ^{40}Ca is a suggested first target for use at LEAR. It should be emphasized that a study of the S matrix for the $\bar{p}$-A calculation reveals the features seen are generally due to anomalies in fewer partial wave than in the heavy-ion case and one can speak of genuine single-particle resonances.

Polarisation

Measurement of $\bar{p}$-polarisation is of considerable interest and the results are also displayed in Figure 3. Large polarisations $P(\theta)$ obtain in the backward hemisphere for potentials yielding orbiting but not for the "background" example. On the other hand polarisations from these high-ℓ states seem smaller at more forward angles. Polarisation arises from a one-body spin orbit potential $V_{\bar{N}}^{LS}$ which should be added to the optical potential. Unlike the nucleon-nucleon case where the most obvious short range contributions to $V_{\bar{N}}^{LS}$ come from the underlying two-body spin orbit force, i.e. from ϵ and ω-exchange. In the $\bar{N}$-A situation ϵ and ω are of opposite G-parities and cancel, leaving as the dominant contribution the $\bar{N}N$ I=0 tensor force, coherently attractive, in second order. Even the sign of V^{LS} is not known at low energies and measurements of $\frac{d\sigma}{d\Omega}$ and $P(\theta)$ among other things yield this information.

The single-particles resonances calculated for $\bar{p}+^{16}O$ vary from $\Gamma \sim 15$ MeV for $E_{res} = 13$ MeV to $\Gamma \sim 150$ MeV for $E_{res} = 126$ MeV. They are worthy of detailed experimental and theoretical study.

OTHER ASPECTS OF $\bar{N}$-A PHYSICS

Total x-Sections

A relatively easy experimental parameter to obtain in the early stages is the $\bar{p}$-A total cross-section. Although one expects this cross-section to vary smoothly with energy any significant indication that σ_{tot} exceeds the naive geometrical limit $\sigma_G = 2\pi (R + \lambda)^2$, where $R = [(5/3) \langle r^2 \rangle]^{1/2}$ is an equivalent uniform nuclear radius, will imply a strong sensitivity to reactions and annihilation in the tails of the nuclear density. Heavy-ion and proton-nucleus calculations[10] indicate the total reaction cross-section, in a strongly interacting or absorbing situation, is extremely dependent on the geometry of the absorptive optical potentials. A similar situation will obtain for $\bar{p}$-A reactions and the measurement of σ_R as a function of A and of energy should be fruitful. Transparency as evidenced for example by $\sigma_{tot} < \sigma_G(R)$, with R determined from the real optical potential, will be of particular importance for $\bar{p}$-A resonances.

Standard Nuclear Structure, Fission

It will be possible to employ low energy anti-protons as a means of studying nuclear structure in a more or less conventional fashion. Inelastic excitation of giant resonances comes immediately to mind with the isotopic spin differences, amongst others, between NN and $N\bar{N}$ forces creating new selectivities for the $\bar{p}$-A excitation. The overall nuclear mechanism for such reactions will undoubtedly be peripheral, non-annihilation direct reactions may involve collisions in the far tails of the surface. Annihilation channels such as $(\bar{p},\pi)$ will occasionally demonstrate the angular distributions characteristic of direct reactions to given final states. One should also look for the more exotic $(\bar{p},p)$ reaction, due say to annihilation on a correlated nucleon pair in the nucleus and subsequent emission of a substitution nucleon in the forward direction. It is also somewhat hopeful to search for resonant $\bar{p}$ + (A-1) states and transitions between such states by observing $(\bar{p},p\gamma)$ or perhaps more realistically $(\bar{p},p\pi)$.

Since a low energy antiproton, when absorbed, deposits small momentum but large energy ($\sim 2m_{nucleon}$), heating of the residual nucleus is likely. One can then look for heavy particle fragmentation and/or fission. Polikanov has indeed proposed to look for $\bar{p}$-induced fission of hypernuclei, the latter first produced via the reaction $\bar{p}+p \rightarrow K^+ + K^-$ and subsequent absorption of the K^- in an actinide target. Creation of stable, lighter, hypernuclei is also possible.

Annihilation Mechanisms : Unusual Matter

many-body annihilation scenario can be anticipated from the two-b easurements at rest

$$\bar{p} + p \rightarrow n\pi \quad , \quad n \sim 5$$

$$\rightarrow \text{Kaons , few percent}$$

Many-body channels of increasing complexity from one π to several π emission are expected. One possibility, in analogy with relativistic heavy-ion production, is to took for Bose-correlations among pairs of emitted pions. This correlation function will in

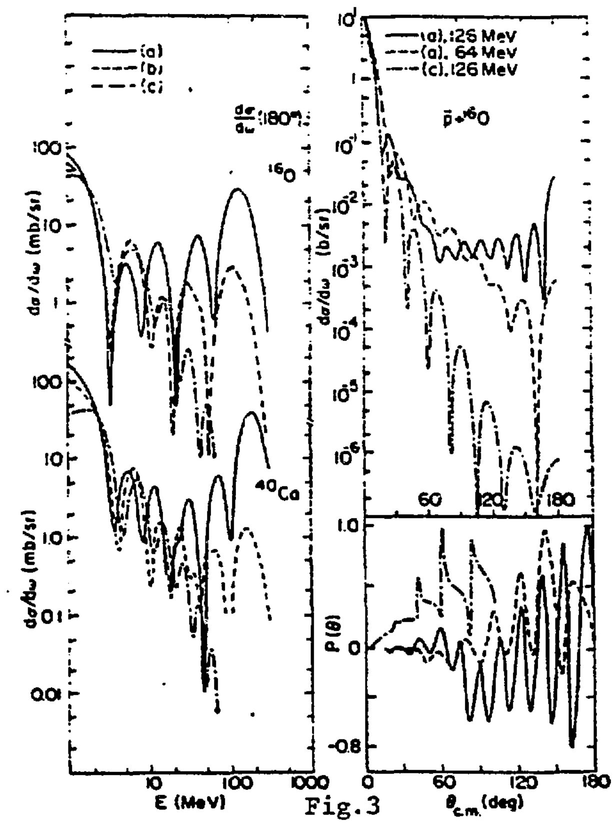
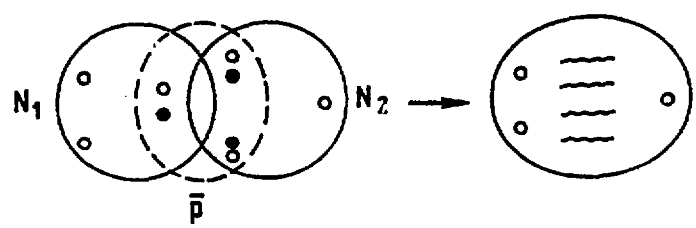


Fig.3



$\bar{p}$ ANNIHILATION ON TWO NUCLEONS

Fig.4

principle determine the size of the hot spot generated in the nucleus by the annihilating antiparticle. Further the annihilation of a single $\bar{p}$ in a nucleus adds to the system an energy m_N plus some kinetic energy. One might hopefully deposit 1-2 GeV. This energy is considerably in excess of that from the absorption of a single π but for a large nucleus any heating produced is minimal. Nevertheless in a collision with a very light target, $\bar{p}$+h or $\bar{p}+\alpha$ one may in a truly central collision heat up the nuclear core appreciably. It is unlikely one will in this fashion reach the threshold for a normal-abnormal transition .

The apparent contrast between the nucleon's size as a confined system of three quarks and its role as a more or less unaltered entity inside a nucleus is a subject on which $\bar{p}$ annihilation may cast some light. This question of possible changes in nucleon substructure inside a nucleus, the possibility of hidden colour, gluon-quark systems, is surely one of the most interesting to pursue in the study of nuclei. One very speculative but amusing possibility comes to mind. The antiproton incident on a very light nucleus may truly annihilate on a pair of touching or overlapping nucleons, in the sense that 2 quarks annihilate in nucleon 1 and a third quark in nucleon 2. The residual three quarks are then left widely spaced and the system may exist for a short time as an extended bag of 3 quarks and up to say 6 gluons. With the total energy involved such an extended object is surprisingly close to equilibrium size ($\sim$ 1.6 fm). Its anomalous formation may possess low probability and its decay be hard to identify but its existence would surely be welcome. The ($\bar{p}$,p) reaction referred to above would in fact arise in this situation.

Fig.4 graphically illustrates the formation of the 9 quark bag (6q+3$\bar{q}$) which may evolve into a 3 quark + n-gluon system after annihilation. A possible decay mode is a fissionning of the extended object into a nucleon (or Δ) and perhaps a single meson (π, ρ, ε, etc). Both hadrons would be emitted with considerable kinetic energy despite a low $\bar{p}$-momentum. The existence of relatively narrow structure in such a decay, of width less than the mass (2-3 GeV), would be extremely interesting. The existence of slightly overlapping pair of nucleons is not an unprobable event and such annihilation modes should be sought on light targets, even on the deuteron.

I wish to thank my colleague Carl Dover for sharing his thoughts on some of these matters.

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