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CAPTURE IN-FLIGHT OF LOW-ENERGY $\bar{p}$'s IN P
H^0 AND D^0, etc.

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As discussed at the LEAR workshop, Tignes (1985), the realization of high intensity, low-momentum antiproton beams at LEAR leads to a large variety of exciting new experiments, including those involving trapped $\bar{p}$'s. However, most proposed experiments concentrate on scattering (elastic or inelastic) and capture processes in gases or solids in which the lower limit on the $\bar{p}$ momentum is about 200 MeV/c. In such experiments, atomic information is obscured by collisions with target atoms where also low-energy x-rays are absorbed and annihilation information is not complete as it would be at threshold energies where simple wave functions can be obtained. Thus large areas of physics have not yet been considered at LEAR. For example information is needed regarding: (1) The kinetic energy of the $\bar{p}$ at capture and its cross-section dependence on the relative velocity of the capture nucleus. (2) The lifetimes of the excited atomic states. 3) Very low energy or threshold annihilation of $\bar{p}$'s on polarized protons or deuterons. (The complete characterization of the wave functions involved should reveal new exciting physics now obscured because present experiments only measure spin average data) - to name but a few areas of importance.

In this "Letter of Intent", we propose a new and unique universal method which will allow high formation rates($\geq 10^5$/s) for capture-in-flight production of exotic (nuclear) polarized atomic systems for the study of the beforementioned new physics areas (and others). The general technique consists in merging a polarized neutral nuclear beam from a standard atomic polarization source with a stored cooled $\bar{p}$ beam of the same velocity. The $\bar{p}$'s can either be stored at LEAR (or in a lower energy ELENA-type ring, if built) at ~100-1000 keV beam energies or at ~10^{-2} eV energies in a $\bar{p}$ ion trap. We are prepared for either technical development, if necessary. Most of the hardware is possessed by us or will be developed by us.

The apparatus will be flexible. Any polarized nuclear beam can be fed in as a simple "corotating" duel beam to an antiproton beam at variable (and relative) beam energies in almost table-top detection geometry with little LEAR space requirement. Because the $\bar{p}$ capture will be on neutral atoms, the capture cross sections are maximal and the enormous capture rates ($\geq 10^5$/s) must only be limited by beam collimation for experimental convenience. For example, at the higher energies, the ETH atomic sources can deliver I_{H^0} = 25 μA with polarization (P) = 80% and I_{D^0}= 25 μA with P_Z = 60% and P_{ZZ}= 90%. At the lower energies (eV), the ETH source can emit polarized beams at rates ≈ 10^{17} particles/s. For these lower energies a $\bar{p}$ ion trap will be developed by the Los Alamos, Texas A&M, and Rice University collaboration. Such traps may even create polarized $\bar{p}$'s to allow polarized nucleon polarized $\bar{p}$ measurements. Also the ion trap can revolutionize LEAR experiments as the apparatus can be portable and so the measurement can take place away from LEAR.

As an illustration of the type of particle physics information yielded by this experimental approach, consider the weak (0.2%) annihilation branch $H^0\uparrow + \bar{p} \rightarrow \bar{p}p\uparrow \rightarrow \pi^+ + \pi^-$. By gating on the atomic L x-ray preceding annihilation an alignment plane is created in the center-of-mass system. The angular correlation between $\pi^\pm$ and the direction of the L x-ray with respect to the given proton polarization direction would completely determine the threshold partial wave amplitudes except for an overall phase. The polarization condition does not just determine an extra parameter; it determines the necessary and sufficient parameter to complete the problem. An equivalent measurement with the $K\bar{K}$ branch would also completely determine the corresponding threshold partial wave amplitudes. Such information answers whether annihilation to $\pi^+\pi^-$ and K^+K^- are dynamically the same. Thus the data provide important tests for quark models of these annihilations, yet the predictions are model independent. Similar experiments with polarized $D^0\bar{p}$ yield the $\bar{p}n$ interaction parameters. With polarized higher Z nuclei, information regarding spectator quark interactions would be revealed.

The beforementioned ideas are discussed in more detail and more quantitatively in the contribution to the LEAR workshop (Tignes 1985) enclosed. To repeat a wide variety of new information in atomic physics ($\bar{p}$-capture cross sections and lifetimes as functions of Z,E) and nuclear-particle physics (systematics of $\bar{p}p$-, $\bar{p}n$-, and $\bar{p}$ spectator quark- interactions in numerous annihilation branches) at threshold energies with clean conditions can be studied via simple, elegant apparatus using polarized exotic atoms. In the history of physics, it has often been seen that experimental characterization of a problem in a complete way has lead to entirely new discoveries and theoretical ideas.

PLEASE NOTE: this paper should be included with the Letter of Intent, PSCC/85-42/I 71.

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CAPTURE IN-FLIGHT OF LOW-ENERGY $\bar{p}$'s IN POLARIZED H^0, D^0, $^3He^0$, ETC

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Presented by B.I.Deutch.

Abstract: The formation in-flight of bound exotic atomic systems by low-energy parallel beams of antiprotons and polarized light nuclei is discussed. For the $p\bar{p} \rightarrow \pi^+ + \pi^-$ annihilation channel, the angular distribution between the preceding L X-ray and the π with respect to the proton spin direction would completely determine the threshold annihilation amplitudes. An equivalent measurement with K's would answer whether annihilation to $\pi^+ + \pi^-$ and $K^+ + K^-$ is dynamically the same.

I Introduction

Before discussing the reasons for the following approach to investigate antiproton ($\bar{p}$) threshold energy annihilation by capture-in-flight of antiprotons with polarised neutral nuclei such as H^0, D^0, $^3He^0$, ··· etc., it would help to have a visual idea (see Fig.1) of the typical gedanken experiment to which we refer. Corotating (parallel) beams are achieved simply by sending a high current (∿25 μA) polarized neutral beam of H^0 (or D^0 etc.) from a standard atomic beam source at a matched parallel $\bar{p}$ velocity ($v_{H^0} = v_{\bar{p}}$) through one leg of a $\bar{p}$ storage ring. High capture cross sections result from Auger capture of the $\bar{p}$ with the nucleus (i.e. $\sim 10^9 \times$ radiative capture cross sections) which will allow observation of important exotic-atom annihilation decay channels at high counting rates. For example, by gating with the atomic L X-ray preceding the annihilation channel $p\bar{p} \rightarrow \pi^+ + \pi^-$, a polarised angular distribution determination between the π's and the L X-ray would completely calibrate the $p\bar{p} \rightarrow \pi^+ + \pi^-$ partial waves

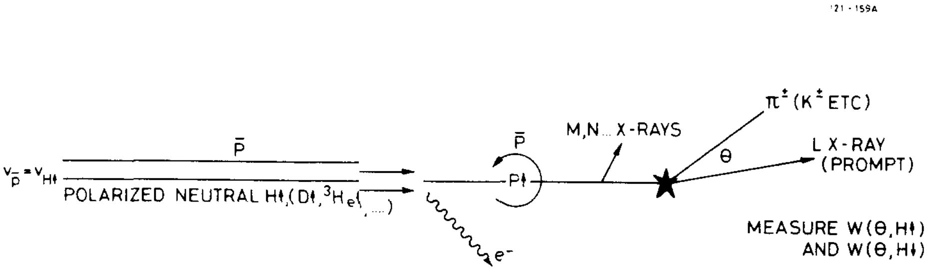

Fig.1. Schematic view of a polarization angular distribution experiment W(θ,H↑) after $\bar{p}$ capture-in-flight by a polarized neutral nucleus. A polarized neutral nuclear beam is sent into one leg of a $\bar{p}$ storage ring parallel to the $\bar{p}$ beam at a matching velocity. By Auger electron capture an exotic atom is formed (illustrated for polarized protonium) which decays in a beam tube outside the ring. The angular distribution W(θ,H↑) between the prompt L X-ray and annihilation radiation (shown for $\pi^{\pm}$ decay) for 2 opposite nuclear spin directions is determined at the same fixed geometry.

in the $p\bar{p}$ interaction at threshold. A similar measurement with the $K^{\pm}$ channel answers the question (in ratio) whether annihilation to $\pi^+\pi^-$ and K^+K^- are dynamically the same. Thus this experimental approach provides important tests of quark models for these annihilations. In a like manner, experiments with polarized $D\bar{p}$ (exotic polarized deuterium) would characterize the $\bar{p}n$ interaction.

II GENERAL CONSIDERATIONS

A. Hardware Exists.

Two technical developments have taken place which allow high formation rates for capture-in-flight production of exotic (nuclear) polarized atomic systems. First, high currents of cooled stored $\bar{p}$ beams at low energies are available at LEAR ($I = 10^9$ $\bar{p}$/s, $\Delta p/p = 10^{-3}$ at $E_{\bar{p}} \gtrsim 5$ MeV; even higher currents will be shortly available ($I = 10^{10}$ $\bar{p}$/s). At a lower storage energy ($E_{\bar{p}} \leq 5$ MeV), the $\bar{p}$ beam will have a large but lower current ($I \simeq 10^8$ $\bar{p}$/s). Second, intense highly polarized (P) beams of charged protons and deuterons from standard atomic beam sources$^{(1)}$ are available (at ETH, $I_{H^+} = 100$ μA with P = 80% and $I_{D^+} = 100$ μA with P = 60%. At Saturn there are similar beams with $\Delta p/p = 10^{-4}$). Neutral polarized beams of H^0 and D^0 at $I \sim 25$ μA will be shortly available at ETH. There is also progress in the production of intense polarized (P ∿ 10%) higher Z beams. Neutral polarized beams (1 - 10 μA) of: ^{7}Li, ^{11}B, ^{12}B, ^{13}C, ^{14}N, ^{15}N, ^{35}Cl and others have been created by asymmetric spectral reflection or transmission (see Appendix A and Table 1) at energies from 100 keV to 40 MeV.

B. Why measure $\bar{p}$ capture-in-flight? (see also Gastaldi ref.11)

1. Atomic physics. The atomic Auger $\bar{p}$ capture cross sections have not yet been measured.

It is important to experimentally determine Auger $\bar{p}$ capture-in-flight cross sections for exotic atom formation as a function of $\bar{p}$-nucleon center of mass velocity both from a theoretical point-of-view since this in itself is a fundamental theoretical atomic physics question and from an experimental point-of-view for information regarding cross sections lead to practical machine designs for corotating beams. For example, the cut-off transverse momentum of $\bar{p}H^-$ capture is not known experimentally although experiments are being designed on the basis of assumed $\bar{p}H^-$ capture rates.

2. Nuclear-particle physics. Some brief points follow:

a) The annihilation channels are heavily populated and because the capture is in flight (vacuum) the particle range and X-ray range are large. b) The angular momentum of the annihilation partial waves are tagged unambiguously by gating the previously emitted X-ray of the atomic state since this has known angular momentum. For example, for $p\bar{p} \rightarrow \pi^+ + \pi^-$ or $K^+ + K^-$, the L X-ray tags the P wave annihilation , c) The threshold amplitudes are simpler and thus can be calibrated with fewer independent measurements.

C. Why measure $\bar{p}$ capture-in-flight with polarized nucleons?

Threshold polarization determinations are essential to completely characterize the amplitudes (interactions). Detailed information on the $\bar{p}p$, $\bar{p}n$, and isospin 0 and 1 interactions will be yielded from measurements with the polarized exotic atoms $\bar{p}p$, $\bar{p}D$, and $\bar{p}^3He$, respectively. A later example should clarify this statement.

III EXPERIMENTAL CONDITIONS

A. Constraints

1) Beam matching ($v_{\bar{p}} = v_{nucleon}$)

To achieve a maximum capture cross section, the corotating beams must be closely matched in velocity, the transverse velocity match (beam cooling) being the most sensitive. Longitudinal velocity matching means that the energy of the polarized beam scales with its mass number M (i.e. at the lowest LEAR energy since $E_{\bar{p}} = \frac{1}{2} M v_{\bar{p}}^2 \simeq 5$ MeV, thus $v_{\bar{p}}$ is constant). The lowest beam energy of H^0, D^0, and $^3He^0$ would be 5, 10, and 15 MeV, respectively, for the present estimates of LEAR's minimal beam energy. Clearly these estimated energies are far too high for experimental convenience. They would necessitate the acceleration of the polarized nucleons in nuclear accelerators for proper velocity matching as well as long subsequent flight paths after LEAR in order to measure the annihilation. With respect to the latter, for protonium with its 2 μsec atomic lifetime, the detection equipment would have to be placed over 50 m away in the absence of electrostatic systems constructed to shorten the atomic lifetime.

The best solution to avoid such experimental problems would be to build an additional and lower energy $\bar{p}$ storage ring in the 10 keV to 1 MeV range. Atomic beam sources can at present deliver polarized H and D beams in an energy range $10\text{ keV} \lesssim E \lesssim 1\text{ MeV}$ to match the antiproton velocity in such a storage ring. A lower $\bar{p}$ beam energy would also ease the transverse energy match i.e., a less stringent beam cooling would be required.

2) Neutral (polarized) beams for maximum Auger capture cross sections.

As calculated by Bracci et al.(12), the maximum Auger capture cross section is achieved for protonium when the $\bar{p}$ is captured by neutral hydrogen with a maximum value $\sigma(\bar{p}p) \simeq 4 \times 10^{-14}\ \text{cm}^2$ when the center of mass velocity $\Delta v \leq 10^{-4}$ c (i.e. for beam energy less than 1 MeV at $\Delta p/p \leq 10^{-3}$). This maximum cross section is about 4×10^2 larger than geometric and over 10× greater than the maximum calculated $\bar{p}H^-$ cross section from negative hydrogen. Atomic beam apparatus can produce ∿50 μA of polarized, accelerated H^- or D^- beams which can be focussed towards an entrance port at LEAR and be neutralized at that point with only about 50% loss of the beam current.

3) L-X ray detection in vacuum.

This will necessitate development of bakeable semiconductor counters such as CdTe.

4) Depolarization effects.

The polarized proton will be partially depolarized as the $\bar{p}$ cascades down from its capture state in a high-lying Bohr level to the lower orbits (and finally P-state). A calculation of these depolarization effects are under consideration. Under similar cascading, the muon system suffers about a 10% depolarization.

B. Advantages

This method has three main advantages:

1) High capture cross sections from $\bar{p}$ capture in neutrals, 2) Beam selection flexibility, (All polarized exotic atoms can be produced); and 3) Simplicity.

The cross-section energy cut-off is not known for $\bar{p}$ capture in H^- so the relative H^0 cross section may even be higher than that displayed in ref(12), i.e. $(H^0\bar{p}) \geq 10\sigma(H^-\bar{p})$. One can have a flexible choice of beams without redesign of the storage ring optics. The method uses one leg of the storage ring as a "corotating" device. One can use protons, deuterons, ^{3}He with impunity. In fact, one can achieve capture rates with polarized beams larger than those planned at present with unpolarized negative hydrogen injection in LEAR.

IV EXAMPLE. MEASUREMENT OF THE POLARIZATION ANGULAR CORRELATION IN THE $\bar{p}p$ DECAY TO $\pi^{\pm}$

A. Principles

To illustrate the type of information which is obtainable by our experimental approach, the analysis of the polarization angular correlation in the following weak (∿0.2%) annihilation branch will serve as an example of the possibilities afforded by polarization measurements made at threshold energies.

$$H^0\uparrow + \bar{p} \rightarrow \bar{p}p\uparrow \begin{array}{l} \nearrow \; ^3P_0 \rightarrow \pi^+ + \pi^- \\ \searrow \; ^3P_2 \rightarrow \pi^+ + \pi^- \end{array} \qquad (1)$$

Specifically, one determines W(θ), the angular correlation between the outgoing $\pi^{\pm}$ and the direction of the L X-ray (emitted just before annihilation) with respect to a given proton polarization direction λ (see fig.2a and Appendix B for details).

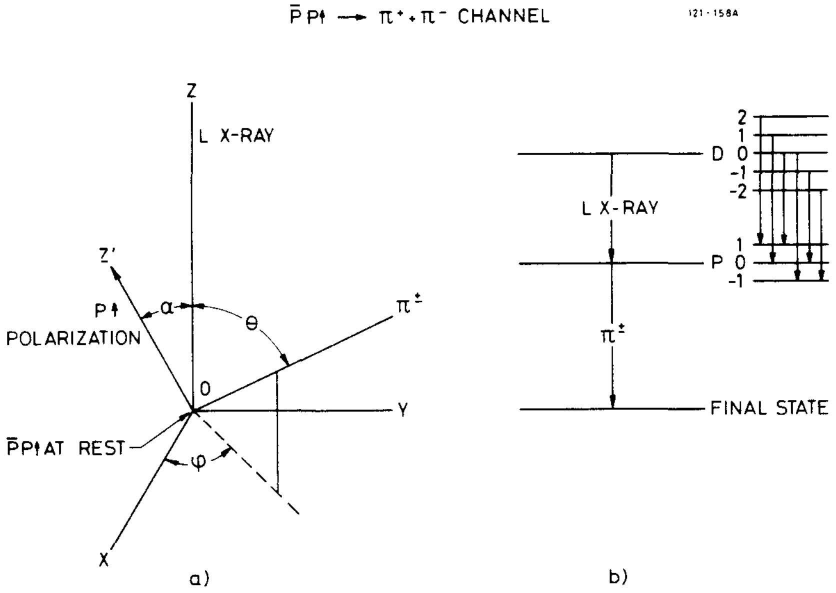

Fig.2a) The $\bar{p}p \rightarrow \pi^{\pm}$ decay in the center of mass coordinate system. The OZ axis represents the Z quantum axis of the last emitted atomic photon (L X-ray) detected before annihilation, OZ' is the axis of the proton polarization λ assumed to lie in the XOZ plane.

b) The cascade: atomic D-state $\xrightarrow{\text{L X-ray}}$ atomic P-state $\xrightarrow{\pi^{\pm}}$ final state, with unresolved atomic magnetic substates indicated. The unresolved spectroscopic components for allowed atomic E1 transitions ($\Delta m = \pm 1$, $\Delta m \neq 0$) between these substates along the OZ quantum axis are shown; they create an atomic P-state alignment (unequal m substate population in the atomic P-state).

Asterix experiments have determined that 98% of the annihilation occurs by

P waves; the L X-ray average energy is 1.7 keV, as measured by a proportional counter surrounding a tube filled with hydrogen stopper gas through which the $\bar{p}$ beam passes. In our proposed polarization experiment, to keep beam lines as short as possible, a bakeable semiconductor-compound detector system, perhaps Cd Te single crystals with resolution ~ 1 keV at 1.7 keV would replace the proportional counter in an Asterix-like detector for L X-ray detection after the exit port (in the relatively high vacuum). These counters would have $\sim 50\times$ the initial pulse height of the proportional counter system.

The role of the L X-ray is vital and its detection performs 3 independent functions. 1) It helps determine the annihilation vertices; 2) It tags the annihilation orbital angular momentum (P wave); 3) and it aligns the P atomic state so that both angular correlation and polarization effects can be measured by in-flight $\bar{p}$ capture (see fig.2b). The last point is worth a comment.

At first glance, it would appear that there is no alignment plane in a center of mass system with which a polarization direction can be defined for capture in-flight experiments (unlike in scattering experiments). This is not the case, for a quantization axis (Z axis) can be defined along the direction of emission of the X-ray by a coincidence condition. As $\Delta m = 0$ transitions are not permitted along this axis for E1 radiation, the net effect is to align the P atomic state (create unequal m sub-level population) which yields an angular correlation $W(\theta)$ between the subsequent annihilation radiation and the X-ray.

B. Counting rates

The counting rate R, the product of the luminosity and cross section, is given by

$$R = I_{\bar{p}} N_p \frac{\ell}{v} \frac{\Delta v}{v} \sigma \tag{2}$$

where $I_{\bar{p}}$ is the current in the storage ring, N_p the polarized beam current density, ℓ the detector length along the flight path, v the velocity of the beam, $\frac{\Delta p}{p} = \frac{\Delta v}{v}$ the beam cooling and σ the cross section. With estimated values for these parameters to be: 2.5×10^{13}/sec, 3×10^{15}/sec/cm^2, 50 cm, 6×10^8cm/sec, 5×10^{-3} and 4×10^{-14}cm^2 then

$$R = 6\times10^5/\text{sec} .$$

Even the counting rate for the low populated (0.2%) branch to $\pi^\pm$ is large. Assuming an effective coincidence L X-ray $-\pi$ solid angle of $d\Omega = 0.1$, this rate is 100/sec.

These estimates are based upon modest input: a low energy storage ring with $\frac{1}{10}$ the present current of LEAR ($\frac{1}{100}$ the 1988 estimated LEAR $\bar{p}$ current); a neutral polarized proton beam of 25 μA at 200 keV energy focussed onto a 3×3 mm beam spot, a beam length (50 cm) corresponding to 200 Cd Te detectors, and the present

LEAR cooling. The counting rates are strikingly high because the neutral hydrogen Auger $\bar{p}$ capture cross section is so enormous. We conclude that for most decay channels, high counting rates are achievable even for $\bar{p}$ capture on <u>polarized</u> nuclei. Remember that the polarized neutral deuteron beam current can be the same as that of a polarized neutral proton beam; also, many interesting annihilation channels have higher branching ratios than that of the $\pi^{\pm}$. The capture rates from neutral hydrogen would be continuous and about $\gtrsim 10\times$ those from corotating H^- beams since the estimated neutral polarized proton beam is about the same as the estimated corotating H^- beam current proposed for LEAR.

C. Results and conclusion

As calculated in Appendix B, for the L X-ray-π plane where $\phi = \alpha = \frac{\pi}{2}$ the polarization directional correlation $W(\theta)$ between the L X-ray and $\pi^{\pm}$ of eq.(B.7) becomes

$$W(\theta) = C_0[1+C_1\cos^2\theta - (-1)^{\lambda+\frac{1}{2}} C_2 \sin 2\theta] \qquad (3)$$

where θ is the angle between the L X-ray and π direction (as shown in fig. 2a), the C parameters are defined in Appendix B, and $\lambda = \frac{1}{2}$ or $-\frac{1}{2}$ refers to opposite proton spin directions.

The experiment determines the C's which are (see Appendix B) functions of the $J = 0$ and $J = 2$ partial wave amplitudes for the process $N\bar{N} \to \pi\pi$ extrapolated to threshold energies. The C_0, a normalization constant, is proportional to the partial decay rates, the C_1 appears if there is a net experimental alignment, and C_2 appears if there is <u>both</u> alignment and polarization. The polarization feature is essential to determine C_2.

Under the assumptions, that the atomic D-state m sublevels are equally populated (i.e. there is no atomic D-state alignment), that the P-state is entirely populated via E1 decays, and that the functions a and b of the S and D annihilation partial waves (see definition in Appendix B) can be extrapolated to values: $a = (1.7 \pm 1.0) - i(0.6 \pm 0.4)\,\mathrm{GeV}^{-1}$, $b = (0.8 \pm 0.2) - i(0.6 \pm 1.0)\,\mathrm{GeV}^{-4}$, our theoretical estimates yield a range of C parameter values: $-0.12 < C_1 < -.05$ and $-.05 < C_2 < +.05$.

The range of these values for different values of atomic P-state alignment are shown in fig. 3 plotted as a function of the P-state (m=0) sublevel m_0 population. The vertical solid line gives the range of C values yielded, assuming E1 transitions from equally populated atomic D-state m sublevels (m_0 is then 30%). Actually, it is possible for the atomic D-state to become partially aligned from the slight charge asymmetry at the moment of capture of the $\bar{p}$ in a high n state if a slight residual alignment is retained by the atomic cascade processes to the atomic D-state after $\bar{p}$ capture. Such a residual extra alignment would help the

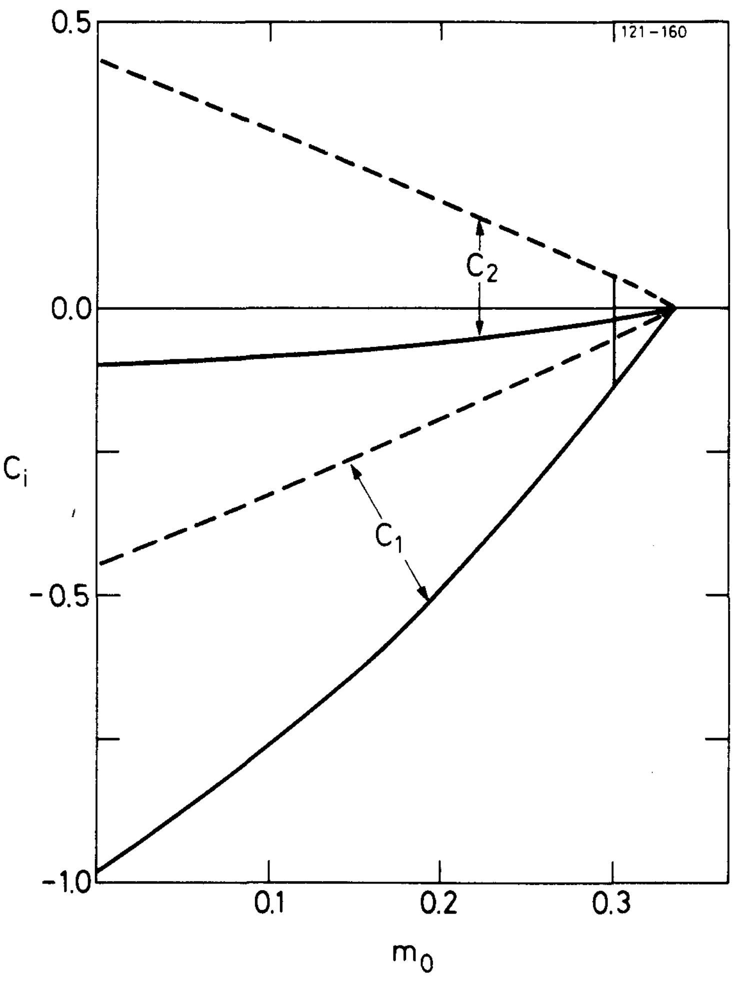

Fig.3. The coefficients C_1 and C_2 in the L X-ray - $\pi^{\pm}$ polarization angular distribution (eq. 3) plotted as a function of m_o, the fractional population of the m = 0 magnetic substate of the atomic P-state. The solid curves represent the average values of the C coefficients whereas the dashed curves represent their values at maximum; all values are based on extrapolated annihilation partial waves (and error) at threshold energies. The values of C_1 and C_2 at $m_0 = 0.3$ (the intersection of the curves with the vertical solid line) correspond to the values obtained under the assumption that the atomic D-state magnetic sublevels are equally populated (no atomic D-state alignment). The coefficients vanish at $m_0 = \frac{1}{3}$ (no atomic P-state alignment).

sensitivity of the measurement, as shown in fig.3, by a lower m_o atomic P-state population due to this increased alignment. Note however, the experiment will be done at very high counting rates at fixed geometry with fast switching between the 2 polarization directions, so the experiment is capable of high precision even for small C coefficients.

Except for an overall phase, the determination of all 3 C coefficients by the proposed experiments yields the threshold partial wave amplitudes. We would like to make the point that the determination of the polarization parameter C_2 is not just the determination of an extra parameter; it is the determination of the necessary and sufficient parameter to complete the problem. An equivalent measurement with the $K\bar{K}$ branch would also completely determine the corresponding threshold partial wave amplitudes. Such information would answer the question whether annihilation to $\pi^+\pi^-$ and K^+K^- are dynamically the same. Thus the data would provide important tests for quark models of these annihilations. Yet the predictions are model independent. Note also that similar experiments with polarized $D^o\bar{p}$ yield the $\bar{p}n$ interaction parameters.

Acknowledgement

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Appendix A

Nuclear Polarization by Anisotropic Collisions.

Large average nuclear polarizations (∿20%) for a number of high intense nuclear beams (∿10 μA) have been achieved by a variety of types of anisotropic collisions. With all these methods, the collision of the atomic beam at the final surface is the most consequent whether it be with a tilted foil surface (transmission geometry) or solid surface (grazing-incidence scattering geometry) for it results in an orientation of the spatial distribution of the orbital angular momentum of excited electronic levels. This orientation of the electronic shell in the ion is partially transferred via the hyperfine interaction in free flight to the nucleus as a vector polarization of the nuclear spins(2) (for $I \neq 0$). The oriented spin from an electron pick-up process at a magnetized nickel crystal surface can also add to the polarization of a nucleus in a similar way. (See review B.I. Deutch(3) to be published Hyp. Int). As shown in the previous review(3), the transverse momentum spread $\frac{\Delta p}{p}$ of the beam from multiple scattering can be calculated from Lindhard's theory; for carbon foil (10 μg/cm^2 thick), $\frac{\Delta p}{p}$ is

5×10^{-3} for most low Z nuclear beams up to nitrogen. Multiple scattering from spectral reflected grazing incidence collisions are even smaller and beam "cooling" $\frac{\Delta p}{p} \leq 10^{-3}$ can be achieved. The following table lists the beams, so far, polarized by these techniques. The beam currents varied around 1 μA. At the low energies, the process both polarized and neutralized the beam in one step.

TABLE 1

ACHIEVED ANISOTROPIC NUCLEAR POLARIZATION P

	I	E(MeV)	P(%)	Target	Ref
^{2}D	1/2	.15	29	Magnetized nickel	4
^{7}Li	3/2	.3	12	2 Cu surfaces	5
^{11}B*	3/2	.3	16	Cu surface	6
^{12}B	1/2	.6-1.3	5	4 C foils	7
^{13}C	1/2	.4	4	2 C foils	8
^{14}N*	1	.35	23	Cu surface	9
^{15}N	1/2	.3	10	2 C foils	8
^{35}Cl	3/2	.33	21	Cu surface	6
^{54}Fe	10+	40	19	17 C foils	10
^{144}Gd	10+	140	10	18 C foils	10

*This is for the neutral beam

Appendix B

We work in the system where the protonium is at rest at the origin and where the z-axis is defined as the direction of the L X-ray observed prior to the annihilation. The proton polarization λ is at angle α to the z-axis and defines the z-x plane (Fig.2a). The probability per unit time per unit solid angle for emission of a π^+ with momentum $\underset{\sim}{q}$ is given by

$$W_\lambda(\underset{\sim}{q},\alpha) = \frac{|\underset{\sim}{q}|}{16\pi^2 M}\,\frac{1}{2}\sum_{m,\sigma} g^{\lambda}_{m\sigma}\,\big|X^{(2P)m\lambda\sigma}_{\underset{\sim}{q}}\big|^2 \tag{B.1}$$

M is the proton mass, $g_{m\sigma}$ is the occupation probability for the protonium state with orbital angular momentum projection m and proton spin projection σ on the z-axis. The amplitude X is given by

$$X^{(2P)m\sigma_1\sigma_2}_{\underset{\sim}{q}} = \frac{1}{(2\pi)^3}\int d^3\underset{\sim}{p}\int d^3\underset{\sim}{r}\int d^3\underset{\sim}{r}'\; e^{-i\underset{\sim}{p}\cdot\underset{\sim}{r}}\, e^{-i\underset{\sim}{q}\cdot\underset{\sim}{r}'} \tag{B.2}$$

$$<\sigma_1|\underset{\sim}{\sigma}\cdot\big(g_1(\underset{\sim}{r},\underset{\sim}{r}')\underset{\sim}{p} + g_2(\underset{\sim}{r},\underset{\sim}{r}')\underset{\sim}{q}\big)|\sigma_2>\phi_{(2P)m}(\underset{\sim}{p})$$

where $\phi_{(2P)m}(\underset{\sim}{p})$ is the normalized Fourier transform of the initial 2P orbital wavefunction, i.e.

$$\phi_{(2P)m}(\underset{\sim}{p}) = R_{2P}(p)\; Y^{1}_{m}(\Omega_{\underset{\sim}{p}}) \qquad (B.3)$$

The two form factors g_1 and g_2 can be related to the physical amplitude for $p + \bar{p} \to \pi^+ + \pi^-$ where the initial $p\bar{p}$ state has orbital angular momentum $L = 1$. They can be parametrized as follows

$$\begin{aligned} g_1\,(\underset{\sim}{r},\underset{\sim}{r}') &= a_1 \delta^{(3)}(\underset{\sim}{r})\, \delta^{(3)}(\underset{\sim}{r}') \qquad (B.4)\\ g_2(\underset{\sim}{r},\underset{\sim}{r}') &= a_2 \underset{\sim}{\nabla} \delta^{(3)}(\underset{\sim}{r}') \cdot \underset{\sim}{\nabla}\, \delta^{(3)}(\underset{\sim}{r}) \quad . \end{aligned}$$

Since the values of p^2 involved are small we make a suitable extrapolation to threshold giving

$$\begin{aligned} a_1 &= \frac{4\pi}{M} C_+^{(o)} - \frac{20\pi}{\sqrt{6}} (M^2 - \mu^2) C_-^{(2)} \qquad (B.5)\\ a_2 &= - \frac{60\pi}{\sqrt{6}} C_-^{(2)} \end{aligned}$$

where μ is the π mass and where

$$\begin{aligned} C_+^{(o)} &= (1.7 \pm 1.0) - i(0.6 \pm 0.4)\ \mathrm{GeV}^{-1} \qquad (B.6)\\ C_-^{(2)} &= (0.8 \pm 0.2) - i(0.6 \pm 1.0)\ \mathrm{GeV}^{-4} \quad . \end{aligned}$$

In order to obtain some numerical estimates we assume the proton 100% polarized and assume that the probabilities $g^{\lambda}_{m\sigma}$ are independent of λ and σ and are equal to ρ, or $(\rho-1)$, respectively for the $m=0$ and $m=\pm 1$ substates of the 2P level. We then obtain

$$W_\lambda(p,\alpha) = C_o(\rho)\,[1+C_1(\rho)\cos^2\theta - (-1)^{\lambda+\frac{1}{2}} C_2(\rho)\sin 2\theta\, \sin\phi\, \sin\alpha] \qquad (B.7)$$

with

$$\begin{aligned} C_o(\rho) &= \frac{1}{32\pi^2} \sqrt{1-x^2}\, |A|^2 \left[1+(1-\rho)\left(\frac{\varepsilon_2}{2} - \varepsilon_3\right)\right] \qquad (B.8)\\ C_1(\rho) &= (1-3\rho)\, \frac{\varepsilon_3 - \varepsilon_2/2}{1+(1-\rho)\left(\frac{\varepsilon_2}{2} - \varepsilon_3\right)}\\ C_2(\rho) &= \frac{1-3\rho}{2}\, \frac{\varepsilon_1}{1+(1-\rho)\left(\frac{\varepsilon_2}{2} - \varepsilon_3\right)} \end{aligned}$$

$$A = \frac{1}{(2\pi)^3} \sqrt{\frac{4\pi}{3}}\, Ka \qquad\qquad K = \int_0^\infty p^3 R_{2P}(p)\, dp$$

and

$$\begin{aligned} \varepsilon_1 &= - \frac{15}{\sqrt{6}} (1-x^2)\, \frac{\mathrm{Im}\,ab^*}{\left|a - \frac{5}{\sqrt{6}}(1-x^2) b\right|^2} \qquad (B.9)\\ \varepsilon_2 &= \frac{225}{6} (1-x^2)^2 \left| \frac{b}{a - \frac{5}{\sqrt{6}}(1-x^2) b} \right|^2 \end{aligned}$$

$$\varepsilon_3 = -\frac{15}{\sqrt{6}}(1-x^2)\frac{\mathrm{Re}[ab^* - \frac{5}{\sqrt{6}}(1-x^2)|b|^2]}{|a - \frac{5}{\sqrt{6}}(1-x^2)b|^2}$$

where

$$a = C_+^{(o)}M \qquad (B.10)$$

$$b = C_-^{(o)}M^4 \quad .$$

If we assume that the populations of the 2P levels are entirely due to E1 processes from equally populated D-levels we find $\rho = 0.3$ and so obtain the values quoted in the text.