PROCEEDINGS OF THE 10 MAY 1989
ANTIPROTON TECHNOLOGY WORKSHOP

A compilation of presentation materials from the workshop held at Brookhaven National Laboratory, jointly sponsored in accordance with the AL/DoE Memorandum of Agreement for Applied Research in Energy Storage support from Brookhaven National Laboratory.

May 1989

Editor: Gerald D. Nordley

Approved for Public Release

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FOREWORD

This special report comprises the presentations provided by speakers at the Antiproton Technology Workshop held at Brookhaven National Laboratory (BNL) 10 May 1989 jointly sponsored under the Astronautics Laboratory (AFSC) / Department of Energy-BNL Memorandum of Agreement for support of Applied Research in Energy Storage (ARIES). This special report has been reviewed and approved in accordance with the distribution statement on the cover an on the DD Form 1473.

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ROBERT C. CORLEY
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This workshop, held at Brookhaven National Laboratory, 10 May 1989, was a follow-on to the Antiproton Science and Technology Workshops held at the RAND Corporation in Santa Monica through October 1987 following the Air Force Project Forecast II initiative in Antiproton Technology. The workshop was attended by about 50 researchers from a wide variety of disciplines, including medicine, particle physics, and the aerospace industry. New, more efficient technology for a variety of scientific, medical, and industrial uses could result from antiproton experiments proposed by workshop participants. Antiprotons are particles of antimatter which release highly penetrating radiation when they are stopped in normal matter. According to presentations at the Antiproton Technology Workshop this radiation can be used, in very small quantities, to image objects and determine their composition and density. In larger amounts, the radiation could be used to kill cancer tumors or produce highly localized heating and shock waves. DOE plans are contingent on potential user support.
Block 16.

Storage support from Brookhaven National Laboratory.
EXECUTIVE SUMMARY

1. Background

New, more efficient technology for a variety of scientific, medical, and industrial uses could result from antiproton experiments proposed by a workshop of government, industry and academic researchers at Brookhaven National Laboratory, Wednesday 10 May 1989. Antiprotons are particles of antimatter which release highly penetrating radiation when they are stopped in normal matter. According to presentations at the Antiproton Technology Workshop this radiation can be used, in very small quantities, to image objects and determine their composition and density. In larger amounts, the radiation could be used to kill cancer tumors or produce highly localized heating and shock waves. The Alternate Gradient Synchrotron, or "AGS", located at Brookhaven is one of the few particle accelerators in the world capable of making the number of antiprotons needed to perform the experiments.

The workshop was a follow-on to the Antiproton Science and Technology Workshops held at the RAND Corporation in Santa Monica through October 1987 following the Air Force Project Forecast II initiative in Antiproton Technology. The workshop was attended by about 50 researchers from a wide variety of disciplines, including medicine, particle physics, and the aerospace industry.

2. Workshop Results

Aerospace uses include the detection of physical or chemical flaws in the manufacture of composite materials, with implications for increased aviation safety and lighter, less expensive rockets.

An existing market of about $100 billion a year in medical imaging and radiotherapy has attracted the interest of private investors. Demonstrations of rapid, low radiation imaging of hard tissues and killing cancer tumors might prove the viability of a new, privately funded accelerator to provide antiprotons for medical and industrial uses.
Atomic chemists want to make antihydrogen to see if it obeys the same physical rules as ordinary hydrogen. Antihydrogen would be made by combining antiprotons with the anti-electron, or positron, the first form of antimatter discovered back in 1935.

Physical scientists are interested in radiation effects and small but intense shock waves that could be produced by pulsed antiproton beams. Protection of spacecraft from solar storms and meteor impacts are among many uses of radiation and shock data.

Particle physicists are interested in broken symmetries in particle reactions which one might expect to have identical outcomes, but don't. Such reactions help tell us how the universe was made and what its ultimate destiny might be.

Antiproton Workshop members came from organizations as diverse as the Lahey Clinic in Boston, the Astronautics Laboratory at Edwards Air Force Base, General Dynamics Corporation in Fort Worth, and the University of Illinois. The workshop agenda is provided as table 1. Workshop attendance is provided as table 2.

The only source of antiprotons suitable for many of the experiments discussed is the European accelerator in Switzerland, which has long waiting lines for experimenters. The researchers generally agreed that an antiproton source in the United States, perhaps based on the Brookhaven AGS accelerator, Fermilab's accelerator, or the booster ring planned for the Superconducting Supercollider will make United States science and technology significantly more competitive in areas discussed. Significant informational activities concerning antiproton technology continue within DOE. Potential user interest expressed as serious proposals is a significant determinant of DOE support.

*The workshop was jointly sponsored by the Astronautics Laboratory and Brookhaven National Laboratory (DOE).*
# Table 1. Antiproton Technology Working Group Final Agenda

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<th>Time</th>
<th>Session</th>
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<td>Informal discussions</td>
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<td>Welcome and Administrative Remarks</td>
<td>Dr. S. Baron, BNL; Maj. G. Nordley, AL</td>
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<td><strong>IMAGING AND ANALYSIS - T. KALOGEROPOLOUS, SYRACUSE</strong></td>
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<td>Stopping Power of MeV Proton and Antiproton Beams</td>
<td>R. A. Lewis</td>
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<td>Recent Simulation Results of ASTER</td>
<td>Robert Muratore</td>
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<td>Pbar Testing of Hydrogen Effects in Sealed Carbon-Carbon Composites</td>
<td>Harris Carter</td>
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<td>Potential for Antiprotons in Radiation Oncology</td>
<td>M. Leibenhaut, MD</td>
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<td>Prospects for a Commercial Antiproton Source</td>
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<td>Status of AL Studies Relating to Condensed Antimatter</td>
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<td>Electromagnetic Traps for Atomic Antihydrogen</td>
<td>Isaac Silvera</td>
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<td>Antihydrogen Production</td>
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<td>David Goodwin</td>
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<td>T. Kalogерополус</td>
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<td>John Callas</td>
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<td>Concepts for Experimental Determination of Radiation Shielding and Metal Clad Pellet Performance</td>
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<td><strong>Rockwell International, Rocketdyne Div</strong></td>
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<td>Mr. Jim McClanahan</td>
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<tr>
<td>6633 Canoga Ave</td>
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<tr>
<td>Canoga Park CA 91304</td>
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<tr>
<td><strong>Charles F. Pellegrino</strong></td>
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<td>360 Shore Rd, 31</td>
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<tr>
<td>Long Beach NY 11561</td>
<td></td>
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Search for CP Violation in Pbar-P to J/ψ
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Studies of Rare Modes of Pbar-P Annihilation
C. B. Dover, Brookhaven N.L.

Antiproton Production Calculation by the Multistring Model VENUS
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H. Takahashi, Brookhaven N. L

* Copies of viewgraphs were unavailable at the time of compilation (17 May 1989). They may be inserted if received later.
STOPPING POWER OF MeV PROTON
AND ANTIPROTON BEAMS

R. A. LEWIS

LABORATORY FOR ELEMENTARY PARTICLE SCIENCE
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PA

Note: We regret that copies of the transparencies used in Dr Lewis' excellent presentation were not available for inclusion in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP HELD AT BROOKHAVEN NATIONAL LABORATORY 10 MAY 1989
RECENT SIMULATION RESULTS OF ASTER

ROBERT MURATORE

DEPARTMENT OF PHYSICS
SYRACUSE UNIVERSITY

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
Recent Simulation Results of ASTER

Robert Muratore
Syracuse University
Abstract. ASTER, an imaging technique proposed several years ago, is now ready to be built. ASTER uses antiprotons to form direct three dimensional images of the target density profile. Useful images can be obtained with less than one million antiprotons, well within current production levels. ASTER has potential advantages over other imaging techniques, including flexibility, speed, lower dose, and less ambiguity. Simulations show that the scattering of antiprotons by target nuclei reduces the correlation of image and target, but increasing the number of antiprotons used by less than an order of magnitude overcomes this effect.

When complicated technology is used in medicine, reassuring names are attached to the machines and techniques. One speaks of CAT scans, PET, and MRI (née NMR). Today I will talk about an imaging technique which has been discussed before at these meetings, ASTER, named after the wildflower. Since I am limited to about ten minutes, I will keep my talk simple. Here is the outline:

I. ASTER is ripe.

It is my contention that this flower has formed its fruit, and that not only is this fruit ripe for picking, but neither is it spoiled, as some have suggested.

A. ASTER uses antiprotons to image densities, and enough antiprotons are currently produced.

I will begin by reviewing ASTER.\textsuperscript{1,2,3,4,5} ASTER is an acronym for Antiprotonic STERiography. In the ASTER imaging technique, still on the drawing board,
a beam of antiprotons are sent into a target. Collisions with electrons slow the antiprotons down, according to the well known stopping power

\[ \frac{dE}{dx} = D \rho \frac{Z}{A} \beta^2 \left[ \ln \frac{2m_e c^2 \beta^2}{I(1 - \beta^2)} - \beta^2 \right], \]

where \( E \) is the kinetic energy of the particle, \( x \) is the distance traversed, \( Z \) is the proton number, \( A \) is the atomic mass, \( \beta \) is the speed relative to the speed of light, \( D \) is a constant approximately equal to 0.30707 MeV cm\(^2\)/g, \( \rho \) is the density, \( m_e \) is the electron mass, and \( I \) is an empirical function of \( Z \) which represents the average ionization potential of all electrons in an atom.\(^6\)

The important features are the inverse square relation of the stopping power and the speed, which results in the Bragg peak, and the direct dependence on the density.

ASTER (a third definition here) means star (as in *). When the antiprotons have come to rest, they annihilate on a nucleon. Outward from the annihilation site stream various particles. In a bubble chamber photo, this event looks like a star (Fig. 1). Among the particles produced are charged pions. These are of sufficient energy to exit a target the size of the human body, and of sufficient mass to be deflected just a small amount before emerging. By detecting the directions of these pions and tracing their paths back to the intersection point with the antiproton path, the annihilation site can be determined precisely.

In this way, the range as a function of energy, \( R(E) \), can be determined for the target, and \( R(E) \) can be mapped to \( \rho(R) \), a density profile.

Simulations of ASTER imaging confirm the estimates of the number of antiprotons needed for a scan, \( N \):

\[ N \sim \frac{\text{volume}}{\Delta x \Delta y \Delta z} \times \left( \frac{\sigma_v \rho}{\Delta x \delta \rho} \right)^2 \]

where the antiprotons are assumed to be travelling initially in the \( x \) direction, \( \Delta x \), \( \Delta y \), and \( \Delta z \) are the step sizes with which the beam is incremented in the various directions, \( \sigma_v \) is the error in determining the vertex, and \( \delta \rho / \rho \) is the contrast resolution. To image a slice of 10 \( \times \) 10 \( \times \) 0.5 cm\(^3\) requires \( 2 \times 10^5 \) antiprotons, for 1% contrast resolution and 1.5 mm spatial resolution within the slice. To image a whole
organ might require 20 slices, or $4 \times 10^6$ antiprotons, well within current production levels. The corresponding dose is about 200 $\mu$Gy = 0.02 rads. Considering the biological effect of protons, the dose is about a tenth of the natural average annual background in the United States.$^6$

B. ASTER has advantages over other imaging techniques.

ASTER appears to be lower in dose for comparable images than x-ray CT, as shown in a comparison of an ASTER simulation (Fig. 2) of the imaging of a Plexiglas and water phantom and the actual x-ray CT image of the same phantom. The phantom is an 8 cm diameter Plexiglas disk inside a 10 cm diameter Plexiglas cylinder filled with water. In the 3 mm thick disk the letter E is engraved to a depth of 1.5 mm. In the simulation, this cylinder was immersed in a rectangle filled with water. An x-ray CT scan (Fig. 3) was made of the cylinder in the plane containing the engraved disk. The dose imparted by the ASTER simulation was 100 $\mu$Gy, over two orders of magnitude less than that imparted by the CT scan, approximately 30 mGy.

The table in Fig. 4 gives an overview of ASTER with other techniques. No one technique seems better than all the others for every situation. Similarly, ASTER will be complementary to the other techniques. Nonetheless, ASTER has potential for lower dose, higher resolution, faster scans, and imaging of elements as well as density. Perhaps most importantly, ASTER avoids the uncertainties introduced by back-projection techniques. Finally, ASTER is a flexible technique, as the following discussion shows.

C. The scattering of antiprotons does not spoil the image quality.

There has been some question as to whether the scattering of the antiprotons off the nuclei will irretrievably lower the resolution of ASTER. In water, the antiproton beam spreads out with a width of $\sigma_y = 0.0195R^{0.966}$. There is a well defined centroid, so resolution can be maintained by increasing the number of antiprotons used. In heterogeneous media, one can imagine that some of the antiproton paths will sample regions of different density, hopelessly convoluting the relation of stopping position to density profile. However, this is not the case, as I will show by considering individual antiproton paths in water, and by showing successful images.
of highly heterogeneous targets.

In terms of individual paths, it is reasonable that transverse scattering will not ruin ASTER images. This is because the average density in a small region is obtained from the difference in the mean stopping positions of two cohorts of antiprotons with nearly the same energy. In engineering terms, one would say that one is looking at the difference between two integrals, and integration suppresses the noise.

Fig. 5 shows the paths of many antiprotons in water. The horizontal (longitudinal) and vertical (transverse) scales are the same, and the three dimensional paths have been projected onto the plane. Next, I considered only the antiprotons stopping in a small transverse bin. If the initial energy of the antiprotons is varied just a bit, the antiprotons still sample the same region in space. That is, a group of paths stopping about \( R \) tends to sample the same portion of the target as a group of paths stopping about \( R + \Delta R \). This is shown in Figs. 6, 7, 8, and 9. This is true even though I have included the finite beam width in the Monte Carlo.

The sampling of the same region in space by the antiprotons is a statistical phenomenon. Therefore, it suggests that the scattering problem can be overcome by increasing the number of antiprotons, a method already required by the straggling. To test this, I simulated the imaging of a "random" target, which was the most heterogeneous thing I could think of. ASTER is a very flexible tool, and the imaging can be oriented to best advantage. I imaged this random slice longitudinally, so that each antiproton travelled in the slice. And I imaged the random slice transversally, so that the antiprotons travelled through a centimeter of water before encountering the slice perpendicular to the plane. The transverse orientation is shown in Fig. 10, the random target in Fig. 11, and the transverse image in Fig. 12.

The heterogeneous nature of this target convolutes the longitudinal image more than the transverse image. So for a given number of antiprotons, the transverse image will be better.

The quality of the image can be shown by correlating the image and the target. I define a correlation number \( C^{-1} \), where

\[
C^2 \equiv \sum_j \sum_k (\rho_{1jk} - \rho_{2jk})^2 / n,
\]
\(\rho_{1jk}\) and \(\rho_{2jk}\) are the densities of the target and image at the \(jk\)th pixel, and \(n\) is the number of pixels used for comparison. The correlation increases as the number of antiprotons increases for both the transverse and longitudinal imaging (Fig. 13). The correlations match when about four to nine times as many antiprotons are used in the longitudinal case as in the transverse case. So increasing the number of antiprotons by an order of magnitude will overcome severe heterogenous effects. After this increase is made, ASTER still imparts an order of magnitude less dose than x-ray CT.

If the decrease in correlation is due to the heterogeneous convolutions, than the effect will begin to show up in the transverse case as the slice is lowered deeper into the water, so that the antiproton beam is more spread out when it reaches the slice. This is shown in Fig. 13 by the decrease in correlation between transverse image and target as the depth increases.

References
1 deGuzman, Allan F. Ph.D. dissertation, Syracuse University, 1986.
18-NOV-1988 22:12:03.39

total # pbars stopping = 194811
total # pbars injected = 212973

file = E.dat.3
height above slice (cm) = 1.000
slice width along beam (cm) = 0.500
segment length (cm) = 0.050
percent error in density = 1.000
white, black densities (g/cm**3) = 1.100 1.050
horiz, vert magnifications = 1.000 1.000

Fig. 2
### Table: IMAGING TECHNIQUES

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<tr>
<th>system</th>
<th>CT&lt;sup&gt;a&lt;/sup&gt;</th>
<th>MRI</th>
<th>ultrasound&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PET</th>
<th>ASTER</th>
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<td>induced emf</td>
<td>echoes</td>
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<td>sound</td>
<td>concentration</td>
<td>(&amp; elements)</td>
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<td>&quot;</td>
<td>density, elasticity</td>
<td>biochemical</td>
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<td>tran. or ver.</td>
<td>transform</td>
<td>transform</td>
<td>vertex</td>
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<td>transducer</td>
<td>decay</td>
<td>$\bar{p}$</td>
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<td>rf coil</td>
<td>transducer</td>
<td>γ-ray det.</td>
<td>drift ch.</td>
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<td>2 mm</td>
<td>2 mm</td>
<td>~ 1 mm</td>
<td>&lt; 0.5 mm</td>
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<td>0.01 s</td>
<td>10 to 1000 s</td>
<td>&lt; 0.01 s</td>
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<tr>
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<td>(nonionizing)</td>
<td>(nonionizing)</td>
<td>varies</td>
<td>0.0001 Gy</td>
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follow.for.26

3-MAY-1989 11:00:43.39

diamtr  rhom  R  dR  magy  ncatch  up  down
0.100  1.000  7.500  0.050  1.000  20  10.000 -10.000

Fig.5

\[ \frac{\dot{Y}}{\text{cm/magy}} \]

\[ z \text{ (cm)} \]
follow.for.26

3-MAY-1989 11:10:19.23

diamtr rhom R dR magy ncatch up down
0.100 1.000 7.500 0.050 10.000 15 0.100 0.000

![Graph](image)
follow.for.26

3-MAY-1989 11:11:45.57

diamtr  rhom  R  dR  magy  ncatch  up  down
0.100  1.000  7.250  0.050  10.000  15  0.100  0.000

![Graph](z (cm) vs. y (cm/magy))

**Fig. 4**
<table>
<thead>
<tr>
<th>diamtr</th>
<th>rhom</th>
<th>R</th>
<th>dR</th>
<th>magy</th>
<th>ncatch</th>
<th>up</th>
<th>down</th>
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<tr>
<td>0.100</td>
<td>1.000</td>
<td>6.000</td>
<td>0.100</td>
<td>2.000</td>
<td>8</td>
<td>-0.300</td>
<td>-0.400</td>
</tr>
</tbody>
</table>

Fig. 8
follow for 26


diamtr  rhom  R         dR         magy  ncatch  up     down
0.100   1.000   6.500       0.100   2.000   8     -0.300   -0.400

Fig. 9

Y (cm/magy)

0  2  4  6  8  10

z (cm)
file = random2.dat.1

white, black densities (g/cm**3) = 1.050 0.950
horiz, vert magnifications = 1.000 1.000
file = astert.dat.7

target = random2.dat.1

white, black densities (1/cm^3) = 1.050 0.950
horiz, vert magnifications = 1.000 1.000

\[
\frac{\Delta p}{E} = 10\%
\]

\[
\Delta y = 1 \text{ cm}
\]

slice thickness = 0.2 cm

\[
N_F = 4.7 \times 10^5
\]

\[
\left( \frac{N_F}{\text{pixel}} \right) = 175
\]

segment length = 0.2 cm

Fig. 12
$\Delta p/p = 2\%$

transverse

correlation, $C^{**-1}$

deepth, $L$ (cm)

transverse ($L=1\text{cm}$)

longitudinal

correlation, $C^{**-1}$

$\delta p/p$ (%)
$P_{\bar{b}}$ TESTING OF HYDROGEN EFFECTS
IN SEALED CARBON-CARBON COMPOSITES

HARRIS CARTER

GENERAL DYNAMICS FORT WORTH
FORT WORTH, TX

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
UNCLASSIFIED

Rationale and Concept for NDE Application of Antiprotons (u)

- Early applications might include non-destructive evaluation (NDE) of aerospace materials

- Advanced carbon-carbon structures present
  - ✔ Special NDE problems (e.g. need for "backscatter" rather than transmission)
  - ✔ Special features suggesting $\bar{p}$'s for NDE (vs ultrasound or x-rays)

**Assumption:** Useful Sources will be $\bar{p}$'s trapped at $\leq$ Kev energies or stabilized in chemical complexes

**Suggested NDE mode:** Use low energy $\bar{p}$'s as portable source of $\pi^-$ mesons

**Purpose:** Determine atomic ratios O/C and H/C deep in Carbon - Carbon structures

Annihilation at source: $\bar{p} + p \rightarrow \pi^0 + \pi^+ + \pi^-$ (K.E. $\sim 250$ Mev)

**Reactions:**

Reactions in Target:

- $\pi^-$ (stopped) + p $\rightarrow$ n + $\gamma$ (129 Mev)
- $\pi^-$ (stopped) + O $\rightarrow$ $\pi^-$ O mesic atom + 178 Kev x-ray
ADVANCED CARBON-CARBON: HIGHER MAGNIFICATION SHOWING INCOMPLETE REACTION IN CONVERSION COAT
Need for NDE to Sample Atomic Ratios in Thick C-C Structures (u)

a) Residual Oxygen and Hydrogen Indicate Incomplete Pyrolysis

\[
\begin{align*}
\text{CH}_2 \text{OH} \text{CH} \text{H} \text{H} \text{H} \text{CH} \text{OH} \rightarrow \text{CH} \text{CH} \text{C} = \text{O} + \text{H}_2\text{O} + \text{HCHO}
\end{align*}
\]

b) Hydrogenation of C-C in High Temp H\text{2} Environment is Possible Reversion Mechanism

\[
\begin{align*}
\text{C} - \text{C} - \text{C} - \text{C} - \text{C} - \text{C} - \text{C} - \text{C} \rightarrow \text{C} - \text{C} - \text{C} - \text{C} - \text{C} - \text{C} - \text{C} - \text{C} + 2\text{H}_2
\end{align*}
\]

- Energetic \( \Pi^- \) from \( \bar{p} + p \) Annihilation Could Reveal (a) Poor Cure or (b) in Use Hydrogenation at Points Deep in Carbon-Carbon Structure by \( \gamma \) and X-ray Backscatter
Proposed Deep-Target Chemical Diagnostics using $\Pi^-$ from $\bar{p}$ Annihilation ($u$)

- In practical case, x-ray counts from $10^8 \bar{p}$ might not exceed $10^3$; but:
  - Effective clutter would be low due to gating & low count rate
  - X-rays from, say, $\Pi^-\ O$ could be easily counted and identified
RANGE OF NEGATIVE PIONS IN C-C;
NON-RELATIVISTIC ESTIMATE.

(Only 7% of $\bar{p} + p$ pions are <50 MeV)

AV RANGE: $R$ (CM)

RANGE (CM)

KINETIC ENERGY (MEV)
**X-Rays from 2 P→IS Transitions in Π⁻ Mesic Atoms and Attenuation in Carbon-Carbon (u)**

<table>
<thead>
<tr>
<th>Π⁻ Atom</th>
<th>X-ray energy (KEV)</th>
<th>Mass abs coef in C-C (ρ = 1.5 gm/cc): μ(cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.4</td>
<td>~ 150</td>
</tr>
<tr>
<td>C</td>
<td>100</td>
<td>.23</td>
</tr>
<tr>
<td>O</td>
<td>178</td>
<td>.19</td>
</tr>
<tr>
<td>(Fluorescent X-ray from normal O atom)</td>
<td>(.65)</td>
<td>(~1000)</td>
</tr>
</tbody>
</table>

X-ray line degradation through 5 cm of C-C:
- C(100 Kev) = 1/3.1
- O(178 Kev) = 1/2.6

- Oxygen, implying poor cure, could be identified in thick (e.g., 5 cm) C-C structures
- X-rays from Π⁻ H would not be observed; presence of H might be inferred from Π⁻ C reduction due to competitive orbital capture of Π⁻ by H
THEORETICAL POTENTIAL OF ANTIPROTONS IN RADIATION ONCOLOGY

Mark H. Liebenhaut, M.D.

Department of Radiation Therapy
Lahey Clinic Medical Center
Boston MA

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
Potential Radiation Damage

A) Direct Effects - Damage DNA Itself

B) Indirect Effects - Form Free Radicals

\[
\begin{align*}
\text{OH}^* \\
\text{DNA}^* \\
\text{DNA}^* + O_2 & \rightarrow \text{DNAOO}^*.
\end{align*}
\]
Oxygen Enhancement Ratio = \frac{\text{Dose Hypoxic}}{\text{Dose in Oxygen}}

x-rays OER = 2.5-3
neutrons OER = 1.6
Relative Biological Effect = \( \frac{\text{Dose}}{\text{Dose}_r} \)

RBE varies with:
1) system or tumor studied
2) amount of damage in that system
FIG. 6-11. Variation of the OER and the RBE as a function of the LET of the radiation involved. The data were obtained by using T1 kidney cells of human origin, irradiated with various naturally occurring α-particles or with deuterons accelerated in the Hammersmith cyclotron. Note that the rapid increase of RBE and the rapid fall of OER both occur at about the same LET, namely about 100 keV/μ. (Redrawn from Barendsen GW: in Proceedings of the Conference on Particle Accelerators in Radiation Therapy. US Atomic Energy Commission, Technical Information Center, LA-5180-C, October 1972, pp 120-125)

Figure 9.3. Central axis depth dose distribution for different quality photon beams. Field size, 10 x 10 cm; SSD = 100 cm for all beams except for 3.0 mm Cu HVL, SSD = 50 cm. Data are from Reference 13 and the Appendix.

Figure 14.8. Comparison of central axis depth dose distributions of the Sagittaire linear accelerator (continuous curves) and the Siemens's betatron (dashed curve). [Reprinted with permission from: Tapley (35).]

Source: Khan, pp. 314.
**FIG. 15-6** Depth-dose curve for 187-MeV protons from the Uppsala synchrocyclotron. The dose reaches a sharp peak at a depth of about 23 cm. (Redrawn from Larsson B: Br J Radiol 34:143–151, 1961)

Source: Hall, pg. 311.
FIG. 15-7. Illustrating the way in which the Bragg peak for a proton beam can be spread out. Curve A is the depth-dose distribution for the primary beam of 160-MeV protons at the Harvard cyclotron, which has a half-width of only 0.6 cm. Beams of lower intensity and shorter range, as illustrated by curves B, C, D, and E, can be added to give a composite curve S, which results in a uniform dose over 2.8 cm. The broadening of the peak is achieved by passing the beam through a rotating wheel with sectors of varying thickness. (Redrawn from Koehler AM, Preston WM: Radiology 104:191-195, 1972)

Source: Hall, pg. 312.
FIG. 15–8. Cross-section of the dose distribution that can be obtained in the treatment of an imaginary carcinoma of the cervix, using a four-field technique with $^{60}$Co $\gamma$-rays, 11-MeV x-rays from a betatron, and 160-MeV protons from the Harvard cyclotron. (From Koehler AM, Preston WM: Radiology 104:191–195, 1972)

Source: Hall, pg. 313.
Source: Hall, pg. 24.
FIG. 15-10. Depth-dose curve for carbon ions in which the Bragg peak has been spread out over 10 cm by the use of a ridge filter. The ions had an initial energy of 400 MeV/nucleon, corresponding to a total energy of 4.8 GeV. The spread-out peak is located between 12 and 22 cm deep. The lower curve represents the physical absorbed dose. The upper curve represents the biologically effective dose; it is, in fact, the product of dose and RBE, calculated at the level of 50% cell survival. (By courtesy of Dr. J.D. Chapman)

Source: Hall, pg. 318.
Figure 3. Variation of energy deposition by beams of protons and antiprotons with depth in an absorber. Each curve normalised to 1 at a depth of 0.5 g cm$^{-2}$.

PROSPECTS FOR A COMMERCIAL ANTIPROTON SOURCE

BRIAN VON HERZEN
ANTIMATTER TECHNOLOGY CORPORATION
HILO, HI

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
Prospects for a Commercial Antiproton Source

Brian Von Herzen, Ph.D.

Antimatter
TECHNOLOGY CORPORATION
Objective:

To develop the production facilities, transport systems, and equipment needed to apply antimatter to problems in medicine, aerospace, and academic research.
Current Efforts

- to obtain complete funding for the production, distribution, and application of antimatter.

- to develop a cost-effective source for antiprotons.

- to develop a portable system capable of storing antiprotons and delivering them to remote sites.

- to develop the necessary imaging, diagnostic and therapeutic equipment for medical applications.
Funding Being Sought

$195 million for a dedicated production facility, or an extension of an existing facility

$15 million to develop a portable storage device capable of transporting antiprotons to remote sites.

$35 million for medical applications, including imaging, diagnosis, medical clinics, and development.

$245 million needed for commercial break-even
Possible Antiproton Sources

- Collaboration with Brookhaven
- Collaboration with Fermilab
- Collaboration with a future facility
  - Advanced Hadron Facility at Los Alamos
  - Triumf in Canada
  - SSC Collaboration
- Dedicated production facility
Transport and Storage Systems

- Medical Tabletop ring by Prof. Robert Wilson
- Design studies in RAND proceedings by researchers at UCLA and Los Alamos
  - Penning traps
  - Superconducting storage rings
- Molecular storage of antimatter
Imaging and Treatment

- Proton therapy at Harvard Cyclotron, and Mass General Hospital (4500 patients treated).
- Antiprotons are thought to be much more effective than protons, leading to reduced mortality.
- Imaging experiments at BNL (Kalogeropoulos et al.)
- Acceptance of particle treatment by the medical community (Loma Linda medical cyclotron installed).
Potential Markets

- Cancer Treatment
- Medical Imaging
- Non-destructive Testing
Cancer Treatment

- $40 billion spent per year on cancer treatment
- 1 million new cases of cancer each year
- Over half of the patients receive radiation therapy.
- Antiprotons are the most selective particles in being able to deliver radiation to the tumor while leaving overlying tissues unharmed.
- A ten percent market penetration in the short-term could be expected to produce revenues of over $1 billion per year.
Medical Imaging Market

• The medical imaging market is even larger than the cancer market ($50 billion).
• CT scans produce too much radiation.
• Magnetic resonance imaging has limitations to certain types of tissue.
• Benefits from combined imaging and therapy.
• No really satisfactory techniques exist for mammography.
Non-Destructive Evaluation

- Aerospace applications for critical components
  - Turbines
  - Composites
  - Structural members
  - Inspection of aging aircraft
- Aerospace spends 2% of sales on non-destructive test
- Aerospace sales amount to over $50 billion per year
- Aerospace NDE is already a billion dollar market
- Electronic Industry
  - Inspection of solder joints
  - Automated annealing of cold solder joints
References


PROSPECTS FOR EXCITING EXTREME STATES
IN NUCLEAR MATTER WITH INTENSE
ANTIPROTON BEAMS

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THE PENNSYLVANIA STATE UNIVERSITY

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
EXCITING EXTREME STATES IN NUCLEAR MATTER USING INTENSE ANTI proton BEAMS

AUTHORS:  E.O. Minor
T.A. Armstrong
R. Bishop
V. Harris
R.A. Lewis
C.A. Smith

Air Force Systems Command
USAF grant
U.S. National Science Foundation

WORKSHOP ON ANTIPROTON TECHNOLOGY

MAY 10, 1989
BNL
- PWC's
- Counters
- Drift Chambers
Binary Annihilation $^\overline{p}N$

\[ E_n = \frac{2(938) - 6(116)}{6} \approx 215 \text{ MeV} \]

$\sqrt{s} = 1300 \text{ MeV} \quad \text{for } nN$
**NUCLEAR RESPONSE TO EXCITATION ENERGY $E^*$**

- **If** $E^* \leq 2-3$ MeV, the nucleus de-excite by thermal evaporation
  
  \[ \rightarrow \bullet \quad \text{(compound nucleus, N. BOHR)} \]

- **If** $E^* \geq 2-3$ MeV, the nucleus fragment,
  
  \[ \rightarrow \bullet \quad \text{(multi fragmentation)} \]

- **If** $E^* \gg 8$ MeV, the nucleus disintegrates into $p, d, t, \ldots$
annihilation at rest

\[ \text{Charged Multiplicity} \]

\( A^{1/3} \)

\[ \begin{array}{c}
\text{exp} \\
\text{INC} \\
\text{primordial}
\end{array} \]

E. Hernandez, E. Oros, Valencia. Private communication

PS153 \{ Carbon \( \langle N_{\alpha} \rangle = 2.59 \pm 0.04 \)

PS153 \{ Uranium \( \langle N_{\alpha} \rangle = 2.32 \pm 0.02 \)

64

**McGaughey et al.**

**PS183**

**Uranium**

**Carbon**

\[ \{ \text{PS183 (at rest)} \} \quad \text{McCaughhey et al. (608 MeV/c)} \]

**URANIUM \( \pi^+ \)**

- Momentum, MeV/c: 0 - 1000
- Integrated Multiplicities:
  - \( \langle N_{\pi^+} \rangle \) stopped \( \beta \) 66
  - Uranium: 0.93
  - Carbon: 1.12

**CARBON \( \pi^+ \)**

- Momentum, MeV/c: 0 - 1000
Photons

\[ \pi^0 \rightarrow 2\gamma \]
\[ \eta \rightarrow \gamma \gamma \]
\[ \eta \rightarrow 3\pi^0 \rightarrow 6\gamma \]
\[ \eta \rightarrow \rho^0 \gamma \rightarrow 4\gamma \]
\[ \eta \rightarrow \pi^+\pi^-\eta \rightarrow 2\gamma \]
\[ \omega \rightarrow \pi^+\pi^-\eta \rightarrow 4\gamma \]
\[ \omega \rightarrow \pi^0\pi^0 \rightarrow 3\gamma \]

\[ \bar{p}p \text{ production.} \]
\[ \langle m^2 \rangle = 0.072 \pm 0.01 \]
\[ \langle m_\pi \rangle = 0.155 \pm 0.01 \]
\[ \langle m_\eta \rangle = 3.1 \]
\[ \langle m_\omega \rangle = 1.8 \]

J. Proc. of the Fourth Int. Symp. on NP Interactions, May 2-4, 1975, Syracuse, N.Y.
J. Cugnon, P. Denato, J. Vandecauter, Liège. Preprint
ENERGY TRANSFER

\[ E_{\text{TRANS}} = 18.76.6 - \sum_{i = \{n^2/n\}} <n_i> <E_i> \]

<table>
<thead>
<tr>
<th></th>
<th>(&lt;n_i&gt;) MeV</th>
<th>(&lt;E_i&gt;) MeV</th>
<th>(&lt;n_{i+2}&gt;) MeV</th>
<th>(&lt;E_{i+2}&gt;) MeV</th>
<th>(E_{\text{TOT}}) MeV</th>
<th>(E_{\text{TRAN}}) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>3.62 ± 0.22</td>
<td>19.6 ± 1</td>
<td>2.59 ± 0.03</td>
<td>3.55 ± 2</td>
<td>1706 ± 45</td>
<td>120 ± 45</td>
</tr>
<tr>
<td>Uranium</td>
<td>2.73 ± 0.18</td>
<td>18.5 ± 1</td>
<td>2.31 ± 0.02</td>
<td>3.77 ± 2</td>
<td>1380 ± 34</td>
<td>497 ± 34</td>
</tr>
</tbody>
</table>

COMPARISONS:

- **Carbon**: E. Hernandez, E. Oset (Prediction) (n=4)
  - P. Jassolette et al. (Prediction) Oxygen 260 MeV
  - E. Hernandez, E. Oset (Pred)
  - P. Jassolette et al. (Pred)

- **Uranium**: E. Hernandez, E. Oset (Pred)
  - P. Jassolette et al. (Pred)

- \(E^* / A\)
  - \(\leq 2.3\) MeV
  - \(\geq 2.3\) MeV
  - \(> 7.8\) MeV

**Future Behavior**
- Thermal evaporation
- Multi fragmentation
- Nucleus disintegration: p, d, t, ...

---

*Footnotes*

**EXCITATION ENERGY $E^*$**

For $\bar{p} + \text{Mo}$

$E^*$ scales by a factor of 5 between $\bar{p}$ annihilation at rest and $\bar{p}$ at 2.0 GeV.

$\sim 280 \text{ MeV} = \text{Total ejection K.E.}$

$\bar{p} - \text{Uranium annihilation}$

$$E^* = 1876.6 - E_\pi - W_{ej} = 226 \text{ MeV \ (at rest)}$$

But, at 2 GeV:

$E^* = 5 \times E^*(\text{rest}) = 1133 \text{ MeV}$

$\frac{E^*}{A} = 4.76 \text{ MeV}$

*Multi-fragmentation!*
WHAT'S THE POINT?

ENERGY DISTR. (A=27 FRAGS)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>27Al_{13}</th>
<th>154W_{74}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragment</td>
<td>14N</td>
<td>99Al_{13}</td>
</tr>
<tr>
<td>Range (THICKNESS), T</td>
<td>10^4 Å</td>
<td>0.5 \times 10^4 Å</td>
</tr>
</tbody>
</table>

Cross Section, σ
- 0.36 b
- 1.3 b

Mean Free Path, λ
- 46 cm
- 1.2 cm

Yield
- 2.2 \times 10^6 \rho^{2}
- 4.2 \times 10^6 \rho^{2}

\[ \sigma / A^{1/2} \approx 40 \text{ b} \]
\[ \lambda = (\sigma / A \rho)^{-1} \]
\[ \nu = \frac{1}{\lambda} R^{2} \]
STATUS OF ASTRONAUTICS LABORATORY
STUDIES RELATING TO CONDENSED
ANTIMATTER

GERALD NORDLEY
APPLIED RESEARCH IN ENERGY STORAGE OFFICE
ASTRONAUTICS LABORATORY (AFSC)
EDWARDS AFB, CA

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
ANTIMATTER PROGRAM AREAS

ANTIPROTON PRODUCTION
OVERVIEW

ANTIMATTER STORAGE
OVERVIEW
HYDROGEN CLUSTER IONS
SOLID ANTIHYDROGEN STORAGE

ANTIMATTER ANNIHILATION
OVERVIEW

FUTURE DEVELOPMENT
ANTIPROTON PRODUCTION

MOTIVATION

O U.S. SOURCE FOR U.S. EXPERIMENTS
NATIONAL SCIENCE AND TECHNOLOGY BASE
CERN BUSY, UNEASY ON DEFENSE WORK
ENABLING FOR DEFENSE RELATED USES

O EVALUATE FEASIBILITY OF SCALE-UP
ENABLING FOR FORECAST II PROPULSION
GOAL OF $1M/mg
NO OTHER KNOWN "CUSTOMER"
ANTIMATTER STORAGE

MOTIVATION

- Develop portable antiproton storage
  - Enable remote experiments
  - Establish technology base
  - Facilitate near term uses

- Understand cluster ion science
  - Propellant molecule growth
  - Contact-free nucleation
  - Cluster to solid transition energy

- High density antihydrogen storage
  - Technological spinoff
  - Enabling for forecast II propulsion
AIR FORCE ANTIMATTER APPLICATIONS

Antihydrogen Energy Storage

Antiprotons

Positrons

Antihydrogen

Cluster ions

Storage System

ELECTROSTATICALLY CHARGED ANTIHYDROGEN ICE

Trap
Contact-Free Storage....

**PAYOFF:**
- Effective Storage
- Portable
- Enables Near Term Uses
  - NDE of Nozzles, Fuels, Propulsion Materials
  - High Energy Physics at Universities
  - Medical Research
HYDROGEN CLUSTER ION PROJECT  AFAL/AFOSR

SCIENTIFIC OBJECTIVE

- Determine Associative and Dissociative Pathways for Trapped Cluster Ions
  
  - Initially, develop technique to follow reaction pathways for \( \text{H}_5^+ \) systems using a dense non-neutral plasma as a "pseudo-wall" to absorb the energy of association:
    
    \[
    M^+ + \text{H}_3^+ + \text{H}_2 \rightarrow \text{H}_5^+ + M^{++}
    \]
    
    \[
    M^+ + \text{H}_5^+ + \text{H}_2 \rightarrow \text{H}_7^+ + M^{++}
    \]
  
  - Larger \( \text{H}_n^+ \) systems as experience is gained

- Assess Potential of Bulk Antihydrogen Nucleation via Cluster Ions

APPROACH

1. Fill the trap with cluster ions of a selected size

2. Introduce molecular hydrogen, allowing it to interact with the trapped ions
   - use proven electromagnetic cooling techniques to maintain temperature

3. Measure size and radial distribution of products through NMR and/or mass spec
PAYOFF/POTENTIAL APPLICATIONS

o Bridge between theory and experiment on cluster ion formation & growth
  - Explain semi-empirical models for free expansion nozzles
  - Create new models for contact free processes

o Illuminate third body cooling processes in non neutral plasmas (pseudo walls)

o Provides versatile experimental apparatus in an active field
  - Cluster Ion Beam Experiments (Y.T. Lee et al., UCB)
  - Models for anti-cluster ion nucleation and growth (Saxon, SRI; Turner, AFIT)
  - Contribute to understanding cluster ion formation and deposition processes relevant to ion-matrix HEDM systems (Bae and Cosby, SRI)
  - Related to surface impact studies (Friedman, BNL and others)

o Explore measurement techniques in ion trap environment
ANTIHYDROGEN ICE STORAGE

U. HAWAII (DR JIM GAINES)
BROOKHAVEN NL (DR JIM POWELL)

- Preliminary results

- HOW STABLE IS SOLID ANTIHYDROGEN EXPOSED TO ANNIHILATION REACTION?
  - 10 mg iceball will withstand 300 Annihilations/s

- WHAT TYPE OF VACUUM DOES THIS IMPLY?
  - Number density Similar to Interstellar Space
    Based on: 100m/s atom velocity
    100% cross section
    Classical law

- WHAT ELSE DO WE NEED TO KNOW?
  - Real cross sections
  - Very high Vacuum Material Behavior
  - Synergistic effects
AIR FORCE ANTIPROTON TECHNOLOGY

Path of Antiproton Technology Development
Antimatter Publications 1988 - Supported at Least in Part by AFAL

- General


- Antiproton Production

(4) Takahashi, Hiroshi, and Werner, Klaus, "Antiproton and Antineutron Production by Relativistic Heavy Ion Collision", BNL technical note (Journal article in preparation)

- Antiproton Storage


- Antiproton Annihilation and Applications


* Formally reviewed publications
ELECTROMAGNETIC TRAPS
FOR
ATOMIC HYDROGEN OR ANTIHYDROGEN

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PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
Electromagnetic Traps for Atomic Anti hydrogen (in Hydrogen)

Isaac F Silvera
Dept of Physics
Harvard University
Cambridge, Ma 02138
Three types of traps:

1. Static Magnetic Trap
2. Laser Trap
3. Microwave Trap

I shall discuss hydrogen as the problems are the same for antihydrogen.
Hyperfine States of Hydrogen

\[ |m_s, m_i\rangle \]

\[ |d\rangle = |\uparrow\uparrow\rangle \]

\[ |c\rangle = |\uparrow\downarrow\rangle - \alpha |\uparrow\uparrow\rangle \]

Low field seekers (electron spin up)

\[ |b\rangle = |\uparrow\downarrow\rangle \]

High field seekers (electron spin down)

\[ |a\rangle = -|\downarrow\uparrow\rangle + \alpha |\uparrow\uparrow\rangle \]

\[ H = -\vec{B} \cdot (\vec{I}_e + \vec{I}_n) + A \vec{I} \cdot \vec{S} \]

electron spin = 1/2 \[ \frac{1}{2} \]

nuclear spin = 1/2 \[ \frac{1}{2} \]

Total spin: \[ F = I + S = 1 \text{ or } 0 \]
For static magnetic fields
Maxwell's equations do
not allow a field maximum
in Free Space.

A Field Minimum is allowed

No restriction on AC fields
(microwave or laser)
STATIC MAGNETIC TRAP

uses field minimum

Trap potential \( U >> kT \)

Trapped states

relaxation: magnetic dipole
spin-exchange

\[
\frac{dn}{dt} = -G n^2
\]

Rates are very rapid

But \( n = 10^4 \text{ cm}^{-3} \) \( \tau_{1/2} = 1 \text{ sec} \)

\[
\frac{1}{n} = \frac{1}{N} \frac{1}{\beta_{1/2}}\]

\( \tau_{1/2} = 1/G \)

MIT (Kleppner + Greif et al.)

Amsterdam (Walraven et al.)

\( 10^{10} \) Trap \( 10^{11} \text{ atm} \)

Densities \( 10^{12} - 10^{13} \text{ cm}^{-3} \)
Laser cooling of hydrogen

\[ n=2 \xrightarrow{\text{Lyman-alpha at 1216\AA}} n=1 \]

Laser light can cool and trap (Phillips et al; Chu et al; Pritchard) ENS group

Cool to quantum limit: \( T_{\text{min}} = \frac{\hbar}{2} = 2.2 \text{mK} \) Lyman-\( x \)

\( \hbar = \) spontaneous emission rate

\[ U \]

Dipole Trap Potential \( U \)

\( \delta = \omega - \omega_0 \)

Deepest potential at \( \delta = -\hbar \)

But severe heating of gas due to spont. emission

For Na Chu et al used \( \delta \geq 10^3 \hbar \) to minimize heating but potential - few mK
Red-Shift, Absorption

Spontaneous Emission

LASER SPONTANEOUS COOLING
Laser power is a major problem.
For 1216 Å sources are pulsed, non-linear harmonic generators

\[ \text{Current sources} \sim 10^{10} \frac{\text{photons}}{\text{sec}} \quad (1 \text{Watt} = 6 \times 10^{17} \frac{\text{photons}}{\text{sec}}) \]

Very large improvements possible
but still pulsed at \( \sim 30 \text{ hz} \)
\[ \text{tox} = 33 \text{msec} \]

Trapped atoms rapidly expand during off time

\( \bar{\nu} \) at 2.2 mK \( \sim 3 \text{meters/sec} \)

Off time expansion
\[ \Delta X = \bar{\nu} \times \text{toff} = 3 \text{m/sec} \times 33 \text{msec} \]
\( \sim 10^2 \text{ cm} \)!
New Trap: Microwave Trap

Just like laser trapping, but no spontaneous emission

Dressed atoms: Diagonalize atomic states and radiation field (N-photons).

Dressed states

\[ |11\rangle = \cos \theta |c, N-1\rangle + \sin \theta |b, N\rangle \]
\[ |12\rangle = -\sin \theta |c, N-1\rangle + \cos \theta |b, N\rangle \]

State 12\rangle seeks highest microwave field

Confocal resonator cavity

\[ U_{\text{trap}} = \frac{\hbar}{2} U_{\text{Rabi}} \]
\[ U_{\text{Rabi}} = \frac{\hbar}{2} c B_{\text{microwave}} \]

Agosta, Silva, Verteer + Stofef
Trap Potential
\[ \frac{U}{\hbar \omega_{\text{rabi}}} \]

\[ S = \omega - \omega_0 \]
\[ |1\rangle = \cos \theta |c, N-1\rangle + \sin \theta |b, N\rangle \]
\[ |2\rangle = -\sin \theta |c, N-1\rangle + \cos \theta |b, N\rangle \]

Plot of the admixture of \( |1\rangle \) or \( |2\rangle \) states into \( |1\rangle \) or \( |2\rangle \) states.

Fig. 1b
bare state relaxation

\[ \text{State } |2\rangle : \text{ trapped} \]

\[ \text{Static trap at } B=5.0T \]

\[ \text{Microwave Trap at } 5.0T \]

\[ \text{Static trap at } B=0.05T \]

\[ \text{Fig. 2} \]
Advantages of μ-Wave trap

No spontaneous heating  \( T_{spont} \approx 10^7 \) years

Microwave Technology well developed

Difficulties

- Require microwave fields of several hundred gauss
  at \( \nu \approx 50 \) Ghz.
- Has not yet been built (To appear PRL next week)

Loading - A long story for another time
ANTIHYDROGEN PRODUCTION

ARTHUR RICH

DEPARTMENT OF PHYSICS
UNIVERSITY OF MICHIGAN
ANN ARBOR, MI

PRESENTED AT THE ANTI PROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
Anti-Hydrogen: Formation and Applications

Presented by: Arthur Rich
Physics Dept.
University of Michigan
Anti-Hydrogen: Formation and Applications

I - Introduction

II - Methods of \( \bar{\Lambda} \) Production

A - Overview

B - Specific Methods

1. \( e^+ + \bar{\beta} \rightarrow \bar{\Lambda} + h\nu \) (1 pass and recirculating \( e^+ \) beam)

2. \( e^+ + p + n h\nu \rightarrow \bar{\Lambda} + (n + 1) h\nu \) \( (n = 0, 1, 2 \ldots) \)

3. \( P\bar{s} + \bar{\beta} \rightarrow \bar{\Lambda} + e^- \)

4. \( \bar{p} + e^+ + e^+ \rightarrow \bar{\Lambda} + e^+ \)

III - \( \bar{\Lambda} \) - Applications

IV - Conclusions
COLLABORATORS

UNIVERSITY OF MICHIGAN – EXPERIMENTAL

RALPH CONTI – POSITRONIUM (Ps) 1sS1 DECAY RATE (λT) FINE STRUCTURE (n=2) TRANSITIONS AND CP TEST; ANTI-HYDROGEN (H) FORMATION

WILLIAM FRIEZE – e+ - Ps CONDENSED MATTER RESEARCH; e+ IMAGING; H

DAVID GIDLEY – λT (Gas and Vacuum); e+ - Ps CONDENSED MATTER AND POLARIZED e+ SURFACE MAGNETISM RESEARCH; e+ IMAGING; H

HENRY GRIFFIN (CHEMISTRY) – INTENSE e+ SOURCE DEVELOPMENT (H)

JEFFREY NICO – λT (Vacuum)

MARK SKALSEY – WEAK INTERACTION TESTS via PRECISION BETA DECAY POLARIZATION MEASUREMENT, INTENSE e+ SOURCE DEVELOPMENT

TOM STEIGER – INTENSE e+ SOURCE DEVELOPMENT (H)

JAMES VAN HOUSE – SEARCH FOR e- HELICITY IN OPTICALLY ACTIVE MOLECULES USING POLARIZED e+ BEAMS; e+ IMAGING; H

PAUL ZITZEWITZ – λT (Vacuum); H: OPTIMIZATION OF POLARIZED e+ BEAMS

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WILLIAM FORD ROBERT LEWIS YUKIO TOMOZAWA
GORDON KANE LEONARD SANDER EDWARD YAO

UNIV. OF TORONTO PRINCETON UNIV.
DEREK PAUL FRANK CALAPRICE
WEAK INTERACTIONS

CERN-HEIDELBERG-DARMSTADT WAKE FOREST UNIV. GM RESEARCH LAB
HELMI POT, et al. ROGER REGSTROM WESTRUM CAPEHART
ANTI-HYDROGEN ORIGIN OF BIOLOGICAL ACTIVITY SURFACE MAGNETISM

100
H APPLICATIONS

1. TCP Tests
   Hyperfine Structure
   Lamb Shift
   Fine Structure
   Electronic Structure (Rydberg) and \( m_\bar{p} \) (inertial), \( \mu_\bar{p} \)

2. Production of Polarized \( \bar{p} \)
   i. Transfer of Polarization from an Initially Polarized \( e^+ \) Beam -
      \( e^+(\uparrow) + \bar{p} \rightarrow \bar{H}(\uparrow) \rightarrow e^+(\uparrow) + \bar{p}(\uparrow) \)
   ii. Optical pumping, Resonant Ionization, Lamb Shift Spin Filter -
       \( e^+ + \bar{p} \rightarrow \bar{H}; \bar{H} + n\hbar\nu \rightarrow \bar{H}(\uparrow) \rightarrow \bar{p}(\uparrow) + e^+(\uparrow) \)

3. Astrophysics
   \( \bar{H} + H \rightarrow [\bar{p}p + Ps; \bar{p} + p + Ps; \bar{p}p + e^+ + e^-; \bar{p} + p + e^+ + e^-] \)
   \( \bar{H} + H \rightarrow \bar{H} + H \)

4. \( \bar{H} \) - Gravity Interaction
   \( m_\bar{p} \) (inertial)/\( m_\bar{p} \) (inertial) - \([\omega(\bar{H} - hfs)/\omega(H - hfs)]\)
   \( m_\bar{p} \) gravitational -

5. Atomic Physics
   \( \bar{H} + \text{Matter} \rightarrow \bar{p} + e^+ + \text{Matter} \) (stripping)
   \( \bar{H} + \text{Matter} \rightarrow \bar{H} + \text{Matter} \) (elastic and inelastic scattering)

6. \( \bar{H} \) - Energy storage
Positron Capture Method

\[ a) \, e^+ + p \rightarrow n + h\nu \]
\[ b) \, e^+ + p + n\nu \rightarrow n + (n + 1)h\nu \]
\[ c) \, e^+ + p + e^+ \rightarrow n + e^+ \]
\[ d) \, e^+ + p + e^- \rightarrow n + e^- \]
\[ e) \, p_n + p \rightarrow n + e^- \]

Applications

I

1) Spectroscopy using Doppler-shifted lasers
2) Polarized \( \vec{p} \)
3) Lamb shift
4) Hyperfine structure

II

1) Lamb Shift
2) Hyperfine structure
3) Precision spectroscopy
4) Polarized \( \vec{p} \)

III

1) Precision spectroscopy in atom traps
2) Gravitational interaction
3) Compact energy storage
Pilot experiment for antihydrogen production at LEAR

Ann Arbor - EML - CERN - Heidelberg - Kadsruhe Collaboration

Proposal 188
F1 Production by Radiative Recombination – Projected Rates (1 pass)

Assume equal area, non-relativistic, $\bar{p}$ and $e^+$ beams. Then

$$R(e^+ + \bar{p} \rightarrow \bar{\Lambda} + h\nu) \approx n(e^+) \langle \sigma v \rangle (e^+ - \bar{p}) (N(\bar{p}) \eta)$$

where: $$n(e^+) = e^+/\text{cm}^2 \text{ in (e$^+$, } \bar{p} \text{) overlap region}$$

$$e^+ \text{ source } n = \frac{R(e^+/s)}{A(L = v \times 1 \text{ sec})} \sim \frac{(4 \times 10^{11}) \times (10^{-4})}{10^{-2} \text{ cm$^2$} \times 10^{10} \text{ cm}} \sim 1 \text{ cm}^{-3}$$

$$\sigma_1 (\infty \rightarrow 1) = 2\pi \left[ \left( \frac{\alpha \omega^2}{c^2} \right) \left( \frac{\omega}{\beta_r} \right)^2 \right] = \frac{2\pi^2 a_e^2}{\beta_r^2} \text{ cm}^2$$

$$\sigma = \sum \sigma_i \sim 3\sigma_1 \sim 0.5 \pi a_e^2 / \beta_r^2$$

$$\langle \sigma v \rangle \sim \frac{a_e^2 c}{\beta_r} \sim \frac{(4 \times 10^{-38}) \times (3 \times 10^{10})}{6 \times 10^{-4}} \sim 2 \times 10^{-12} \text{ cm$^2$/s}$$

$$T_f \sim 0.1 \text{ eV}$$

$$N(\bar{p}) = \text{number of } \bar{p} \text{ stored in LEAR} \approx 10^{11} \text{ (Cooled - } 10^{10})$$

$$\eta = \text{fraction of } \bar{p} \text{ ring overlapped by e$^+$ beam} \approx 4 \text{ m/80 m} \approx 0.05$$

$$R \sim 1 \times (3 \times 10^{-12}) \times (5 \times 10^{8}) \sim 10^{-2}/\text{s} \sim 30\text{ hr}^{-1} \sim 3 \text{ h}^{-1}$$
Production by Radiative Recombination

Using Recirculating e{

\[ R_3(e^+ + \bar{\nu} \rightarrow \bar{\nu}) \approx n_s(e^+) \alpha_x(N(\bar{\nu})n) \]

\[ \alpha_x = \langle \sigma_v \rangle \approx \frac{n_s^2}{\beta_x^2} \nu \approx 10^{-19} \times 10^{17} \]

\[ \frac{R(e^+/s)}{A(L = 10^3 \text{cm})} = \frac{(4 \times 10^{11}) \times 10^{-5}}{10^{-3} \times 10^3} \approx 4 \times 10^6 \text{ cm}^{-3} \]

\[ e^+ \text{ - accumulated, cooled, pulsed and recirculated (10 m e}^+ \text{ storage ring)} \]

\[ R_3(e^+ + \bar{\nu} \rightarrow \bar{\nu}) = (4 \times 10^9) \times (3 \times 10^{-12}) \times (5 \times 10^6) \approx 6000 / s \]
Production by Radiative Recombination:
Recirculating e⁺ and Stimulated Recombination

\[ R_s(e^+ + \beta \rightarrow \varpi) \approx n_s(e^+) \alpha_s N(\varpi) \eta G \]

\[ e^+ \text{ storage} \quad n_s \equiv \frac{R(e^+/s)}{\lambda(L = 10^2 \text{cm})} = \frac{(4 \times 10^{11}) \times 10^{-6}}{10^{-8} \times 10^3} \sim 4 \times 10^1 \text{ cm}^{-3} \]

\[ e^+ \text{ - accumulated, cooled, pulsed and recirculated (10 m storage ring)} \]

\[ LEAR \rightarrow e^+ \text{ from accumulator and pulser} \]

\[ \Gamma \rightarrow e^+ \text{ storage ring (} \gamma \approx \frac{10^8 \text{ m/s}}{10^3 \text{ m/s} \approx 100 \text{ ms)}} \]

\[ G = \text{ Stimulated recombination gain factor (} e^+ + \beta + h\nu \rightarrow \varpi + 2h\nu) = \]

\[ = \frac{n^3 J(MW/cm^2)}{2 (T_e/0.1 \text{eV})} \]

If \( \lambda_{Lab} = 321 \text{ nm (} \lambda_{CM} = \frac{\lambda}{(1 - \beta)} \gamma = 364 \text{ nm for } \infty \rightarrow 2) \)

then \( G \sim 16 \) for \( T_e \sim 0.1 \text{ eV} \)

Commercial 20 MW/cm² excimer laser (250 Hz, 20 ns pulse) \( G \sim 10^3 \)

Finally - If pulsed \( e^+ \) matches laser (stead pulse)

\[ R_s(e^+ + \beta \rightarrow \varpi) = (4 \times 10^8) \times (3 \times 10^{-12}) \times (5 \times 10^9)(G) \sim 6000 \text{ G/s} \]

\[ C_W - (CO/CO_2 \sim 20 \text{W}) \quad m > 10, \ G \sim 10^3 \text{ but} \]

\[ \text{re-emergence and field emerage problems} \]
Position Accumulator and Pulsar

(a) $^{22}$Na Source $V_{c1}$ $V_{g1}$ $V_{c2}$ $V_{g2}$ out $e^+$

B (uniform) $\rightarrow$

Moderator $R_1$ (Remod) $R_2$ (Remod)

$5kV$ $\rightarrow$ $5kV$

$20\mu s$ (≈ 5V/Trap period)

(b) $V_{c1}$

$20ns$

$V_{g1}$

$V_{c2}$

$\epsilon_{H}(W) \times \cdots \times \epsilon_{HR}$

$E_{H}(W) \sim 10^2 \epsilon_{H}(W)$

$\frac{\# of e^+/pulse \sim 4 \times 10^{11} \times (3 \times 10^{-4}) \left(\frac{1}{3}\right)^2 \times 2 \times 10^{-3}}{2 \times 10^5/pulse \sim 2 \times 10^5/pulse}$

$\frac{1}{sec} \sim 2 \times 10^5 \times 50 \sim 10^7/s$
Positron recirculator

a) circular device

circumference: 15 m, vacuum: 10^{-12} Torr
magnetic field 200-600 G, e^+ energy: 20-100 keV

b) linear device
**Applications**

1. **TCP Tests**
   Hyperfine Structure
   Lamb Shift
   Fine Structure
   Electronic Structure (Rydburg) and $m_P$ (inertial), $\mu_P$

2. **Production of Polarized $\bar{p}$**
   i. Transfer of Polarization from an Initially Polarized $e^+$ Beam -
   \[
   e^+ (\uparrow) + \bar{p} \rightarrow \bar{H}(\uparrow) \rightarrow e^+ (\uparrow) + \bar{p}(\uparrow)
   \]
   \[
   \bar{P}_0(e^+) = \bar{P}_0(e^+) = \bar{P}_0(e^+) = \bar{P}_0(e^+)
   \]
   ii. Optical pumping, Resonant Ionization, Lamb Shift Spin Filter -
   \[
   e^+ + \bar{p} \rightarrow \bar{H}; \quad \bar{H} + nhv \rightarrow \bar{H}(\uparrow) \rightarrow \bar{p}(\uparrow) + e^+ (\uparrow)
   \]

3. **Astrophysics**
   \[
   \bar{H} + H \rightarrow [\bar{p}p + Ps; \quad \bar{p} + p + Ps; \quad \bar{p}p + e^+ + e^-; \quad \bar{p} + p + e^+ + e^-]
   \]
   \[
   \bar{H} + H \rightarrow \bar{H} + H
   \]

4. **$\bar{H}$ - Gravity Interaction**
   \[
   m_P \text{ (inertial)}/m_P \text{ (inertial)} = [\omega(\bar{H} - hfs)/\omega(H - hfs)]
   \]
   \[
   m_P \text{ gravitational -}
   \]

5. **Atomic Physics**
   \[
   \bar{H} + \text{Matter} \rightarrow \bar{p} + e^+ + \text{Matter (stripping)}
   \]
   \[
   \bar{H} + \text{Matter} \rightarrow \bar{H} + \text{Matter (elastic and inelastic scattering)}
   \]

6. **$\bar{H}$ - Energy storage**
Anti-Proton Polarization via $\bar{H}$ Formation

with Polarized Partons

1. $\bar{H}$ hfs $\alpha (m=1)$
   \[ e^+ \bar{p} \xrightarrow{\text{Triplet}} \frac{1}{\sqrt{2}} \left( \downarrow \uparrow, \uparrow \uparrow, \frac{1}{\sqrt{2}} \left( \downarrow \downarrow + \uparrow \uparrow \right) \right) \]
   \[ \omega \left[ 1.5 \text{GHz}, \gamma = 10^{-9}, N \approx 10^4 \text{(H)} \right] \]
   \[ \text{Singlet} \]
   \[ \frac{1}{\sqrt{2}} \left( \downarrow \downarrow - \uparrow \uparrow \right) \]
   # hfs cycle
   \[ \frac{1}{\sqrt{2}} \left( \downarrow \downarrow - \uparrow \uparrow \right) \]
   \[ \omega \left( L(\text{hfs}) \approx 10^{-7} \text{cm} \right) \]

2. $\bar{H}$ Formation from Polarized $e^+$-Unpol. $\bar{p}$
   \[ (1/2) \]
   \[ e^+ \xrightarrow{\text{H}} \frac{1}{\sqrt{2}} \]
   \[ (1/2) \]
   \[ \frac{1}{\sqrt{2}} \left( \downarrow \uparrow \right) \xrightarrow{\text{H}} \frac{1}{\sqrt{2}} \left( \downarrow \uparrow \right) \]

3. $\bar{p}$ Polarization
   \[ P(\bar{p}) = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} = \frac{2 + \frac{1}{4}}{2 + 1} = \frac{1}{2} \left( \frac{1}{2} \right) = \frac{1}{4} \left( P(e^+) \right) \]
Polarized $\bar{p} -$ Projected Rates

**Rate**

$$R_S(e^+ + \bar{p} \rightarrow \bar{\alpha}) = (4 \times 10^5) \times (3 \times 10^{-12}) \times (5 \times 10^8) G \sim 600 \text{ G/s}$$

**Polarization**

1) If no attempt is made to maximize $P(e^+)$, $P(e^+) \sim 0.15$

2) To increase $P(e^+)$ use Be absorber to reduce low energy $e^+$ from beta spectrum (recall $P_{\text{Long}} = (v)/c$)

3) Maximize $P^2 I \Rightarrow P(e^+) = 0.5$ but $n_S = 1.5 \times 10^5$ (\text{200 G/4})

**Result**

$$R_S(\bar{\alpha}) \sim R_S(\bar{p}) \sim (2 \times 10^7 - 2 \times 10^8) \text{ G/day at } P(\bar{p}) \simeq \frac{1}{2} P(e^+) \simeq 0.25$$
Polarized $\bar{p} -$ Projected Rates and Uses

\[
\begin{align*}
\bar{p} + p & \\
\rightarrow & \\
\pi^+ + \pi^- & \\
K^+ + K^- & \\
\bar{n} + n &
\end{align*}
\]

\[
A_\parallel = \frac{1}{P_{\bar{p}}P_p} \frac{\sigma_T(\uparrow_{\bar{p}} \uparrow_p) - \sigma_T(\downarrow_{\bar{p}} \downarrow_p) - \sigma_T(\uparrow_{\bar{p}} \downarrow_p) + \sigma_T(\downarrow_{\bar{p}} \uparrow_p)}{\sigma_T(\uparrow_{\bar{p}} \uparrow_p) + \sigma_T(\downarrow_{\bar{p}} \downarrow_p) + \sigma_T(\uparrow_{\bar{p}} \downarrow_p) + \sigma_T(\downarrow_{\bar{p}} \uparrow_p)}
\]

where $P_{\bar{p}}$ and $P_p$ are the longitudinal polarizations of the antiproton beam and proton target, respectively, and the $\sigma_T$ are the measured total cross sections with the sense of polarizations indicated by the arrows. A similar asymmetry $A_\perp$ could be measured for the $p$ and $\bar{p}$ polarized transversely to the incident $\bar{p}$ direction. Each asymmetry could be measured to a precision

\[
\delta(A) = \frac{1}{\sqrt{N_{\text{event}} P_{\bar{p}}P_p}}
\]

where $N_{\text{event}}$ is the total number of $\bar{p}$ interacting in the target. If the target thickness is chosen so that 20% of the incident $\bar{p}$ interact in the target (a sufficiently small fraction to avoid degradation of the asymmetry by multiple scattering events) and given $P_{\bar{p}} = 0.25$ and $P_p \sim 0.12$, ($P_p$ is a typical value for the effective proton polarization in a hydrocarbon target with 70% hydrogen proton polarization) then in one day of running one can attain

\[
\delta(A) = \pm \frac{1}{\sqrt{0.2 \times 3 \times 10^7 \times 0.25 \times 0.12}} = \pm 0.01
\]

\[
A_\parallel(p+p) = 0.15 \text{ (}\rho_{\text{lat}} = 1.5 \text{ GeV/c})
\]
CONCLUSIONS

I - HISTORY ($e^+$)

1932 - 72  HEROIC PERIOD

1972 - 85  \[ R(\text{slow } e^+) \sim (10^4 - 10^6)/\text{sec} \]
\[ n(e^+/\text{cm}^3) \sim 1 \]

1985 \rightarrow  \[ R \sim 10^8/\text{s} \]
\[ n \sim 10^6/\text{cm}^3 \]

II - FUTURE

INCREASE IN R, \( n \rightarrow \)

1) IMPROVED QUANTUM ELECTRODYNAMICS AND SYMMETRY TESTS.

2) $e^+$ PLASMA.

3) $e^+$ IMAGING.

4) ANTI-HYDROGEN.

5) BOSE-EINSTEIN CONDENSATION OF POSITRONIUM.

\[
(\lambda_{de8} \sim m^{-1/8})
\]
HEADQUARTERS DOE ANTIPROTON ACTIVITIES

DAVE GOODWIN

OFFICE OF HIGH ENERGY AND NUCLEAR PHYSICS
U.S. DOE ER-20.1/GTN
WASHINGTON, DC 20545

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
WORKSHOP ON ANTIPROTON TECHNOLOGY

BROOKHAVEN, MAY 10, 1989

"HEADQUARTERS DOE ANTIPROTON ACTIVITIES"

DAVE GOODWIN

SPECIAL ASST. TO THE ASSOCIATE DIRECTOR OF THE
OFFICE OF HIGH ENERGY AND NUCLEAR PHYSICS (OHENP)

U.S. DOE, ER-20.1/GTN, WASH., D.C. 20545
(301) 353-4037 (FAX 5079), FTS 233-4037 (FAX 5079)
EFFORTS TO OBTAIN RESOURCES FROM PROGRAM OFFICES

AVERAGE SINCE 10/87 WORKSHOP:

- ONE DOCUMENT PER WEEK
- DISCUSS WITH 2 PEOPLE PER DAY
SUPERCONDUCTING SUPER COLLIDER (SSC) STUDY

MARCH 16, 1989 LETTER FROM DIEBOLD TO SCHWITTERS:
1995 PHYSICS FROM MEDIUM ENERGY BOOSTER (100 TO 200 GeV)
10/2-4/89 OPEN HOUSE IN TEXAS

JIM BENSINGER (BRANDEIS), ROOM 2089C, SSC/URA, c/o LBL,
90/4040, BERKELEY, CA 94720, (415) 486-4772 EXT. 6083,
FTS 451-4772 EXT. 6083, FAX (415) 486-6796

PROVIDED: U. OF MICH. LETTER, 10/88 AND 2/89 RAND REPORTS
AND 14 REPLIES TO SURVEY LETTER

DOCUMENTS: 5 (INCL. FY91 FUNDING ISSUE FOR SSC/BROOKHAVEN)

STATUS: OPEN
SUPERCOMPUTERS

FY88: WORKSHOP ANNOUNCEMENT, NO PROPOSALS

FY89: RFTPs TO 54 WORKSHOP ATTENDEES
ONE PROPOSAL: TAKAHASHI (280 "HOURS"; $100+K)
UP TO 60+HOURS/MONTH AVAILABLE

FY90: 5/15/89 SUPERCOMPUTER ALLOCATIONS COMMITTEE MEETING:
90,000 HOURS FOR HIGH ENERGY PHYSICS (HEP)/SSC,
NUCLEAR PHYSICS (NP), BASIC ENERGY SCIENCES (BES) &
HEALTH ENVIRONMENTAL RESEARCH (HER); EXCL. 27,000
HOURS FOR FUSION
RFTPs TO MOST ATTENDEES OF BOTH WORKSHOPS AND
MIRROR MATTER NOTICE
TAKAHASHI: 380 HOURS (< $150K)

DOCUMENTS: 2

STATUS: OPEN
10/11/88 SURVEY LETTER

319 HEP/SSC
210 NP
271 DOD
54 WORKSHOP ATTENDEES
1 U. OF N.C.
387 MIRROR MATTER
1,242

14 REPLIES (MIRROR MATTER SUMMARIZES): NONE NEGATIVE
BES & HER: 14 REPLIES, 10/88 RAND REPORT & 5/89 WORKSHOP
NOTICE WITH 2/89 RAND REPORT
15TH REPLY: LIPTHANE

DOCUMENTS: 9

STATUS: "CLOSED"
TECHNOLOGY TRANSFER

3/28-29/89: DOE TECHNOLOGY TRANSFER WORKING GROUP:

- LOS ALAMOS, BERKELEY, OAK RIDGE, PACIFIC NORTHWEST, DEFENSE PROGRAMS (DP) AND FUSION

5/9/89: ER TECHNOLOGY TRANSFER STEERING GROUP

- BROOKHAVEN, BERKELEY, OAK RIDGE, ARGONNE, PACIFIC NORTHWEST, BES, HER AND FUSION

4/4/89: $5 MIL./YR. FOR "SMALL SCIENCE" IMAGING/ANALYSIS AND ENERGY DEPOSITION WITH BES, HER, DP, NIH AND MINORITY EDUCATION ($20 MIL./YR.)

FY90 REQUEST FOR SMALL SCIENCE & SUGGESTION FOR MINORITY EDUCATION

DOCUMENTS: 3

STATUS: OPEN
SMALL BUSINESS INNOVATION RESEARCH (SBIR)

RECALL MIRROR MATTER: $50K, $500K

FY88: ELECTRON COOLING (D. LARSON)
    2 TRANSPORTERS (W. WING)
    LASER COOLING ("    ")
    RELATIVISTIC SELF-COLLIDER: RESCOL (B. MAGLICH)

FY89: ANTIPROTON TOPIC (OHENP SIGN): "PREMATURE"
    ELECTRON COOLING (D. LARSON)
FY90 SBIR

HEP/SSC/NP MAY REDUCE FROM 6 TOPICS TO 3 - 5

5/4/89: ANTI PROTON TOPIC

PROVIDED: 15 SURVEY REPLIES, 10/88 & 2/89 RAND REPORTS,
SSC STUDY, SUMMARY FOR HUNTER & BROOKHAVEN PAPER

WILL NEED REVIEWERS

DOCUMENTS: 2

STATUS: OPEN
WEEKLY/BIWEEKLY REPORTS

WEEKLY: FROM OHENP THRU OFFICE OF ENERGY RESEARCH (OER) TO SECRETARY & ALL DOE PROGRAM & OPERATIONS OFFICES

BIWEEKLY: FROM OHENP TO ALL ER OFFICES (INCL. HEP, SSC, NP, BES, HER AND FUSION)

MONTHLY: TO ALL DOE OPS OFFICES AND ER OFFICES

10/87 WORKSHOP: WEEKLY, BIWEEKLY AND MONTHLY

12/1/87 AFAL BRIEFING (OHENP, HEP, BES & HER ATTEND): 2 WEEKLY, BIWEEKLY, MONTHLY, NOTICES AND MINUTES (TO OER, ALL HEP/SSC & NP STAFF & BES, HER, FUSION & DP)
WEEKLY/BIWEEKLY REPORTS

7/26/88 AFAL/AFOSR MEETING: WEEKLY AND BIWEEKLY


5/89 WORKSHOP: 1ST OF 2 WEEKLY, 1ST OF 2 BIWEEKLY & NOTICE TO OHENP, ALL HEP/SSC & NP STAFF & BES, HER FUSION & DP, WITH 2/89 RAND REPORT

RAND ASSOCIATED PRESS ITEM: WEEKLY AND BIWEEKLY

G-2: WEEKLY, BIWEEKLY, MONTHLY & MEMOS (INCL. 14 SURVEY REPLIES)


ANNUAL REPORT TO CONGRESS

DOCUMENTS: 28

STATUS: CONTINUING ACTION
FY88 JASON STUDY

OER MEETING WITH JASON

DOCUMENTS: 3

STATUS: CLOSED

KAON

(KAONS, ANTIPROTONS, OTHERS STRONGLY INTERACTING PARTICLES & NEUTRINOS)

NUCLEAR SCIENCE ADVISORY COMMITTEE (NSAC) REPORT

PROVIDED NP WITH 14 SURVEY REPLIES

AFTER CEBAF & RHIC

DOCUMENTS: 2

STATUS: "OPEN"
PROPOSED USAF/HUNTER MEETING

SUMMARY TO HUNTER (SIGNED BY NP) PROVIDED TO OHENP, ALL HEP/SSC & NP STAFF & BES, HER, FUSION & DP

DOE POINT-OF-CONTACT

DOCUMENTS: 2  

STATUS: "CLOSED"

TENAS ACCELERATOR CENTER (TAC)

$3 MIL. FROM CONGRESS

TAC PARTICIPATION SUGGESTED IN TRIP REPORT ON 10/87 WORKSHOP (PROVIDED TO OER, OHENP, ALL HEP/SSC & NP STAFF & BES, HER; FUSION & DP)

AS OF 8/1/89: NO FURTHER HEP/SSC FUNDING

DOCUMENTS: 1  

STATUS: "OPEN"
ACCELERATOR PRODUCED TRITIUM (APT)

PROPOSED ANSWER TO SENATE QUESTION INCLUDED ANTIPROTONS
JASON & 2/89 RAND REPORTS TO DP (INCL. CONGRESSIONAL LIASON)
ENERGY RESEARCH ADVISORY BOARD (ERAB) SUBPANEL & GAO
EXYDER (XY SELF-COLLIDER):
  o $17.628 MIL. FOR 2 1/2 YR., 10 KG/yr. OF ANTIPROTONS
  INFO. TO DP INCL. ANTIPROTONS
  o 2/4/88 MIGMA MEETING WITH HEP, BES & FUSION (1 G/yr)
DOCUMENTS: 9

STATUS: "CLOSED"
SMALL/DISADVANTAGED BUSINESS (8A)

UP TO $170K/YR.

DOCUMENTS: 7 (IN 1 OF 5 STATUS REPORTS TO AFAL/ANTI-M)

STATUS: "OPEN" (NEED PROPOSAL)

RAND REPORT ON REMOTE POWER

WITH 2/89 RAND REPORT TO: DP, NUCLEAR MATERIALS PRODUCTION & SP-100

DOCUMENTS: 3

STATUS: "OPEN"

ANNUAL MEETING OF NUCLEAR PHYSICS LAB DIRECTORS

RECOMMENDED AGENDA ITEM ON ANTIPROTONS

DOCUMENTS: 1

STATUS: OPEN
INSTITUTIONAL PLANNING REVIEWS

RECOMMENDED AGENDA ITEM ON ANTPROTONS FOR FY88 BROOKHAVEN REVIEW

FY89: 9/13/89 FERMILAB & 7/17-18/89 BROOKHAVEN REVIEWS

ALSO: 8/15-24/89 "PHYSICS AT FERMILAB IN THE 1990S"

DOCUMENTS: 6

STATUS: OPEN

THE PLANETARY SOCIETY

PROVIDE REFS FOR 9/85 AFAL REPORT & WORKSHOP PROCEEDINGS

DOCUMENTS: 1
OER & OHENP INFORMED

OER: 8 WEEKLY, 7 BIWEEKLY, 3 MONTHLY, JASON MEETING, SUMMARY FOR HUNTER, WORKSHOP: RAND & TRIP REPORTS, AFAL BRIEFING MINUTES AND 7 INFORMAL DISCUSSIONS

OHENP: SIGN 8 WEEKLY, 7 BIWEEKLY, SBIR & AFAL BRIEFING (ATTEND); SUMMARY FOR HUNTER, 3 MONTHLY, WORKSHOP: RAND & TRIP REPORTS, AFAL BRIEFING MINUTES, 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT, FY90 FUNDS, SSC, BROOKHAVEN, 14 SURVEY REPLIES, 7 PAPERS/ETC. & 22 INFORMAL DISCUSSIONS
HEP/SSC & NP INFORMED

HEP/SSC: 7 BIWEEKLY, 3 MONTHLY; ALL STAFF: SUMMARY FOR HUNTER, WORKSHOP TRIP REPORT, AFAL BRIEFING MINUTES ("ATTEND") & 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT; WORKSHOP RAND REPORT, FERMILAB, BROOKHAVEN, SSC, 14 SURVEY REPLIES, 40 PAPERS/ETC., WEEKLY STAFF MEETINGS & INFORMAL DISCUSSION WITH 1 PERSON EVERY OTHER DAY

NP: 7 BIWEEKLY, 3 MONTHLY; ALL STAFF: SUMMARY FOR HUNTER (SIGN), WORKSHOP TRIP REPORT, AFAL BRIEFING MINUTES & 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT; KAON/SSC, ANNUAL MEETING, WORKSHOP: RAND REPORT, 14 REPLIES, 1 PAPER, WEEKLY STAFF MEETINGS & INFORMAL DISCUSSION WITH 1 PERSON EVERY OTHER DAY
DP & FUSION INFORMED

DP: TECHNOLOGY TRANSFER, CLASSIFIED RAND REPORT, REMOTE POWER, APT/EXYDAR, SUMMARY FOR HUNTER, AFAL BRIEFING, WORKSHOP: RAND & TRIP REPORTS, 4 PAPERS/ETC. (INCL. SDIO MEETING WEEKLY) AND 10 INFORMAL DISCUSSIONS

FUSION: 7 BIWEEKLY, 3 MONTHLY, SUMMARY FOR HUNTER, WORKSHOP TRIP REPORT, AFAL BRIEFING MINUTES, 5/89 WORKSHOP WITH 2/89 RAND REPORT AND 7 INFORMAL DISCUSSIONS
FUNDING CONSORTIUM

DOE

DOD (E.G., USAF AND SDIO)

NSF

NIH

NASA

PRIVATE (E.G., ANTI-M AND DOD CONTRACTORS)

EUROPE (ITALY AND LEAR)
PROPOSAL

CAPITAL: SSC OR $15 MIL. FOR BROOKHAVEN

$ 10 MIL./YR. OPERATING (AT LEAST $1 MIL./YR. FOR EACH):

(1) PRODUCTION

(2) PRODUCTION R&D

(3) TRANSPORTERS

(4) TRANSPORTER R&D

(5) "APPLIED" R&D (E.G., IMAGING, ANALYSIS & NON-PROPULSION ENERGY DEPOSITION)
PROPOSAL (CONTINUED)

(6) "ANTIGRAVITY"

(7) OTHER HENP R&D

(8) OTHER BASIC R&D ("NON-PROPULSION")

(9) PROPULSION R&D
ANTIPROTON CATALYZED FUSION

T. E. KALOGEROPoulos

DEPARTMENT OF PHYSICS
SYRACUSE UNIVERSITY

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
\[ \bar{P} \text{ CATALYSIS} \]

\[ (\bar{P}\phi l) + d \rightarrow \bar{p}(d d) \]
\[ \rightarrow \text{Mesons + 3 Nucleons} \]
\[ \text{Charge} = +1 \]

\[ \text{EXPECTED RATE (ORDER(? ESTIMATE)} \]

\[ R_P^m \approx R_p^r \cdot \frac{z_p^m}{z_p^r} \cdot \left( \frac{M_p^r}{M_p^m} \right)^3 \]
\[ \times \frac{10^2}{(10^{-11} \cdot 10^{-13})/10^{-6}} \]
\[ \left( \frac{m_p^r \cdot 1}{m_p^m \cdot \eta^2} \right)^3 = 10^3 / n^2 \]

For \( n = 2 \)

\[ R_P \approx (1 - 10^2)\% \]
EVIDENCE

• COMPLETE STUDY OF 3223 $\bar{P}$ ANNIHILATIONS (PRL 33, 1631, 1974) RESULTED IN SEVEN "ZOO" EVENTS

• "ZOO" EVENTS ARE NOT:

\[
\bar{P} + D \rightarrow (\bar{P} \eta) + P_{\text{vis}} (P_{\text{inv}}) \\
\text{or} \\
\rightarrow (\bar{P} p) + \pi_{\text{inv}}. \\
\text{or} \\
\downarrow \text{mesons (Q = -1)} \\
\downarrow \text{mesons (Q = 0)}
\]

• TWO INTERESTING EVENTS

\[
\bar{P} + ^4\text{He} (dd) \rightarrow 2P + 3\pi^- + 2\pi^+ + \eta
\]

\[
\bar{P} + X \rightarrow 3P + 3\pi^- + 2\pi^+ + \eta
\]
### FRAME 285126 EVENT (Two Protons)

**Track** | **E** | **E** | **D** | **P** | **P** | **P** | **E** | **Comments**
---|---|---|---|---|---|---|---|---
\(\pi^-\) (1) | -3.6±.4 | 12.1±3 | 368±26 | 196±14 | 178±13 | -254±18 | 394±24 | 394±24
\(\pi^-\) (2) | 33.2±2 | 101.6±2 | 193±6 | -32±1 | 158±7 | 106±1 | 238±6 | 238±6
\(\pi^-\) (3) | -12.0±.4 | 255.6±.4 | 415±30 | -77±6 | -299±22 | -278±20 | 438±28 | 438±28
\(\pi^-\) (4) | -42.7±.7 | 1.7±.7 | 253±18 | 186±13 | 6±2 | -172±12 | 289±16 | 289±16
\(\pi^-\) (5) | 53.5±.3 | 344.6±.4 | 255±15 | 146±9 | -10±3 | 205±12 | 291±13 | 291±13
P (6) | -21.6±7.3 | 331.2±3.9 | 169 | 139 | -76 | -61 | 953 | stops (1.8 cm)
P (7) | 50.5±.3 | 179.9±.3 | 533±35 | -339±22 | -1±2 | 411±27 | 1078±17 | out (2.6 cm)

\[ \bar{p} + 2d \rightarrow 2p + 3\pi^- + 2\pi^+ + M_H (992±48) \]
\[ \bar{p} + ^4He \rightarrow 2p + 3\pi^- + 2\pi^+ + M_H (955±48) \]

\[ M_H = m_\eta \]

139
\[ \vec{P} + ^4\text{He} /2d \rightarrow 3\pi^+ + 2\pi^+ + 3p + \text{M} \cdot \text{M}^2 (-0.3 \pm 0.2 \text{ GeV}/c^2) \]

NOT A \pi!
SPECIAL SCAN FOR "200" EVENTS

- Film from distant running period than that for "complete study".

- Total $\bar{P}$ events scanned: 8800
  "200" events found: 21

  \[
  BR(200) = (0.24 \pm 0.05)\% 
  \]

- COMPARES WELL WITH THAT OF COMPLETE SCAN:

  \[
  BR(200) = (0.22 \pm 0.08)\% 
  \]

ARE THESE EVENTS EXAMPLES OF $\bar{P}$-FUSION CATALYSIS?
Secondary Interactions: NO!

1) Rate of 'Zoo' events
   ~100 times the expected rate for secondary interactions
2) KE(p) + KE(p) > 140 MeV
   which is not satisfied in the two special events

Chamber Contaminants such as N/O...

- Typical results of chamber gas in %:
  \[ \begin{align*}
  \text{O}_2 & (0.05) ; \text{D}_2 \text{O}(0.4) ; \text{H}_2 \text{O}(0.04) ; \text{HDO}(0.06) ; \\
  \text{N}_2 & (0.2) .
\end{align*} \]

Others "unmeasurable".

But in D_2-liquid these contaminants should freeze out!
WHAT ABOUT $^3$He?

- From the event which fits $\bar{p} + ^3$He, we estimate from its a priori probability a contamination from $^3$He of $\sim 10\%$ (!)
- This is not in line with $BR(300^\circ)$.

CONCLUSIONS

(1) $\bar{p}$-FUSION CATALYSIS IN LIQUID D$_2$ OCCURS WITH A RATE $\lesssim 1/100\bar{p}$

(2) IF POSSIBLE $^4$He CONTAMINATION AT A LEVEL $\gg 1\%$ COULD BE EXCLUDED THEN A GOOD CANDIDATE EVENT FOR $\bar{p}/D_2$ FUSION INDUCED REACTION HAS BEEN OBSERVED AMONG 3000 ANNIHILATIONS.

(3) SEARCH FOR $\bar{p}$ FUSION CATALYSIS AND ITS PROPERTIES IS A GOOD COMPLIMENTARY RESEARCH TO $\mu^-$-Catalysis.
ANTIPROTON INDUCED FUSION REACTION

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Note: We regret that copies of the transparencies used in Dr Toothacker's excellent presentation were not available for inclusion in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
SPECIAL DOE LABORATORY?

BROOKHAVEN MEETING,
MAY 10, 1989

WORKSHOP ON ANTIPROTON TECHNOLOGY
DOE LABORATORY MICROFUSION FACILITY (LMF) FOR TESTING

- Valid operational requirement
- Why have an LMF?
  - Simulate underground explosions in laboratory setting
- Against what contingencies?
  - Nuclear test ban: complete, or more restricted than current limitations
- No "assured design" yet for meeting LMF requirements
WHAT CAN DO WE DO WITH AN LMF?

- Maintain nuclear design competence (complement, validate computations)— ideally, with many tests per year
  - Equation of state; opacity; energy flows; design principles
  - Exploratory research on new concepts
  - Effects simulation
- "Laboratory" facility → maximum energy releases in ~1/10 - 1 ton HE range
- Keep core proficiency program going
  - Prevent technological surprise, breakout
TWO OPTIONS FOR LMF

CONCEPTUAL STAGE (DOE)

- Very high energy laser, particle beam
  - Ignite small TN pellet
- TN energy release
  - 200-1000 MJoules
- Effects simulation
  - Radiation, EMP, etc.
- Projected cost goals
  - $700 to 1000 million
- Construction projections
  - 5-6 years?
  - Available late 90s?

ALTERNATIVE POSSIBILITY

- Use antiproton source
  - Based on J. Solem paper
    (’87 Proceedings)
  - Additional classified paper
    (Solem, Mayer, Augenstein)
  - Other related aspects
    (Pennsylvania State Group - G. Smith, et al)

(Both options have two distinct regimes:
1. Ignite fuel, very local region;
2. Conditions for sustained propagating ignition.
3. >7% in experimental preparations)
ANTIPROTON OPTION FOR LMF

- Initial experimentation
  - Standard initial tools
    - Antiproton source (~$10^{14} - 10^{16}$ antiprotons/year) – use a small factor
    - Portable storage
  - Significant Technical issues
    - Space/time compression of antiproton bunch; target configuration; precision diagnostics (much debate by normal matter effects)
    - Parameterized by Solem; Pennsylvania State group

- Broad-scale experimentation (comparable to laser, PB option plans)
  - Source roughly equivalent to Large Hadron Facility capability
  - Progress in storage, extraction, post-extraction compression
LMF RECOMMENDATIONS

- DOE sponsor **serious look** at antiproton option
  - Comparable ground rules to laser, PB option

- Two cost bases
  - Piggy-back on Large Hadron Facility source, if firmed up; or,
  - Stand-alone source comparable to Large Hadron Facility source

- Evaluate range of simulation experimentation possible
  - Availability for other kinds of experimental uses

- Criteria for antiproton option viability (initial screening)
  - Comparable range of uses
  - Highest cost option (stand-alone source) ≤ laser, PB projections

(For LMF allows basic science input, and inputs in other fields
- e.g., population, power generation)

RAND
MODELING ANTIPROTON - PLASMA INTERACTIONS

(ANTIMATTER THRUSTER MODELING)

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
MISSION $\Delta V$ vs SPECIFIC IMPULSE

Alpha Centauri (50 Years)

TAU (50 Years)

Mars (40 Days)

CNSR, MRSR

$\Delta V$ [m/s]

Delivered Mass as % of Initial Mass

3500 K

Specific Impulse [lbf-s/lbm]
ANTIMATTER THRUSTER CONCEPTS

GAS CORE

\[ \text{Isp} = 1000-2500 \text{ lbf-s/lbm} \]
Efficiency < 50%

SOLID CORE

\[ \text{Isp} = 800-1000 \text{ lbf-s/lbm} \]
Efficiency < 70%

BEAM CORE

\[ \text{Isp} = 10^7 \text{ lbf-s/lbm} \]
Efficiency < 60%

PLASMA CORE

\[ \text{Isp} = 5000-10000 \text{ lbf-s/lbm} \]
Efficiency << 50%
ANTIMATTER THRUSTER ISSUES

- $dE/dx$ in Plasmas
- Photon Attenuation
- Bremsstrahlung Radiation (Electrons, Plasma)
- Synchrotron Radiation (Electron, Plasma)
- Nuclear Processes (Charge Exchange, Fission)
- Particle Decays (Neutrino Losses)
- Confinement (Annihilation Products, Plasma)
- Technology (Magnets, Shielding)
PRELIMINARY MODELING RESULTS

- Very Low Efficiency (<1%)
- Ultra High Loss Mechanisms (Neutrinos, Bremsstrahlung)
- Poor Annihilation Product Confinement (Charged and Neutral)
- Very Challenging Technology (Magnets, Shielding)
CONCEPTS FOR THE EXPERIMENTAL
DETERMINATION OF RADIATION SHIELDING
AND METAL CLAD PELLET PERFORMANCE

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
Concepts for the Experimental Determination of Radiation Shielding and Metal Clad Pellet Performance

Brice Cassenti
RADIATION SOURCE

- Annihilation reaction
  \[ p + \bar{p} \rightarrow n\pi^+ + n\pi^- + m\pi^0 \]

- Neutral pion decay
  \[ \pi^0 \rightarrow \gamma + \gamma \]
Additional Radiation Sources

- **Charge Exchange**
  \[
  \pi^- + p \rightarrow n + \pi^+
  \]

- **Fission**
  \[
  \pi + Z \rightarrow Z_1 + Z_2 + kn
  \]

- Etc.
GAMMA RAY INTERACTIONS

- Compton scattering
  \[ \gamma + e^- \rightarrow \gamma + e^- \]

- Pair creation
  \[ \gamma \rightarrow e^+ + e^- \]
ELECTRON/POSITRON INTERACTIONS

- Gamma ray emission
  \[ e^- \rightarrow \gamma + e^- \]
  \[ e^- \rightarrow \gamma + e^- \]

- Ionization
  \[ e^+ e^- \rightarrow e^+ e^- \]
  \[ e^+ e^- \rightarrow e^+ e^- \]

- Annihilation
  \[ e^+ e^- \rightarrow \gamma + \gamma \]
GAMMA RAY ENERGY DISTRIBUTION

\[
\frac{1}{N_0} \frac{dN}{dE} = \left( \frac{E}{E_0} \right) e^{-\left( \frac{E}{E_0} \right)}
\]

Energy distribution

\[
\frac{1}{N_0} \frac{dN}{dE}
\]

Energy/avg. energy
GAMMA RAY INTENSITY VARIATION

- Tungsten
- \( \pi^0 \) decay

Relative gamma ray intensity

Energy, MeV
ELECTRON / POSITRON INTENSITY

- Tungsten
- $\pi^0$ decay

Relate electron intensity

- $t = 0.1$
- $t = 0.2$
- $t = 0.3$

Energy, MeV
EMBEDDING PROCEDURE

(Donoghue, 1986)

\( \bar{p} p \rightarrow \Xi^\pm \Xi^\mp \)
ENERGY ABSORPTION

- $\pi^0$ Decay

Energy, MeV

Thickness, radiation lengths

- Pb
- W
- Al
SAMPLE CALCULATION

- OTV mission
  - 10 ton payload
  - 5.5 km/s velocity increment
  - 8 mg annihilated

- Shield mass
  - 3.5 tons

- Maximum temperature rise
  - 500 deg C
JPL

ANTIMATTER INTERACTION EXPERIMENT

Target System

Particle Detector Array

Semiconductor Vertex Detector Arrays

P Beam Degrader

Magnetic "Bottle/Nozzle" Solenoids External Solenoid Magnet

Mass Spectrometer

from Callas: Antimatter Spacecraft Propulsion Experiments...
ANTIMATTER INTERACTION EXPERIMENT

from Callas: Antimatter Spacecraft Propulsion Experiments...
PELLET ROCKET CONCEPTUAL DESIGN
PELLET CONTAINEMENT

Fuel

Metal cladding
ANTIMATTER INTERACTION EXPERIMENT

from Callas: Antimatter Spacecraft Propulsion Experiments...
PROGRAM OUTLINES

Perform simulation

Add to JPL Experiment

Compare data and simulations
Summary

- Radiation shielding
- Pellet performance
- JPL Experiment
- Simulations
References


INTRODUCTION TO CP VIOLATION STUDIES

WITH Pbars

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
CP Violation

Kaon decay (Fitch & Cronin, 1964)

\[ K_S \rightarrow 2\pi, \quad K_L \rightarrow 3\pi, \quad \Gamma_L \sim 0.002 \Gamma_S \]

Limitations:

1) Two parameters only, \( \delta \) and \( \delta' \).
   No other CP in (u, d, s) at present.

2) Fundamental question unresolved:
   i) \( |\Delta S| = 2 \) only (superweak)
   ii) \( |\Delta S| = 1 \) (milliweak)
      and \( |\Delta S| = 2 \) by second-order
Hadron decay \( (T.\ D.\ Lee,\ 1966;\ Overseeth;\ Pakvasa,\ 1969) \)

Non-leptonic,

\[ \Xi^- \rightarrow \pi^- + \Lambda \rightarrow \pi^- + \rho \]

\[ \Xi^+ \rightarrow \pi^+ + \bar{\Lambda} \rightarrow \pi^+ + \bar{\rho} \]

Vs.

Compare: decay rate, \( \pi^- \bar{\pi} \)

\[ 2(\bar{\sigma} \cdot \bar{p}) , \quad \alpha \times \bar{\alpha} \]

\[ \beta(\bar{\sigma} \times \bar{\sigma} : \bar{p}) , \quad \beta + \bar{\beta} \]

In principle, 3 new measures of \( CP \)

\[ \Rightarrow \text{All are } |\Delta S| = 1 \]


**Emulsing procedure (Donoghue, 1986)**

\[ \bar{p} p \rightarrow \Xi \Xi \]
\[ \rightarrow \Lambda \Lambda \]

Production: strong interaction, preserves CP

- Perfect antimonelation of initial states,
  \[ \bar{p} = -p, \quad \bar{\Xi} = -\Xi \]

Eliminates major uncertainties.

Estimates for K-M, Higgs, left-right:

\[ \Xi \rightarrow \pi \Lambda \]
\[ |\beta + \bar{\beta}| \sim 10^{-4} \text{ to } 10^{-3} \sim 3 |\pi + \bar{\pi}| \]

\[ \Lambda \rightarrow \pi p \]
\[ |\beta + \bar{\beta}| \sim 10^{-4} \text{ to } 10^{-3} \sim 7 |\pi + \bar{\pi}| \]
Implementation

1) Don't attempt \( \frac{(\pi^0 - \pi^0)}{(\pi^+ + \pi^-)} \sim 10^{-6} \) to \( 10^{-5} \)

2) \( |d + \bar{d}| \approx |d + \bar{d}|_\Xi \) (estimate)

3) \( |\beta + \bar{\beta}| \Xi \) only feasible. N decay analyses.

Conflicting aims:

i) \( \sigma_{\eta} \approx 10 \sigma_{\Xi} \), but CP parameters largest (estimated) for \( \Xi = \Xi \).

ii) For \( \Xi = \Xi \), \( |\beta + \bar{\beta}| > |d + \bar{d}| \); but |d + \bar{d}| simpler, perhaps higher acceptance.
TEST OF NON-CONSERVATION IN

IN $P\bar{P}$ to $\Xi\bar{\Xi}$

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Note: We regret that reproducible copies of the transparencies used in Dr Nathan's excellent presentation were not available for inclusion in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
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10 MAY 1989
STUDIES OF CP VIOLATION WITH

PURE $K^0 - K^0_{\text{bar}}$ BEAMS FROM $P_{\text{bars}}$

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Note: We regret that reproducible copies of the transparencies used in Dr Miller's excellent presentation were not available for inclusion in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
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10 MAY 1989
SEARCH FOR CP VIOLATION IN

$P\bar{p} \rightarrow J/\Psi \rightarrow \Lambda^0 \bar{\Lambda}^0$
SEARCH FOR CP-VIOLATION
IN
\[ \bar{p} p \rightarrow J/\psi \rightarrow \Lambda^o \bar{\Lambda}^o \]

G.A. SMITH
(PENN STATE)

WORKSHOP
ON
ANTIPROTON TECHNOLOGY
MAY 10, 1989
BNL
HIGH RESOLUTION HEAVY QUARK SPECTROSCOPY WITH ANTI PROTONS

NOTE REMARKABLE SIMILARITY BETWEEN SPECTRA OF CHARMONIUM AND POSITRONIUM!

\[ C^{-2/3} \]

\[ +2/3 \]

\[ \text{C} \leftarrow \sim 10^{-5} \text{A} \rightarrow \]

\[ e^+ \]

\[ e^- \]
Table 2
\( \bar{p}p \rightarrow J/\psi \rightarrow e^+e^- \) runs

<table>
<thead>
<tr>
<th>Run</th>
<th>Date</th>
<th>( \sqrt{s} )</th>
<th>( \int L dt )</th>
<th>Events</th>
<th>Mass (MeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11 May 1983</td>
<td>3096.7-3101.0</td>
<td>10.0</td>
<td>16</td>
<td>3097.05 ± 0.22</td>
</tr>
<tr>
<td>2</td>
<td>19 July 1983</td>
<td>3095.8-3097.5</td>
<td>8.0</td>
<td>13</td>
<td>3097.35 ± 0.32</td>
</tr>
<tr>
<td>3</td>
<td>26 July 1983</td>
<td>3096.4-3097.6</td>
<td>18.0</td>
<td>14</td>
<td>3095.69 ± 0.16</td>
</tr>
<tr>
<td>4</td>
<td>3 August 1983</td>
<td>3096.4-3097.0</td>
<td>21.5</td>
<td>34</td>
<td>3096.66 ± 0.13</td>
</tr>
<tr>
<td>5</td>
<td>22 March 1984</td>
<td>3096.1-3098.0</td>
<td>63.5</td>
<td>81</td>
<td>3096.79 ± 0.11</td>
</tr>
<tr>
<td>6</td>
<td>5 April 1984</td>
<td>3096.7</td>
<td>20.0</td>
<td>35</td>
<td>3096.64 ± 0.24</td>
</tr>
</tbody>
</table>

---

R704 (ISR) \[ \overline{p}p \rightarrow e^+e^- \]

**No Co-planarity Cut**

**With Co-planarity Cut** $\sqrt{s} = 2981 \text{ MeV}$

**Total Energy (GeV)** $\sqrt{s} = 3097 \text{ MeV}$
Fermilab E-760
Fermilab - Ferrara - Genoa - Irvine
Northwestern - Penn State - Torino

4AT Electromagnetic Calorimeter

\[ 3S_1 \rightarrow e^+e^- \]
\[ 1S_0 \rightarrow \nu\bar{\nu} \]
\[ 3p \rightarrow 3S_1 \nu \]
\[ \nu \rightarrow e^+e^- \]

etc.

Pb glass

Mass Resolution (E-760)
\[ \approx 30 \text{ keV} \]

Fine Hyperfine Structure

F = \Delta M = a <L·S> + b <T> + c <S_1·S_2>

of P-states?
\[ q \sim 35 \text{ MeV} \]
\[ b \sim 40 \text{ MeV} \]

Confined in scalar gluonic field?

Spin Orbit Tensor Hyperfine?
FERMILAB
FERRARA
GENOA
E-760
IRVINE
NORTHWESTERN
PENN STATE
TORINO

8.9 GeV/c
ACCELERATOR
DEBRACHER
ACUMULATOR
TARGET AND CLEAR
BOOSTER TEST LINE
BOOSTER RING

FERMILAB ANTIPROTON SOURCE

\[ \mathcal{L}_{E760} = 10^{31} \text{ cm}^{-2} \text{s}^{-1} \] (Gas jet)
\[ \mathcal{L}_{LEAR} = 1.5 \times 10^{29} \text{ cm}^{-2} \text{s}^{-1} (2 \times 2 \text{ GeV/c}^2) \]
(POST ACOL) \[ \leq 4436 \text{ MeV} \]
LOOKING AT CP INVARIANCE
AND QUANTUM MECHANICS IN
$J/\psi \rightarrow \Lambda\bar{\Lambda}$ DECAY

M.H. TIXIER ET AL. PHYS. LETT. 212B, 523 (1988)

\[ \sigma = 1 \) CP INVARIANT \]
\[ \delta \cos \theta \Delta n^1 \Delta n^2 \]
\[ 2 \left[ 1 - \left( \frac{P_y}{E_y} \right) \sqrt{1 - \alpha_\Lambda^2} \right] \] 
\[ + \left( \frac{P_y}{E_y} \right) \sqrt{1 - \alpha_\Lambda^2} \] 
\[ \alpha_\Lambda = 0.412 \]

1) CP INVARIANT
2) NO ASSUMPTION ON REL. $\Lambda, \bar{\Lambda}$ POLARIZATION
3) $\frac{P_y}{E_y} = 0.48 (J/\psi)$, $\alpha_\Lambda = 0.412$

$\Lambda$ orthogonal to $N_y$ ($J/\psi$ polarization)
and $\hat{\alpha}$

1847 $J/\psi \rightarrow \Lambda\bar{\Lambda}$ EVENTS
$(8.6 \times 10^8 J/\psi$ DECAYS)

Fig. 7. The $\alpha - \beta$ distribution, MC simulation and data

TO TEST CP, SET $\alpha_\Lambda = -\alpha_\Lambda \alpha_\bar{\Lambda}$. ASSUMING VALIDITY
OF Q.M., $\alpha_\Lambda$ IS EXTRACTED FROM $\alpha - \beta$ DISTRIBUTION
$\alpha_\Lambda = 0.01 \pm 0.10 (-0.07 \pm 0.09$ P. BARNES ET AL. PHYS.
$\Lambda \rightarrow 3 p$, 2003).
**FURTHER TESTS OF CP INVARIANCE IN J/ψ → Λ^0Λ^0**

1) **GOAL:** 10^{-4} ERROR IN A

2) **PRESENT LIMITS:** ∼ 10^{-1}

3) **FIRST STEP → 10^{-2}**

   E-760: \( \text{RATE} = (5 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}) \times (10^{-30} \text{ cm}^2) \times (0.13 \times 10^{-2}) \times (0.64) \times (0.64) \)

   \( \text{BR}_{J/ψ \rightarrow ΛΛ} = 0.027 \text{ sec}^{-1} \)

   \( \text{BR}_{Λ \rightarrow ππ}, \text{BR}_{Λ \rightarrow ππ}^+ \)

   **EXTRAPOLATE DM2 RESULTS (2 \times 10^3 \text{ EVTS}) TO 10^{-2} LEVEL (2 \times 10^5 \text{ EVENTS})**

   \( 2 \times 10^5 \text{ EVTS} \Rightarrow 7.4 \times 10^6 \text{ SEC (2.8 months)} \)

4) **NEXT STEP → 10^{-3}**

   **REQUIRES 2 \times 10^7 J/ψ \rightarrow Λ^0Λ^0, OR ∼ 10^10 J/ψ^0!!**

   J/ψ FACTORY @ \( L \sim 10^{33} \text{ cm}^{-2} \text{ sec}^{-1} \)

   **BEST BET IS PROBABLY e^-e^+ LINEAR COLLIDER??**
RARE MODES OF NUCLEON-ANTINUCLEON
ANNIHILATION

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10 MAY 1989
RARE MODES OF N\bar{N} ANNihilation
PRODUCTION OF
J^Pc EXOTICS IN $\bar{NN} \rightarrow \text{mesons}$
PRODUCTION OF J^pc EXOTICS IN ¯NN → mesons
What is a $J^{PC}$ exotic meson?

$J = \text{total angular momentum}$

$\pi = \text{parity (±)}$

$C = \text{charge conjugation parity (±)}$

$J^{PC}$ exotic quantum numbers cannot correspond to a quark-antiquark ($q\bar{q}$) system as for ordinary mesons ($\pi$, $\eta$, $\rho$, $\omega$...)

**Examples:** $J^{PC} = 0^{--}$, $0^{+-}$, $1^{--}$ are exotic

They must have more complicated structure than $q\bar{q}$

$\rightarrow q^{2}\bar{q}^{2}$, $q\bar{q}g$...

↑ excitation of the gluonic field
THEORETICAL PREDICTIONS FOR MASSES OF EXOTIC:

consider $Q\bar{Q}g$ "hybrids" $(0^{-}\text{or } 1^{--}) Q\bar{Q} \otimes \begin{cases} \text{TE (1^{-})} \\ \text{TM (1^{--})} \end{cases}$

\[ \begin{array}{c} \uparrow \\uparrow \\ 3S_0 \ 3S_1 \end{array} \]

lowest lying are $3S_1 \otimes \text{TE} = \begin{cases} 1^{-+} (1^{-}) \rho_g \\ 1^{-+} (0^{+}) \omega_g \end{cases}$

Mass Estimates and Decays:

1) MIT Bag Model (Barnes, Close, deViron, NP B224, 241 (1983))

\[ M(\rho_g) \approx 1.4 \text{ GeV} , \ M(\omega_g) \approx 1.55 \text{ GeV} \]

(pranowitz, sharpe NP B222, 211 (1983) give larger M's but \approx same splitting)

2) Flux Tube Model (Isgur, Kokoiski, Paton, PRL 54, 869 (1985))

\[ M(\rho_g) = M(\omega_g) \approx 1.9 \text{ GeV} \]

(also $0^{+} (0^{-}, 1^{+}), 2^{+} (0^{-}, 1^{+})$)

Selection Rules: $\rho_g \rightarrow \pi^{\pm} B^\mp, \pi^0 D$; $\rho_g \rightarrow \eta, \eta'$, $\omega$, $K^*$

3) QCD Sum Rules (Latorre et al., Z. Phys. C34, 347 (1985))

\[ M(\rho_g) \approx 1.6 - 2.1 \text{ GeV} \]

$\rho_g \rightarrow \pi \rho$, $K^* \bar{K}$ large, $\rho_g \rightarrow \eta, \eta'$ suppressed
Candidate for a $J^{PC}$ exotic resonance:


reaction \[ \pi^- p \rightarrow X^0 n \]
\[ \Upsilon_{\pi^0 \eta} (l=1) \]

$X^0$ seen as interference effect (asymmetry) with \[ \pi^- p \rightarrow A_2^0 n \]
\[ \Upsilon_{\pi^0 \eta} (l=2) \]

\[ X^0 \text{ is } \begin{array}{c} J^{PC}(I^G) = 1^{-+}(1^-) \end{array} \text{ exotic} \]

\[ M = 1406 \pm 20 \text{ MeV } \]
\[ \Gamma = 180 \pm 30 \text{ MeV} \]

Note: $X$ should be accessible in $\bar{NN} \rightarrow \pi X$

$\rightarrow$ look for optimum channels
Experimental Searches for Exotics

1) **LEAR at CERN**

   JETSET, CRYSTAL BARREL, OBELIX

2) **Brookhaven AGS** E818 Chung et al

   \[ \pi^- p \rightarrow \bar{g}^- p \ \text{at} \ 12 \text{GeV/c} \]

   **Decay chain:** \( \bar{g}^- \rightarrow \pi^- f \rightarrow \pi^+ \pi^- \rightarrow K^+ K^- \rightarrow \pi^+ \pi^- \)

   **Overall reaction:** \( \pi^- p \rightarrow K^+ \pi^- 3\pi^- p \)

3) **KEK (Japan)**

   \[ \pi^- p \rightarrow \bar{g}^- p \ \text{at} \ 6 \text{GeV/c} \]

   **Decay chain:** \( \bar{g}^- \rightarrow \pi^- \pi^- \rightarrow 2\pi \)
Production of $J^{PC}$ exotics in $\bar{p}p \rightarrow \pi^0 X^0$

<table>
<thead>
<tr>
<th>$J^{PC}(I^G)$ of $X$</th>
<th>$\bar{NN}(L=0) \rightarrow \pi^0 X^0 (q_\gamma)$</th>
<th>$\bar{NN}(L=1) \rightarrow \pi^0 X^0 (q_\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^{--}(0^-)$</td>
<td>$^{33}S_1 (q_\gamma = 1)$</td>
<td>$-$</td>
</tr>
<tr>
<td>$0^{--}(1^+)$</td>
<td>$^{13}S_1 (q_\gamma = 1)$</td>
<td>$-$</td>
</tr>
<tr>
<td>$0^{--}(0^+,1^-)$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$0^{+-}(0^-)$</td>
<td>$-$</td>
<td>$^{31}P_1 (q_\gamma = 1)$</td>
</tr>
<tr>
<td>$0^{+-}(1^+)$</td>
<td>$-$</td>
<td>$^{11}P_1 (q_\gamma = 1)$</td>
</tr>
<tr>
<td>$0^{+-}(0^+,1^-)$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$1^{+-}(0^+)$ $\omega$</td>
<td>$^{31}S_0 (q_\gamma = 1)$</td>
<td>$^{33}P_1 (q_\gamma = 0,2), ^{33}P_2 (q_\gamma = 2)$</td>
</tr>
<tr>
<td>$1^{+-}(1^-)$ $\rho$</td>
<td>$^{11}S_0 (q_\gamma = 1)$</td>
<td>$^{13}P_1 (q_\gamma = 0,2), ^{13}P_2 (q_\gamma = 2)$</td>
</tr>
<tr>
<td>$1^{+-}(0^-,1^+)$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

C conservation is strong constraint!
see $X^0$ with both $I = 0, 1$

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Production of $J^{PC}$ exotics in $\bar{p}p \rightarrow \pi^{\pm}X^\mp$

<table>
<thead>
<tr>
<th>$J^{PC}(I^G)$ of $X$</th>
<th>$\bar{p}p (L=0) \rightarrow \pi^{\pm}X^\mp (\ell_q)$</th>
<th>$\bar{p}p (L=1) \rightarrow \pi^{\pm}X^\mp (\ell_q)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^{--}(1^-)$</td>
<td>$^{33}S_1 (\ell_q=1)$</td>
<td>$^{13}P_0 (\ell_q=0), ^{13}P_2 (\ell_q=2)$</td>
</tr>
<tr>
<td>$0^{--}(1^+)$</td>
<td>$^{13}S_1 (\ell_q=1)$</td>
<td>$^{33}P_0 (\ell_q=0), ^{33}P_2 (\ell_q=2)$</td>
</tr>
<tr>
<td>$0^{--}(1^-)$</td>
<td>$^{11}S_0 (\ell_q=0)$</td>
<td>$^{13}P_1, ^{31}P_1 (\ell_q=1)$</td>
</tr>
<tr>
<td>$0^{--}(1^+)$</td>
<td>$^{31}S_0 (\ell_q=0)$</td>
<td>$^{33}P_1, ^{11}P_1 (\ell_q=1)$</td>
</tr>
<tr>
<td>$1^{--}(1^-)$</td>
<td>$^{11}S_0 (\ell_q=1), ^{33}S_1 (\ell_q=1)$</td>
<td>$^{13}P_1, ^{31}P_1 (\ell_q=0), ^{13}P_2 (\ell_q=1)$</td>
</tr>
<tr>
<td>$1^{--}(1^+)$</td>
<td>$^{31}S_0 (\ell_q=1), ^{13}S_1 (\ell_q=1)$</td>
<td>$^{33}P_1, ^{11}P_1 (\ell_q=0,2), ^{33}P_2 (\ell_q=1)$</td>
</tr>
</tbody>
</table>

No constraint from $C$

$I=0 \ X$ forbidden
Production of $J^{PC}$ exotics in $\bar{p}n \to \pi^- X^0$

<table>
<thead>
<tr>
<th>$J^{PC}$ ($I^G$) of $X$</th>
<th>$\bar{p}n (L=0) \to \pi^- X^0$</th>
<th>$\bar{p}n (L=1) \to \pi^- X^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^{--} (0^-, 1^-)$</td>
<td>$^{33}S_1 (\ell_T = 1)$</td>
<td>$^{33}P_0 (\ell_T = 0), ^{33}P_2 (\ell_T = 2)$</td>
</tr>
<tr>
<td>$0^{--} (0^+, 1^+)$</td>
<td>$^{31}S_0 (\ell_T = 0)$</td>
<td>$^{31}P_1 (\ell_T = 1)$</td>
</tr>
<tr>
<td>$0^{+-} (0^-, 1^-)$</td>
<td>$^{33}S_1 (\ell_T = 1)$</td>
<td>$^{31}P_1 (\ell_T = 0, 2)$</td>
</tr>
<tr>
<td>$0^{+-} (0^+, 1^+)$</td>
<td>$^{31}S_0 (\ell_T = 1)$</td>
<td>$^{33}P_1 (\ell_T = 0, 2), ^{33}P_2 (\ell_T = 2)$</td>
</tr>
<tr>
<td>$1^{++} (0^-, 1^-)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1^{++} (0^+, 1^+)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

no constraint from $C$
see both $I = 0, 1$
NON-STRANGE DECAY MODES OF J = 0, 1 EXOTICS

consider \( \psi + \psi, \psi + V, \psi + T, V + V, \psi + S \)

\( \eta = \{ \eta, \eta' \}, \omega = \{ \omega, \phi \}, \phi = \{ \phi, \phi' \}, \sigma = \{ \sigma, \sigma' \}, \Delta = \{ D, E \} \)

<table>
<thead>
<tr>
<th>(J^P (I^G))</th>
<th>Allowed Decays ( X^0 \rightarrow M_1 M_2 (\ell) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0−− (0−)</td>
<td>( \pi^0 \eta^0, \pi^0 \eta^\pm, \eta \omega (\ell=1) )</td>
</tr>
<tr>
<td>0−− (0+)</td>
<td>( \pi^\pm A_2^\mp (\ell=2), \pi^\pm \pi^\mp (\ell=0) )</td>
</tr>
<tr>
<td>0−− (1−)</td>
<td>( \pi^\pm \pi^\mp (\ell=0), \pi^\pm \delta^\pm (\ell=1) )</td>
</tr>
<tr>
<td>0−− (1+)</td>
<td>( \pi^\mp \omega, \eta \pi^0 (\ell=0), \pi^\pm A_2^\mp (\ell=2), \pi^\pm \delta^\mp (\ell=0) )</td>
</tr>
<tr>
<td>0++ (0−)</td>
<td>( \pi^0 B^0, \pi^\pm B^\mp (\ell=1) )</td>
</tr>
<tr>
<td>0++ (0+)</td>
<td>( \pi^\mp \pi^- (\ell=0), \pi^\pm \pi^- (\ell=0, 2), \pi^\pm A_1^\mp (\ell=1) )</td>
</tr>
<tr>
<td>0++ (1−)</td>
<td>( \pi^\pm \pi^- (\ell=0), \pi^\pm \pi^- (\ell=0, 2), \pi^\pm A_1^\mp (\ell=1), \pi^\pm \pi^- (\ell=0, 2) )</td>
</tr>
<tr>
<td>1−− (0−)</td>
<td>( \pi^\pm \pi^- (\ell=0), \pi^\pm \pi^- (\ell=0, 2) )</td>
</tr>
<tr>
<td>1−− (0+)</td>
<td>( \pi^\mp \omega (\ell=1, 3), \pi^\mp \phi^0 (\ell=1), \pi^\mp \phi^0 (\ell=1, 3), \pi^\mp \phi^0 (\ell=1, 3) )</td>
</tr>
<tr>
<td>1−− (1−)</td>
<td>( \pi^0 \phi (\ell=1), \pi^\pm \phi^0 (\ell=1), \pi^\pm \phi^0 (\ell=1), \pi^0 \phi (\ell=1, 3) )</td>
</tr>
<tr>
<td>1−− (1+)</td>
<td>( \pi^\mp \phi^0 (\ell=1, 3), \pi^\pm \phi^0 (\ell=1, 3), \pi^\pm \phi^0 (\ell=1, 3), \pi^\pm \phi^0 (\ell=1, 3) )</td>
</tr>
</tbody>
</table>

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Search for $1^{-+}(1^-)$ exotic in $\bar{p}p \rightarrow \pi^0\pi^0\eta$

**SIGNAL:** \( \bar{p}p \rightarrow \pi^0\pi^0 X^0(l_f=1) \rightarrow \pi^0\pi^0\eta(l=1) \)

**BACKGROUND:** \( \bar{p}p \rightarrow \pi^0\eta\pi^0\eta(l_f=2) \rightarrow \pi^0\pi^0\eta(l=2) \)

\( \bar{p}p \rightarrow \pi^0\pi^0\eta(l_f=0) \rightarrow \pi^0\pi^0\eta(l=0) \)

also $\sigma\eta(l_f=0)$, $f\eta(l_f=2)$ couple to $\pi^0\pi^0\eta$

Experimentally, look for $\pi^0\pi^0\eta \rightarrow \sigma\eta$ (CRYSTAL BARREL)
Exotics in $\bar{p}p$ Annihilation:

A) All neutral modes

1) $\bar{p}p \rightarrow \pi^0 \omega \rightarrow 2\pi^0 (l_\pi = 1)$

2) $\bar{p}p \rightarrow \pi^0 \omega \rightarrow \gamma \gamma (l_\pi = 1)$

3) $\bar{p}p \rightarrow \pi^0 g^0 \rightarrow \pi^0 \eta (l_\pi = 1)$

4) $\bar{p}p \rightarrow \pi^0 g^0 \rightarrow \pi^0 f (l_\pi = 2) 
   \rightarrow 2\pi^0$

B) Charged Modes:

1) $\bar{p}p \rightarrow \pi^\pm g^\mp \rightarrow \pi^\mp B^0 \rightarrow \pi^0 \omega \rightarrow \pi^0 \gamma$

2) $\bar{p}p \rightarrow \pi^\pm g^\mp \rightarrow \pi^\mp D^0 \rightarrow \pi^0 \pi^0 \eta$

3) $\bar{p}p \rightarrow \pi^\pm g^\mp \rightarrow \pi^\mp f^0 \rightarrow \pi^+ \pi^-$
Outlook: 

\[ \bar{N}N \text{ annihilation very promising as a means of producing exotic mesons } X \text{ in reactions } \bar{N}N \rightarrow \pi X \]

Difficulties:

1) \( \Gamma_x \) large \( \rightarrow \) new states are broad resonance
   \( \rightarrow \) detailed amplitude analysis need to extract interference effects

2) branching ratios for \( \bar{N}N \rightarrow \pi X \) likely to be small
   \( \rightarrow \) no good theoretical estimate

Advantages:

1) \( \bar{N}N \) annihilation potentially rich in gluonic excitations

2) \( \bar{N}N \) at rest provides control of initial quantum numbers (\( L = 0 \) or \( L = 1 \))

3) \( \bar{p}p \rightarrow \pi^0X^0, \pi^\pm X^\mp ; \bar{p}n \rightarrow \pi^-X^0 \text{ gives quantum number filtration} \)

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ANTIPROTON PRODUCTION CALCULATION
BY THE MULTISTRING MODEL
"VENUS" COMPUTER CODE

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DEPARTMENT OF NUCLEAR ENERGY
BROOKHAVEN NATIONAL LABORATORY
UPTON, NY

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989
ANTIPROTON PRODUCTION CALCULATION BY MULTISTRING MODEL VENUS COMPUTER CODE

HINOSHI TAKAMASHI
KLAUS WERNER
JAMES POWELL

Brookhaven National Laboratory

WORKSHOP ANTIPROTON TECHNOLOGY
MAY 10, 1989

Brookhaven National Laboratory
Upton, New York, 11973
Fermi Lab Source Performance

F.E. Mills. NIM PA 271 (1985) 176

Proton Energy \( E_{\text{lab}} = 120 \text{ GeV} \)

Antiproton Energy \( = 8 \text{ GeV} \)

Target : Cu

Cross Section Missing Factor \( \approx 2.5 \)

McGormley.
Antiproton Source (CERN, Fermilab)

Hojvat and Van Ginneken

Empirical formula

\[ \frac{E}{\sigma_{\text{lab}}} \frac{d^3\sigma}{dp_3} = \left[ k (1-X_R)^m \text{exp}(-3P_T^2) \right] \]

\[ \times \left[ 1 + 245^2 \text{exp}(8X_R) \right] \left[ \text{exp}\left( \frac{X}{b P_T^2} \right) \text{exp}\left( -c X_R \right) \right] \]

\[ X_R = \frac{E}{E_{\text{max}}} \]

\[ k = 0.065, \quad m = 8.0 \]

<table>
<thead>
<tr>
<th>Target</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>W</td>
<td>0.69</td>
<td>1.38</td>
<td>1.79</td>
</tr>
<tr>
<td>Pb</td>
<td>1.73</td>
<td>1.37</td>
<td>1.33</td>
</tr>
</tbody>
</table>
VENUS
A multistring model
for ultrarelativistic heavy ion collision

- model for 'ordinary' collisions
  (no plasma)
- pp extrapolation (test: pA)
- string fragmentation consistent with \( e^+e^- \), \( \nu p, \bar{\nu}p, \mu p \) data
- Monte Carlo formulation
  (event generator)
- motivated by Regge theory
  (like DPM)
Step Structure

I) Multiple Scattering

Geometry + $\xi_{NN}$ determine NN coll

\[ \sqrt{\frac{Q_{NN}}{\pi}} \]

nucleon move on a straight line

II) Individual NN collision

III) String fragmentation
Multi String Model, Venue Code

Figure 1

(a) $d_b$ (Valence) $p$

(b) $c$

(c) $s_e$ $a$

(d) $a$
**Feynman Field Fragmentation**

\[ \begin{align*}
\begin{array}{c}
\bar{q} \\
\bar{b} \\
\text{baryon} \\
\text{meson} \\
\text{antibaryon} \\
\bar{q} \\
\bar{b} \\
\bar{b} \\
\end{array} & \begin{array}{c}
q \\
\bar{q} \\
\text{meson} \\
\text{baryon} \\
\text{meson} \\
\text{antibaryon} \\
q \\
\end{array} \\
\end{align*} \]

*elementary vertices:*

<table>
<thead>
<tr>
<th>( q \rightarrow q )</th>
<th>( q \rightarrow \bar{b} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>meson</td>
<td>meson</td>
</tr>
<tr>
<td></td>
<td>baryon</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \bar{b} \rightarrow \bar{b} )</th>
<th>( \bar{b} \rightarrow q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>meson</td>
<td>meson</td>
</tr>
<tr>
<td></td>
<td>baryon</td>
</tr>
</tbody>
</table>

**Splitting function (using quark counting)**

\[ f(x) \sim x^\alpha (1-x)^{2n-1} \]

\( n: \) number of spectator

\[ \alpha = \begin{cases} 
3/2 & \text{for baryon prod} \\
0 & \text{for meson prod} 
\end{cases} \]
Table 4.1 The Particle Yield For Proton-Proton Collision (%)

<table>
<thead>
<tr>
<th>Number of Hits:</th>
<th>15000</th>
<th>15000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Energy of Projectile (GeV.)</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>4.53 (5.4)*</td>
<td>11.5 (16.2)*</td>
</tr>
<tr>
<td>$\bar{n}$</td>
<td>4.39</td>
<td>11.2</td>
</tr>
<tr>
<td>$p$</td>
<td>128.7</td>
<td>132.3</td>
</tr>
<tr>
<td>$n$</td>
<td>62.3</td>
<td>67.7</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>262.4</td>
<td>399.2</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>325.1</td>
<td>461.7</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>735.8</td>
<td>1052.5</td>
</tr>
<tr>
<td>$k^-$</td>
<td>15.1</td>
<td>28.4</td>
</tr>
<tr>
<td>$k^+$</td>
<td>24.4</td>
<td>41.4</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>4.39</td>
<td>6.08</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>0.37</td>
<td>1.36</td>
</tr>
<tr>
<td>$\Lambda^-$</td>
<td>2.0</td>
<td>6.3</td>
</tr>
<tr>
<td>$\Lambda^+$</td>
<td>14.1</td>
<td>22.3</td>
</tr>
<tr>
<td>$e^-$</td>
<td>4.4</td>
<td>6.0</td>
</tr>
<tr>
<td>$e^+$</td>
<td>4.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>

* ( ) is calculated by Hojovat and Van Ginneken's empirical formula.
<table>
<thead>
<tr>
<th>Number of Hits:</th>
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<th>5773</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Energy of Proton (GeV.)</td>
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<td>1000</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>7.07(9.0)*</td>
<td>21.38(29.0)*</td>
</tr>
<tr>
<td>$\bar{n}$</td>
<td>6.93</td>
<td>22.37</td>
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<tr>
<td>$p$</td>
<td>213.59</td>
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<td>$n$</td>
<td>218.83</td>
<td>226.64</td>
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<tr>
<td>$\pi^-$</td>
<td>751.96</td>
<td>1154.70</td>
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<td>$\pi^+$</td>
<td>765.16</td>
<td>1168.16</td>
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<td>$\gamma$</td>
<td>1998.35</td>
<td>2921.7</td>
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<td>$\kappa^-$</td>
<td>27.75</td>
<td>65.70</td>
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<td>49.51</td>
<td>89.51</td>
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<td>$\Sigma^+$</td>
<td>28.37</td>
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<td>$\bar{\Sigma}^-$</td>
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<td>$\bar{\Sigma}^+$</td>
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<td>$\Lambda^-$</td>
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<td>$\Lambda^+$</td>
<td>5.54</td>
<td>9.39</td>
</tr>
<tr>
<td>$e^-$</td>
<td>11.33</td>
<td>16.45</td>
</tr>
<tr>
<td>$e^+$</td>
<td>11.33</td>
<td>16.45</td>
</tr>
</tbody>
</table>

* ( ) is calculated by Hojovat & Van Ginneken's empirical formula.
Figure 3.1

\[ X = \frac{P_H}{P_{H,ld} \Delta x} \]
Figure 3.2
Figure 3.3

Iso. Kinostat.
quark Cascade Recombination Model
Analytic
Figure 3.5
Figure 3.6

\[ X = \frac{P_{\mu}}{P_{\mu_{\text{max}}}} \]
Figure 3.9

\[ x = \frac{P_n}{P_n^{max}} \]
Table 4.3 The Particle Yield For Si-Si (%)

<table>
<thead>
<tr>
<th>Number of Hits:</th>
<th>9831</th>
<th>9858</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Energy of Projectile (GeV./A)</td>
<td>200</td>
<td>1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>200</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}$</td>
<td>26.88 (82.5)*</td>
<td>79.86 (260.5)*</td>
</tr>
<tr>
<td>$\bar{n}$</td>
<td>27.41 (81.7)</td>
<td>79.20 (258.4)</td>
</tr>
<tr>
<td>$p$</td>
<td>680.24</td>
<td>710.38 (2238.7)</td>
</tr>
<tr>
<td>$n$</td>
<td>684.46</td>
<td>706.08 (2229.6)</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>2931.60</td>
<td>4353.5 (15226.2)</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>2935.06</td>
<td>4358.07 (15200.8)</td>
</tr>
</tbody>
</table>

* ( )s are at central collision (b=0)
Table 4.4 The Particle Yield For O-Pb Collision ($^+$)

<table>
<thead>
<tr>
<th>Number of Hits:</th>
<th>7000</th>
<th>876</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Energy of Projectile (GeV./A)</td>
<td>200</td>
<td>1000</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>40.04 (78.6)*</td>
<td>124.77</td>
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<tr>
<td>$\bar{n}$</td>
<td>37.84 (77.8)</td>
<td>122.14</td>
</tr>
<tr>
<td>$p$</td>
<td>153.5 (316.3)</td>
<td>1181.73</td>
</tr>
<tr>
<td>$n$</td>
<td>1235.35 (348.1)</td>
<td>1234.24</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>5298.5 (15216.2)</td>
<td>7899.2</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>5421.3 (14835.1)</td>
<td>7756.39</td>
</tr>
</tbody>
</table>

* ( )'s are at central collision (h=0).
Si-Si collision
$E_{lab}/A = 200$ GeV

Figure 4.1
Figure 4.6

\[ x = \frac{P_n}{P_{n_{\text{max}}}} \]
Figure 4.2

Si-Si collision
$E_{lab}/A = 1000$ GeV

$x = \frac{p_n}{p_{n_{max}}}$

$\pi^+ x 10^{-2}$

$\bar{p}$

$\bar{n}$

$x$ vs. $d\sigma/dx$

$\times 10^{-2}$

$10^{-1}$

$10^{-2}$

$10^{-3}$

0

0.5

233
Figure 4.3
Figure 4.5
Si-Si Central Collision
$E_{\text{lab}}/A = 1000 \text{ GeV}$

\[ x = \frac{P_{\text{min}}}{P_{\text{max}}} \]

Figure 4.7
Central Collision

$X_F$ spectrum concentrated to low $X_F$ region

Recent Cern Experiment of Ox-Pb Collision

Pion Production 240 at 200 Gev

107 Venus Calculation

300 Venus Central

Successive Collisions Increase P production

spectator nucleus $\rightarrow$ proton collision

multiple collision $\pi \rightarrow \bar{\pi}$

Modification of Venus Code

- Important Sampling Method
- Russian Roulette

Careful Choice of Parameter is required

Two Calculations of Collision Events

- Creation of the string
- The fragmentation of Strings
- Convolution of two functions

More Sophisticated model

- Flux Tube model
- Quark Gluon Plasma Formation

Dynamics of Plasma expansion and Hadronization

Heinz et al Theory

- Fragmentation model using string model.

- Baldin et al. C-Lu (2.8 GeV/A) $\bar{\pi}/\pi^-$ ratio 60 times of $P$ nucleus collision.