Application of Sol-Gel Technology to High Pressure Polarized ^3He Nuclear Targets

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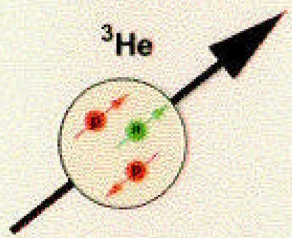
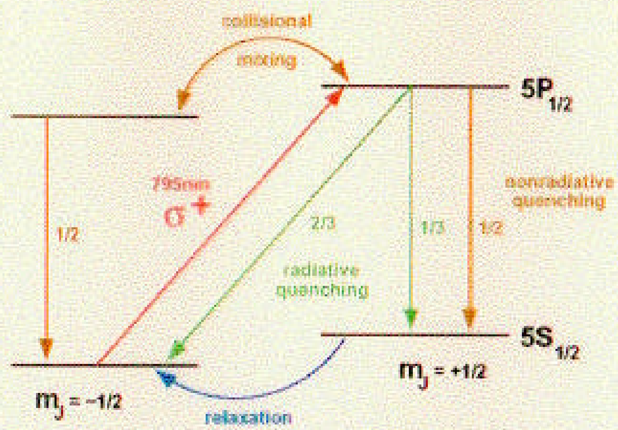
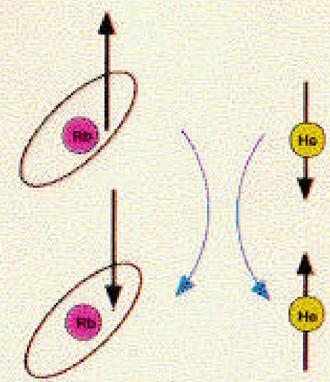


QCD Workshop Charlottesville April 18-21, 2002

Nuclear Spin Polarization of ^{3}He

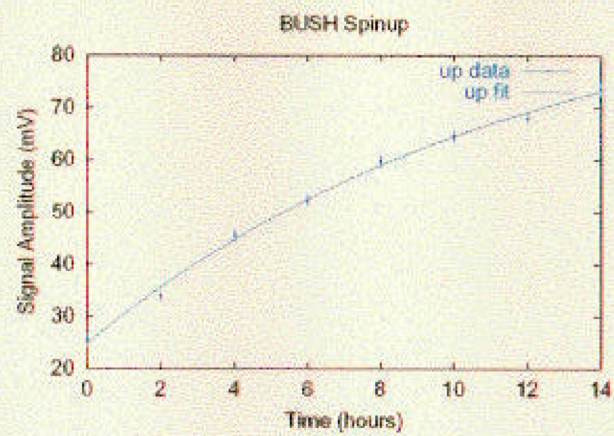


Optical Pumping



Spin Exchange

Helium-3 Polarization



$$P_{He} = P_{Rb} \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma_{He}} \left[1 - e^{-(\gamma_{SE} + \Gamma_{He})t} \right]$$

Spin exchange rate between Rb-atoms and ^{3}He-nuclei

^{3}He polarization decay rate

Typical ^3He Nuclear Target

Pressure:	8-10 atm
Polarization:	35-45%
Lifetime:	35-60 hrs

$$T_{He} = \frac{1}{\Gamma_{He}}$$

Glass from Sol-Gel Processes

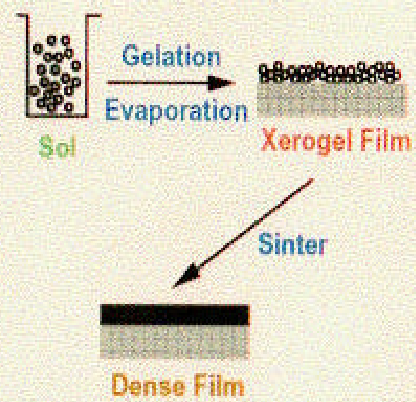
- Chemical route: obtain **glass** at *low* ***temperature*** from liquid solution
- Better homogeneity **and** higher purity **than obtained** with standard glass
- Precise control over **thin glass** film microstructure

Goal: **coat target** cells with thin layer of **pure** aluminosilicate **glass**

Glass Film via Sol-Gel Process

Fill cell with a solution of:

tetraethyl orthosilicate (TEOS)	$SiO_4(C_2H_5)$
water	H_2O
ethanol	C_2H_5OH



Hydrolysis of alkoxide groups (OR where $R=C_2H_5$):

solution

$$\equiv Si-OR + H-OH \rightarrow \equiv Si-OH + ROH$$

Condensation produces silica network:

gelation

$$\equiv Si-OH + HO-Si\equiv \rightarrow \equiv Si-O-Si\equiv + H_2O$$

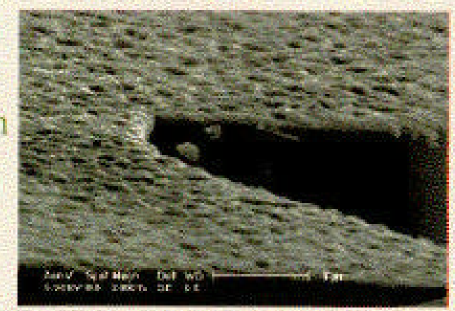
$$\equiv Si-OH + RO-Si\equiv \rightarrow \equiv Si-O-Si\equiv + ROH$$

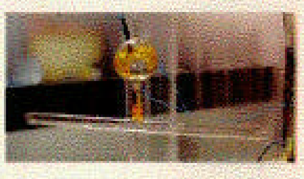
Drying forms xerogel

Sintering is achieved heating the gel to form the glass film

We also dope with:

aluminum nitrate nonahydrate $Al(NO_3)_3\,9H_2O$

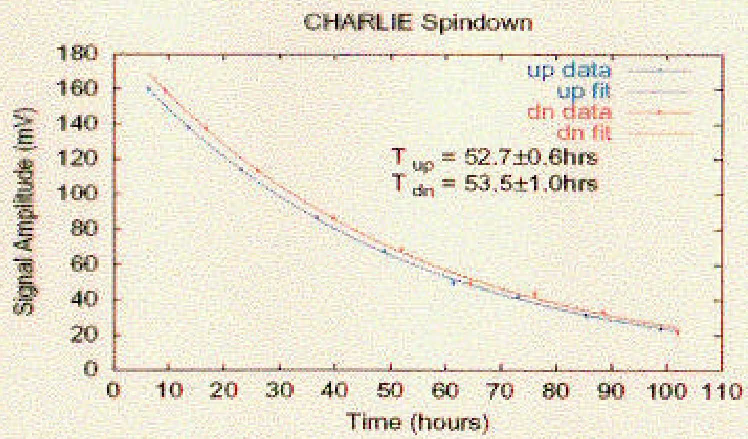


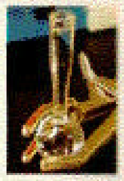


Results for Nuclear Target Cell "Charlie"

- 40 cm, 8.7 amg sol-gel coated Pyrex target cell
- Good lifetime performance

Lifetime	$\Gamma_{dipolar}$	Γ_{wall}
~ 53 hrs	86 hrs^{-1}	140 hrs^{-1}





Results for Small Spherical Cells

	Glass	Pressure	Lifetime	$\Gamma_{dipolar}$	Γ_{wall}
Princeton:	Coated Pyrex	~ 1.9 atm	~ 340 hrs	~ 390 hrs^{-1}	~ 2700 hrs^{-1}
Hsu, Cates, Kominis, Aksay and Dabbs, App. Phys. Lett. Vol. 77, 13 (2000)	Uncoated Pyrex	~ 2.0 atm	~ 240 hrs	~ 370 hrs^{-1}	~ 700 hrs^{-1}
Virginia:	Coated GE-180	~ 2.8 atm*	~ 270 hrs	~ 300 hrs^{-1}	~ 2700 hrs^{-1}
Chaput, Cates, Deur, Rohrbaugh, Singh and Tobias, UVA Physics	Coated GE-180	~ 2.8 atm*	~ 240 hrs	~ 300 hrs^{-1}	~ 1200 hrs^{-1}
	Uncoated GE-180	~ 2.8 atm*	~120 hrs	~ 300 hrs^{-1}	~ 200 hrs^{-1}

*these are preliminary pressures

^{3}He Relaxation Mechanisms

- ^{3}He-^{3}He Magnetic Dipole Interaction relaxation rate:

  $\Gamma_{He\text{-}He} \sim 1/80\ \mathrm{hr}^{-1}$

$$\Gamma_{He-He} = \frac{\left[{}^3He\right]}{744}\ hr^{-1}$$

- Wall relaxation rate:

  $\Gamma_{wall} \sim 1/90\ \mathrm{hr}^{-1}$

- Holding Field Inhomogeneity relaxation rate:

  $\Gamma_{B} \sim 1/2000\ \mathrm{hr}^{-1}$

$$\Gamma_{field} \propto \frac{\nabla B_X^2 + \nabla B_Y^2}{B_Z^2}\, hr^{-1}$$

$$\boxed{\Gamma = \Gamma_{He-He} + \Gamma_{wall} + \cancel{\Gamma}_{field}}$$

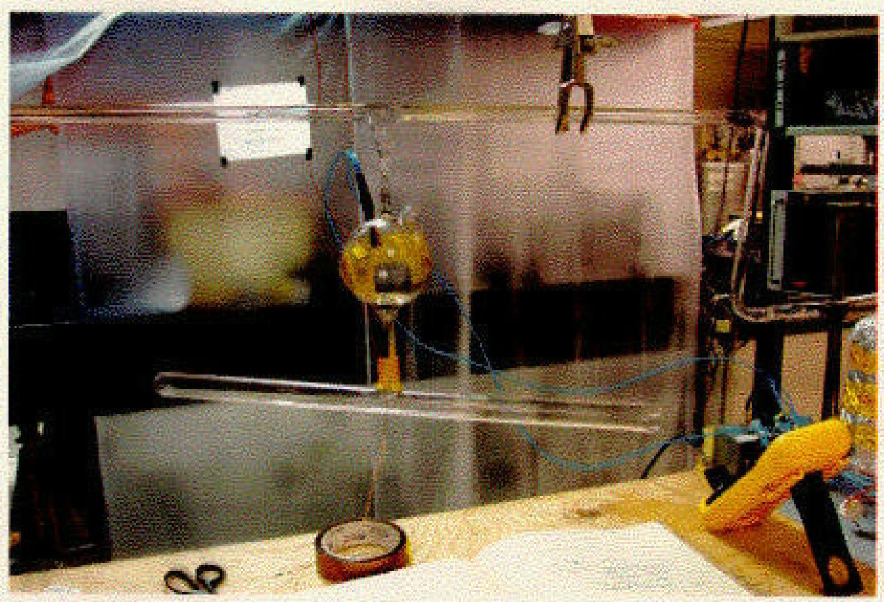
Necessary Glass Properties for ^3He Target

- Minimize **Wall** Relaxation
  - *paramagnetic impurities
  - *microfissures
- Low Helium Permeability
  - ***cell must contain the ^3He**

Glass Structure	Brand	Leak Rate	Fe Impurity
borosilicate	Pyrex	~ 5%/month	62 ppm
aluminosilicate	Corning 1720 (GE-180)	~ 10%/100 yrs	150 ppm

Sol-Gel Coated Cells

GE-180 Sphere



Target Cell "Charlie"

Summary

Sol-Gel

- Coatings seem to improve average lifetime performance in small cells
- Successfully scaled up technology to full-sized target cells
- Provides "standardized" high purity surface while we attack other problems

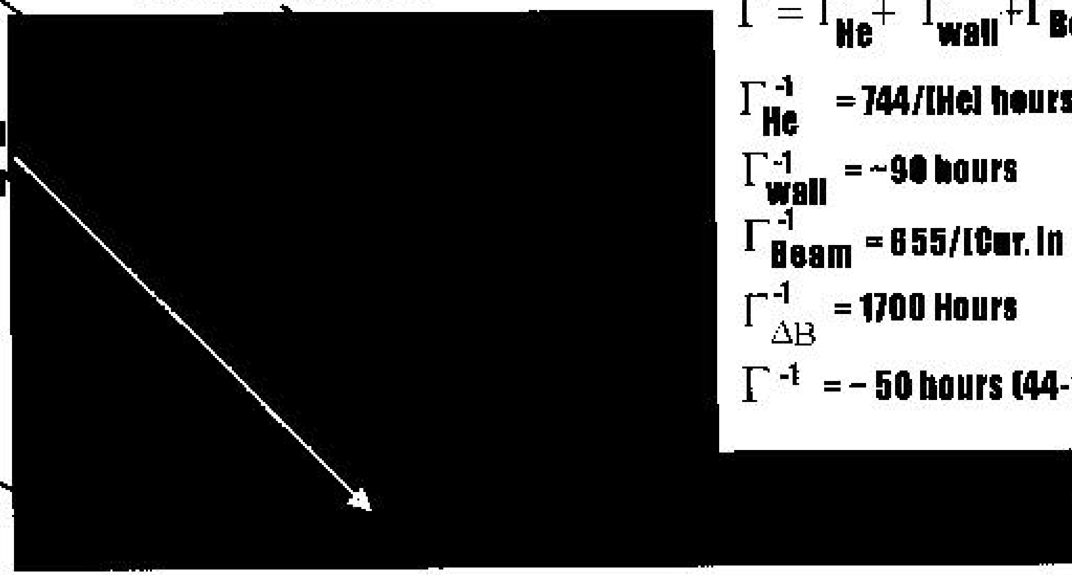
The Polarized ^{3}He Target Cell

Cell made of Aluminosilicate glass (GE 180 or Dow 1720)

Laser Light Polarizes Rubidium Vapor in Pumping Chamber

Electron beam Travels through Target chamber

End Windows ~100 microns Thick



Cell Lifetime

$P(t) = P_0 e^{-\Gamma t}$

$\Gamma = \Gamma_{He} + \Gamma_{wall} + \Gamma_{Beam} + \Gamma_{\Delta B}$

Γ^{-1}_{He} = 744/[He] hours

Γ^{-1}_{wall} = ~90 hours

Γ^{-1}_{Beam} = 655/[Cur. in uA] hours

$\Gamma^{-1}_{\Delta B}$ = 1700 Hours

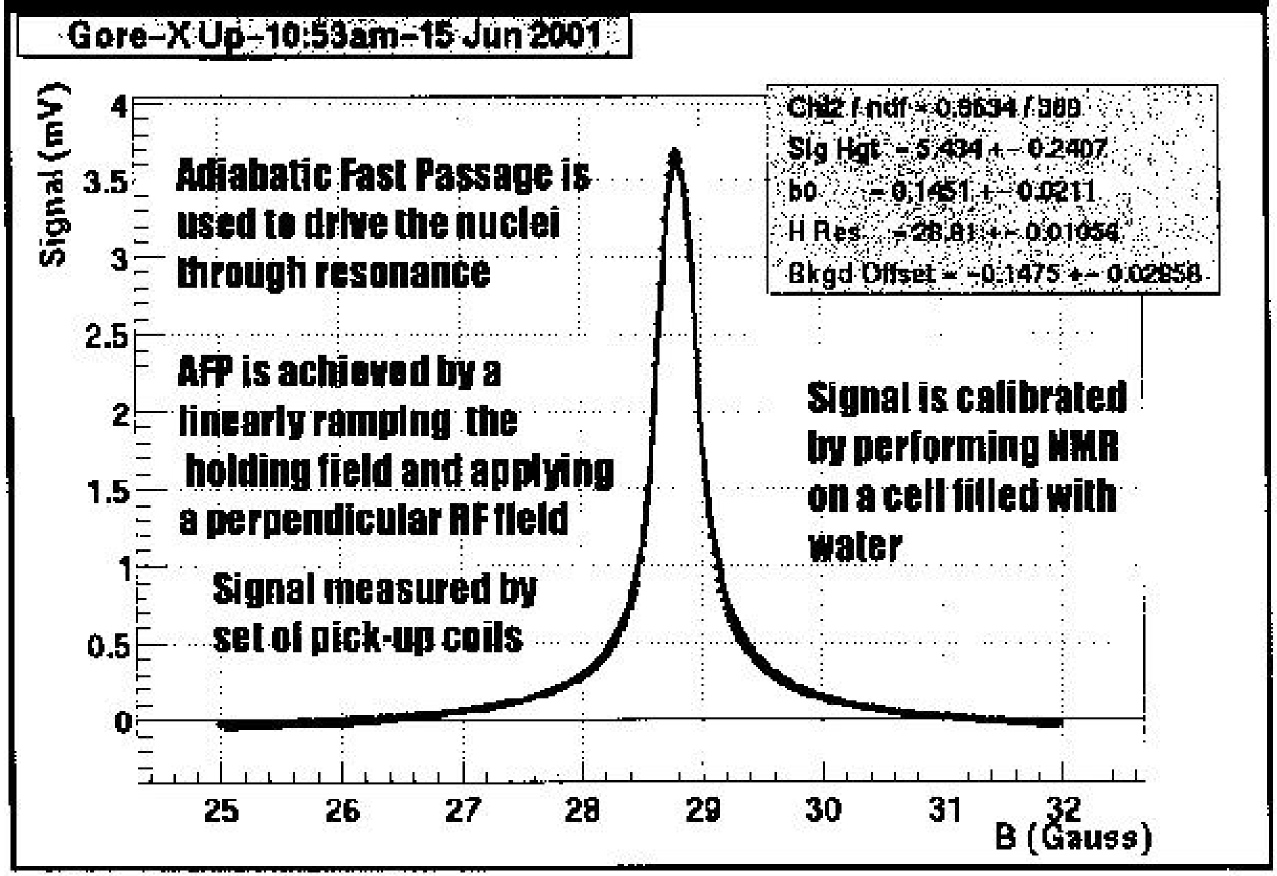
Γ^{-1} = ~ 50 hours (44-84 hours)

Helium Density is 7.5 - 10 atm at room temperature

Cell Density is measured optically using pressure broadening of Rb electron states

Wall and Window Thickness also measured optically using etalon effect

Target Polarimetry using NMR



Adiabatic Fast Passage is used to drive the nuclei through resonance

AFP is achieved by a linearly ramping the holding field and applying a perpendicular RF field

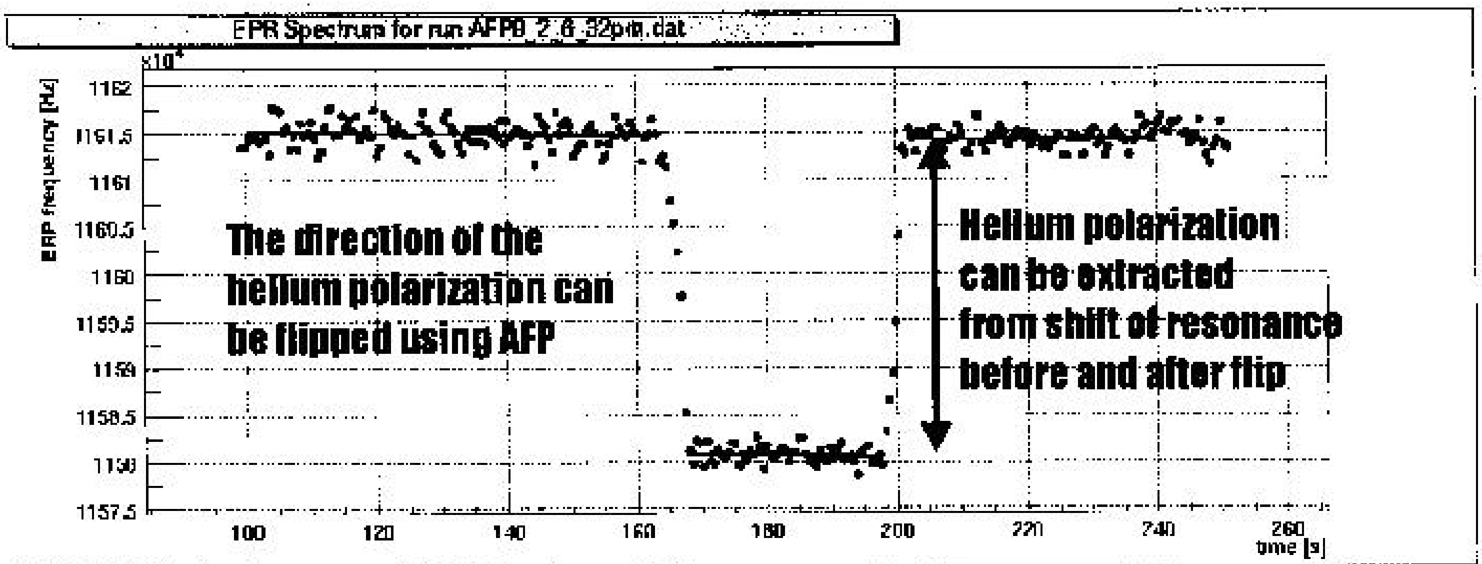
Signal measured by set of pick-up coils

Signal is calibrated by performing NMR on a cell filled with water

Target Polarimetry using EPR

The frequency of the Electron ParamagneticResonance of Rubidium is dependent on the external magnetic field

A component of the external field is from the polarized Helium.

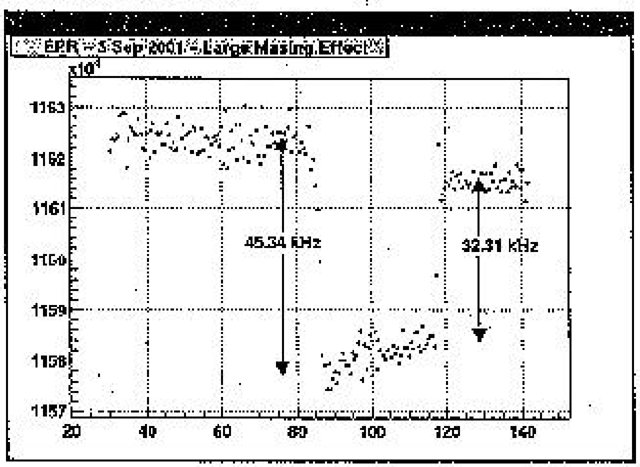


Resonance is excited by a small coil emitting an oscillating magnetic field and is measured by a photodiode

Target Challenges

Masing Effect

Masing results from magnetic coupling between Helium nuclei during AFP and the pick-up coils. Causes sudden losses in polarization.



Masing mostly eliminated by introducing gradient.

Cell Ruptures

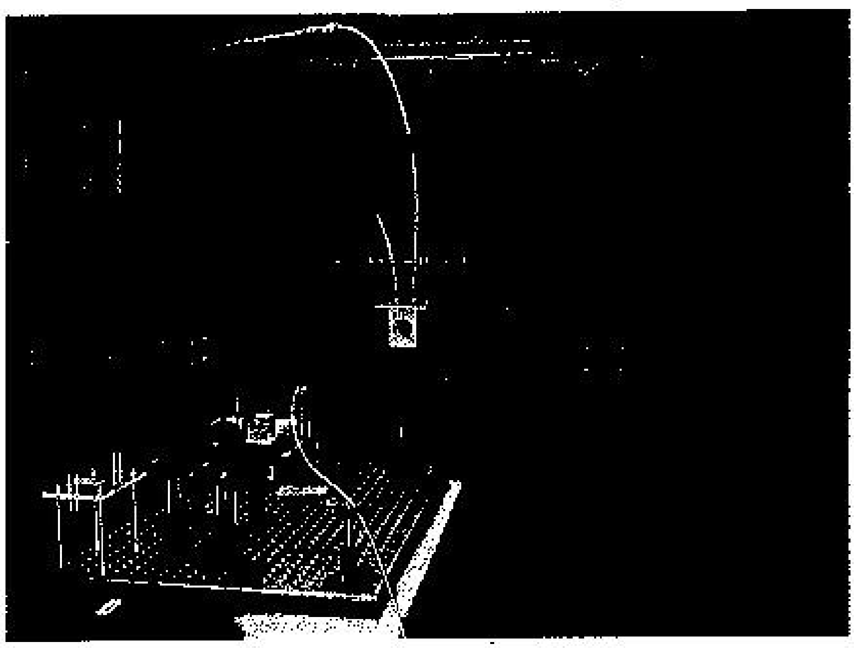
During 1998-1999 had four cells rupture. During summer only had one rupture.

Protective Measures

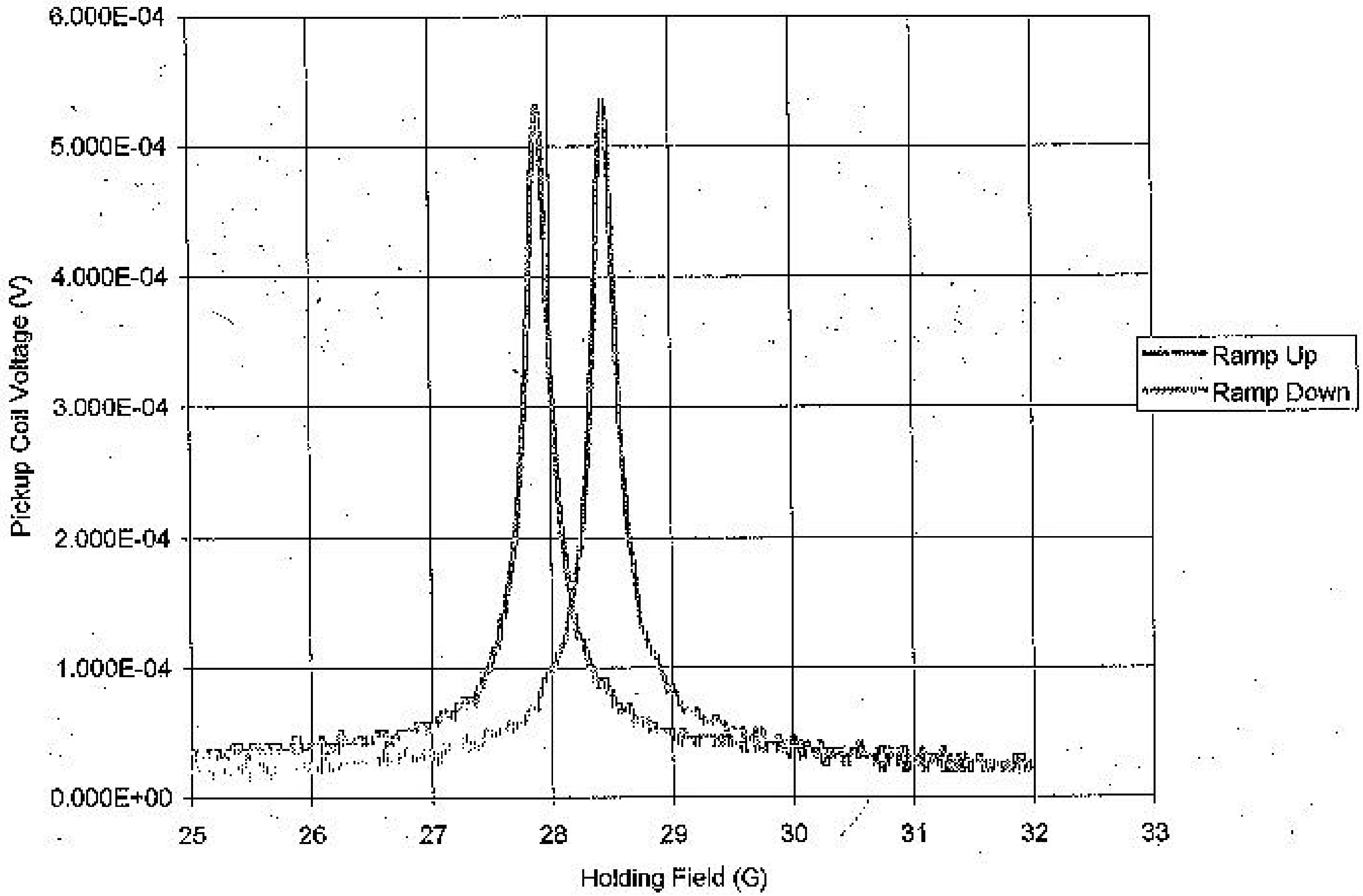
- Rastered Beam
- Density < 10 amgts
- Replace cells when possible
- Beam Ramping

Target Cell Production

- Two facilities for producing Jefferson Lab-type target cells: University of Virginia–G. Cates, College of William and Mary–T. Averett
- University of Virginia: Cell production, polarized target system, cell characterization, medical imaging, cell coatings...
- College of William and Mary: Cell production, new polarized target system recently completed.



undergraduates – D. Milkie
T. Hayford

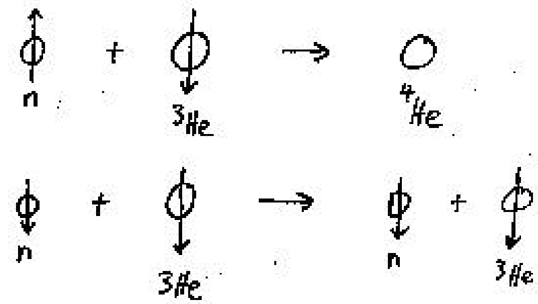


Pickup Coil Voltage (V)
6.000E-04
5.000E-04
4.000E-04
3.000E-04
2.000E-04
1.000E-04
0.000E+00
25
26
27
28
29
30
31
32
33
Holding Field (G)
Ramp Up
Ramp Down

NEUTRON SPIN FILTERS

T. Gentile et al, NIST

- USE $^3\vec{He}$ as neutron spin filter



- Need: Lower pressure, high polarization, large diameter cells.
- Can use Spin Exchange Optical Pumping (SEOP) – Slow
- Also can use meta-stability Exchange Optical Pumping (MEOP) plus compression – Fast
- Need long lifetimes (days) and transportable cells,
- Depolarization mechanisms the same for MEOP, SEOP

T. Gentile - NIST

Sealed SEOP Cells

Name	Glass	Lifetime (h)	^{3}He press (bar)	D x L (cm)
Snoopy	blown GE180	170	3.5	5 x 1.5
Woodstock	blown GE180	140	3.5	4.5 x 1.5
Joe Cool	blown GE180	130	3.5	8 x 1.5
Wilma	blown GE180	650 (840*)	0.85	5 x 4
Bullwinkle	blown GE180	580 (prelim)	1.3	7 x 6
Peabody	blown GE180	170	1.3	7 x 7
Barney	blown GE180	391	1.20	8.5 x 4
Mrs. Peel	blown GE180	180 (prelim)	1.60	7 x 7
Pebbles	blown GE180	350	0.85	10 x 4
Dino	blown GE180	708	0.85	9.5 x 4.5
Yogi	blown GE180	185	0.85	9.5 x 4.5
Astro	blown GE180	580 (730*)	0.85	11 x 4.5
Elroy	blown GE180	97	0.85	11 x 4.5
Rocky	blown GE180	150	0.85	11 x 4.5
Boo-Boo	blown GE180	55	1.3	11 x 4
Natasha	reblown fused silica	751	0.85	5 x 4
Betty	1720/GE180**	260	0.85	5 x 5
Boris	1720/GE180**	60	0.85	5 x 5
Bam-Bam	1720/GE180**	30-130	0.85	9.5 x 5

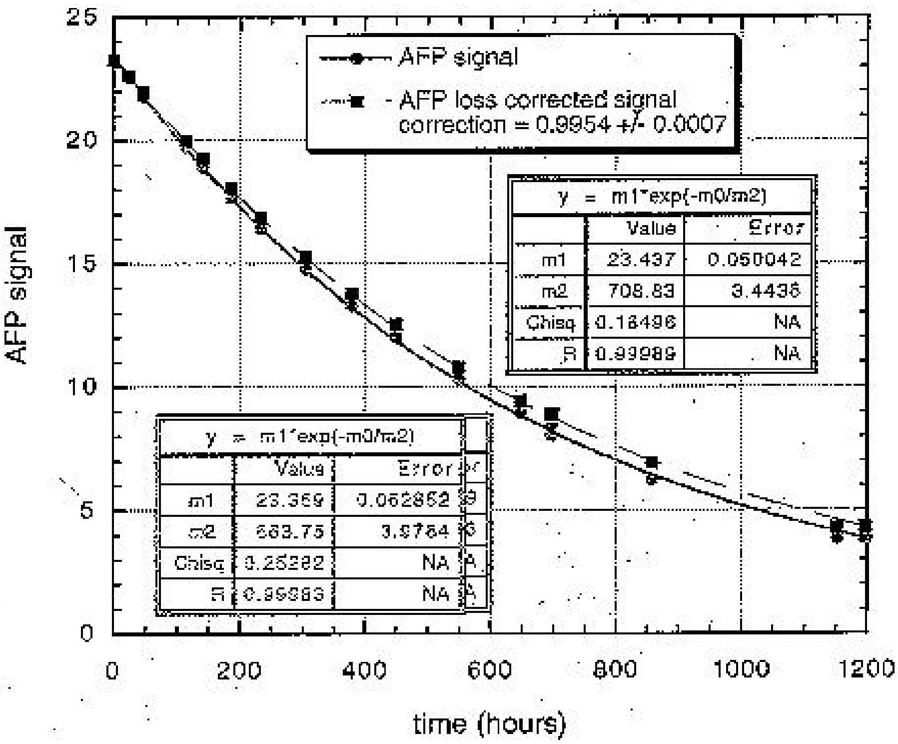
*measured in MEOP FID NMR apparatus

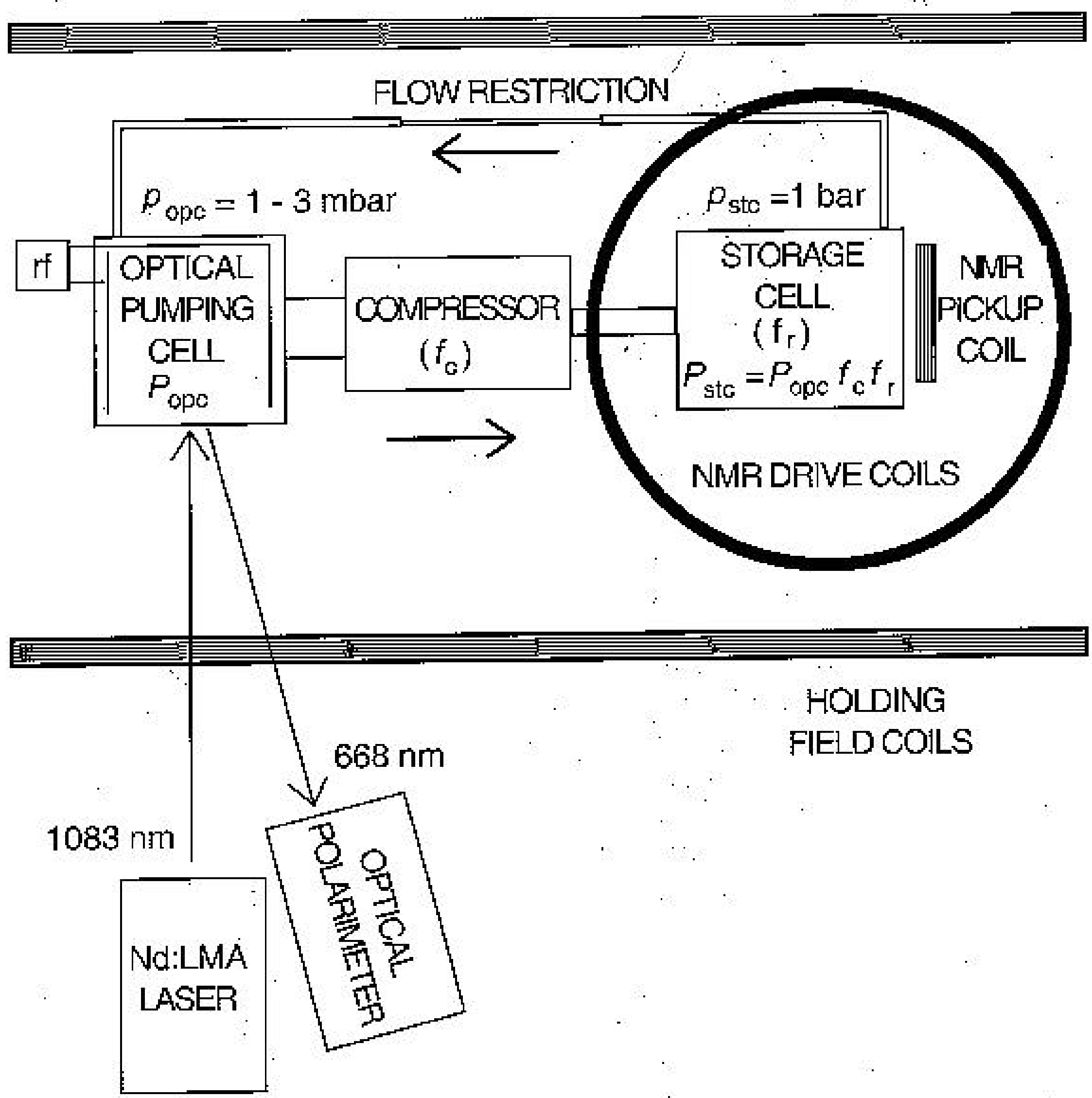
** Corning 1720 body diffusion-sealed to either 1720 or GE180 glass

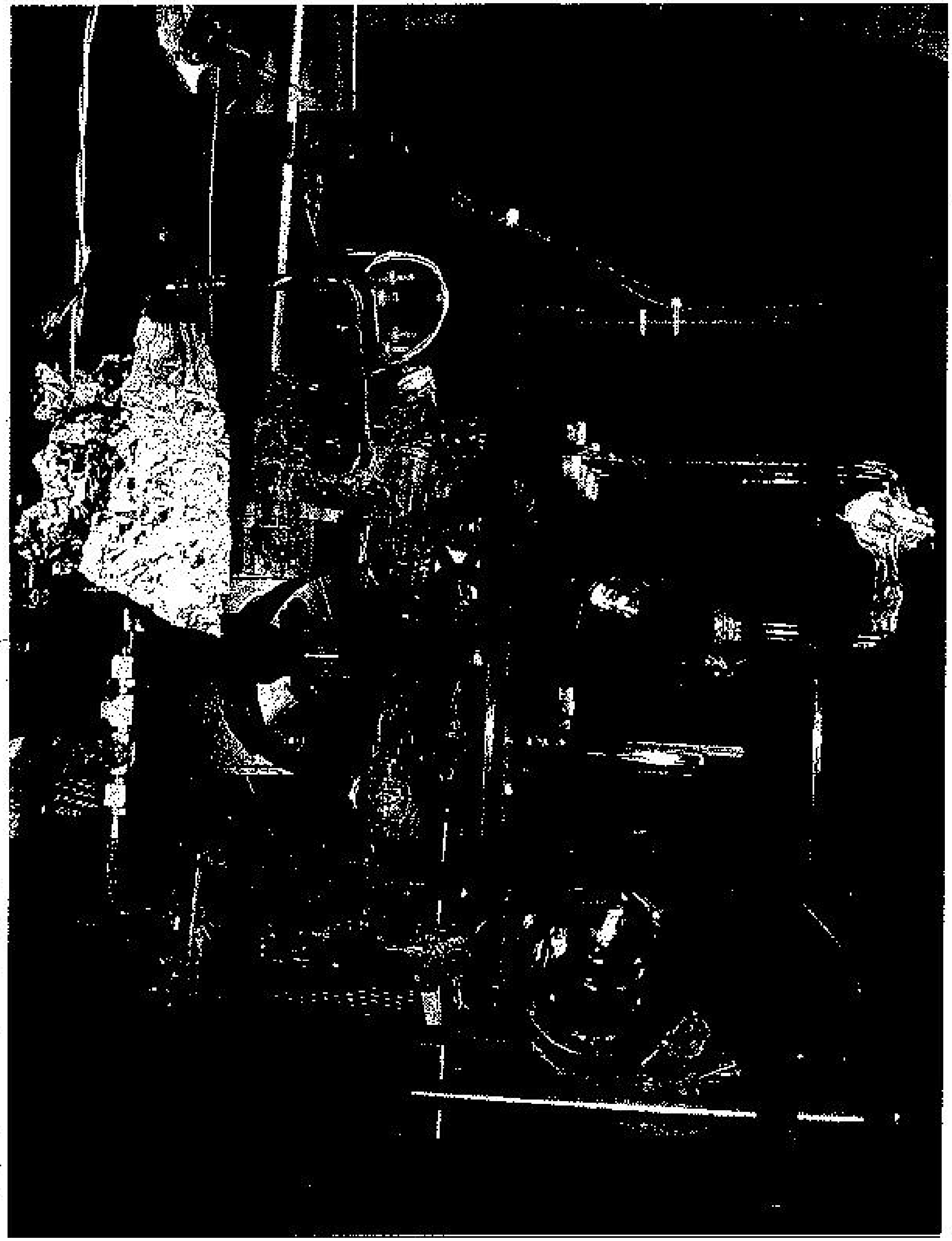
Dipole-Dipole limit for Dino ~ 950 hours

RELAXATION of DINO

Bldg. 245 AFP system, 8/22/01 - 10/11/01




FLOW RESTRICTION
p_{opc} = 1 - 3 mbar
p_{stc} =1 bar
rf
OPTICAL PUMPING CELL P_{opc}
COMPRESSOR (f_c)
STORAGE CELL (f_r)
$P_{stc} = P_{opc} f_c f_r$
NMR PICKUP COIL
NMR DRIVE COILS
HOLDING FIELD COILS
668 nm
1083 nm
Nd:LMA LASER
OPTICAL POLARIMETER



Optically Pumped Polarized ^{3}He Targets for Nuclear Physics Experiments

Todd Averett
Department of Physics
College of William and Mary

Jefferson Lab Polarized ^{3}He Target Collaborators

- Jefferson Lab, J.P. Chen, K. McCormick, ...
- University of Kentucky, W. Korsch
- Massachusetts Institute of Technology, X. Zheng
- University of Virginia, G. Cates, A. Deur, J. Singh, A. Tobias
- College of William and Mary, T. Averett, K. Kramer, V. Sulkosky X. Zhu
- Temple University, Z.E. Meziani

Summary of Polarized ^{3}He Physics Program

Sum Rule Physics

- E94-010 - A Connection between Bjorken and GDH Sum Rules, (Completed Sep - Dec 1998)
- E97-110 - The Generalized GDH Sum Rule for Nearly Real Photons (Scheduled for Aug 2002)

Spin Structure of the Neutron

- E99-117 - The Neutron Asymmetry A_1^n at Large x (Completed Jun - Jul 2001)
- E97-103 - The Search for Higher Twist Effects in the Neutron spin structure function g_2^n (Completed Aug-Sep 2001)
- E01-012 - Neutron Spin Structure in the Resonance Region (Accepted Proposal)

Electromagnetic Form Factors of the Neutron

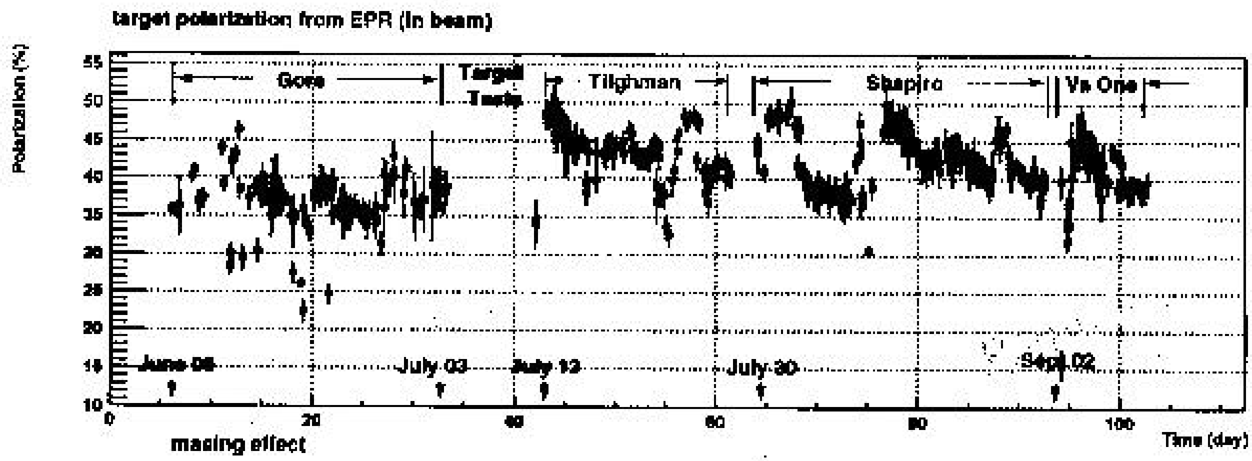
- E95-001 - The Magnetic Form Factor of the Neutron (Completed Jan - Feb 1999)

Other Proposals

- ^{3}He Wavefunction, Electric Form Factor of Neutron, 12 GeV

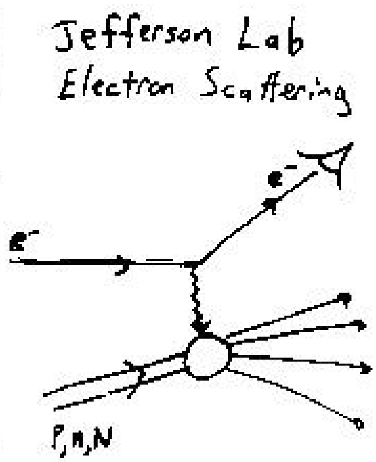
Polarized 3He Target Performance During E99-117/E97-103

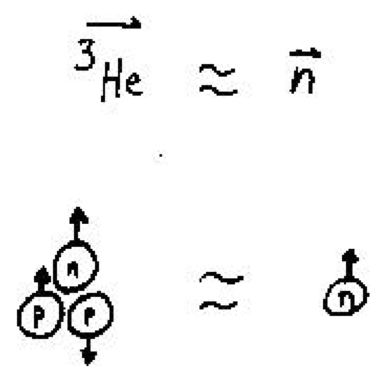
Cell Name	Field direction	0°	90°	180°	270°
Gore	June 06 – July 03	37%		35%	43%
Tilghman	July 13 – July 31	45%		43%	39%
Shapiro	Aug.04 – Aug.31	47%	42%		45%
Virginia One	Sept.04 – Sept.10	44%	40%		40%



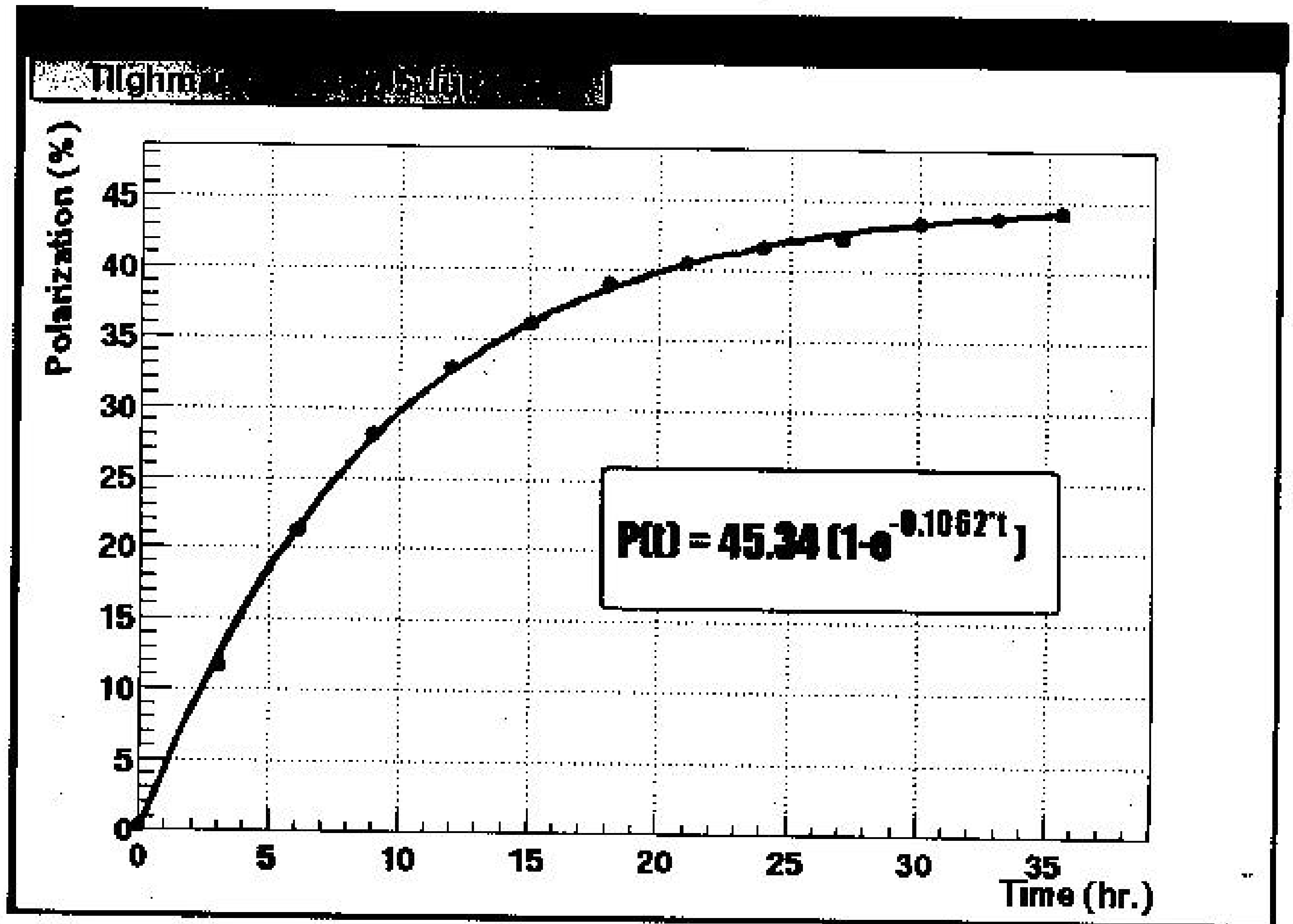
Polarized ^{3}He in Nuclear Physics

- No free neutrons available. Only two viable nuclei for studying neutron spin structure: ^{3}He and ^{2}H. Polarizable, small dilution, relatively simple nuclear structure.
- Needs for successful experiment:
  1. High Polarization
  2. High density of target nuclei
  3. Purest target: no alkali metal, thin container
- Solution: Two chambered, high pressure, long, aluminosilicate glass cell
- Typical Luminosity: $10^{36}/\text{cm}^2\cdot\text{s}$

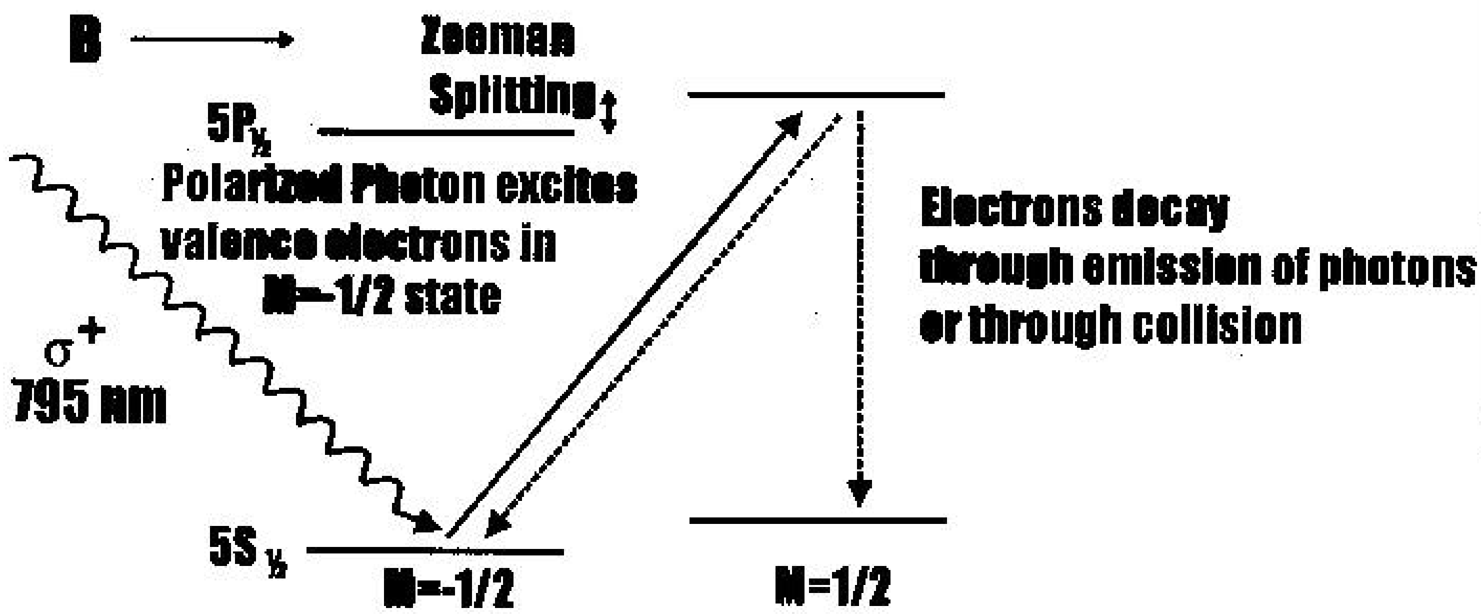




Typical Spin-Up Curve



Polarizing ^3He using Optically Polarized Rb



Optical Polarization of Rubidium

^3He nuclei are polarized by spin-exchange with the Rb valence electrons through their hyperfine interaction

While the Rb polarizes quickly and completely, the cross-section for polarizing the ^3He nuclei is small so process is inefficient

Pictures of the Target System

Time Evolution of Polarization

$$\frac{dP_{He}}{dt} = \gamma_{se} P_{Rb} - (\gamma_{se} + \Gamma) P_{He}$$

- Rb-^{3}He spin-exchange rate, $\gamma_{se} = [Rb] < v\sigma_{se} >$
- $1/\gamma_{se} \sim$ 12hrs
- Depolarization rate, Γ

$$P_{He}(t) = P_{Rb} \frac{\gamma_{se}}{\Gamma + \gamma_{se}} \left(1 - e^{-(\Gamma + \gamma_{se})t}\right)$$

- In the absence of optical pumping, ^{3}He spin relax according to:

$$P_{He}(t) = P_{max} e^{-\Gamma t}$$

- From this spin relaxation curve, we can obtain the depolarization rate Γ, or the lifetime $T = 1/\Gamma$.