Spin-exchange polarized ^{3}He for electron scattering

- Summary of the dramatic progress that has been made, and why.
- Discussion of ongoing limitations to performance.
- Future targets for the JLab 12 GeV era

Special thanks to Jaideep Singh (who was originally invited to give this talk), Peter Dolph, Yunxiao Wang, Yuan Zheng, Maduka Kaluarachchi, Vladimir Nelyubin and Al Tobias. Also to Todd Averett

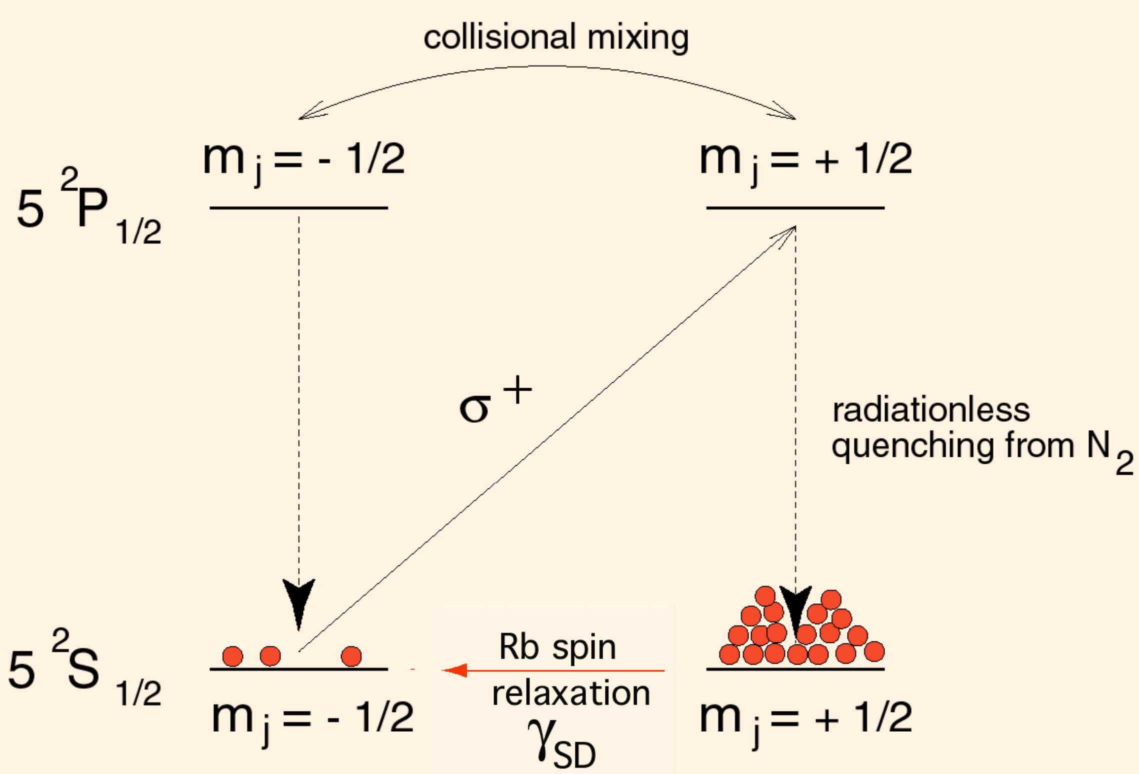
G. Cates, PSTP 2013, Sept. 10, 2013

UNIVERSITY of VIRGINIA

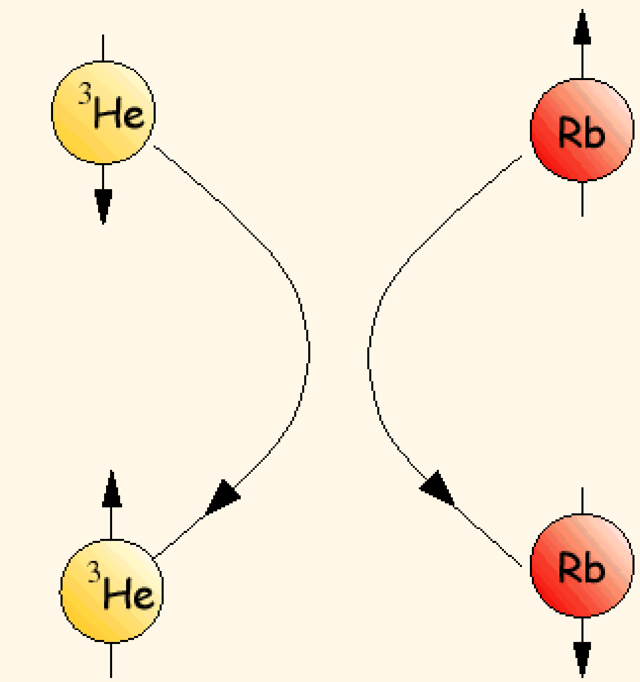
Spin-exchange optical pumping

Two-step process:

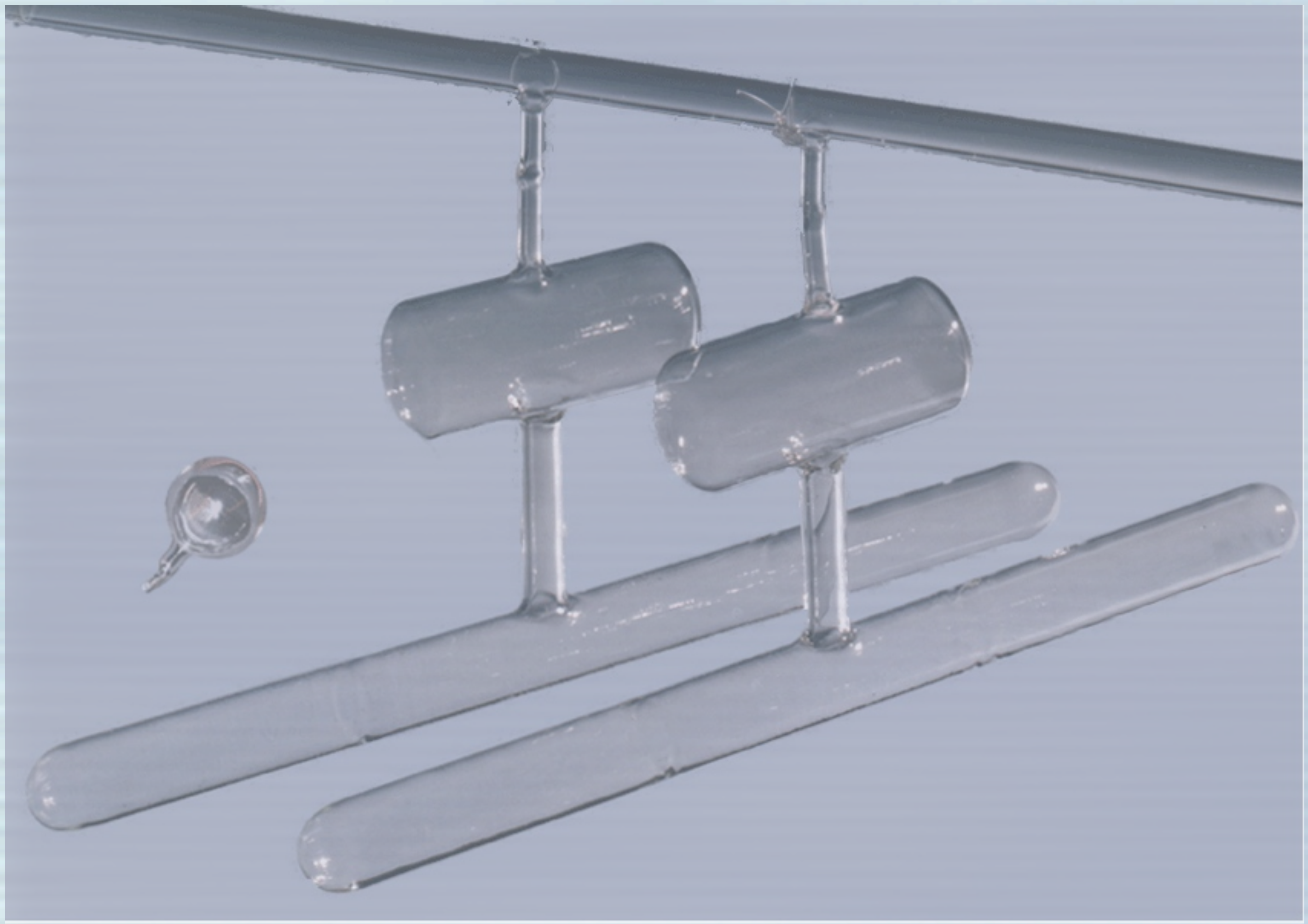
1. alkali vapor is optically pumped.



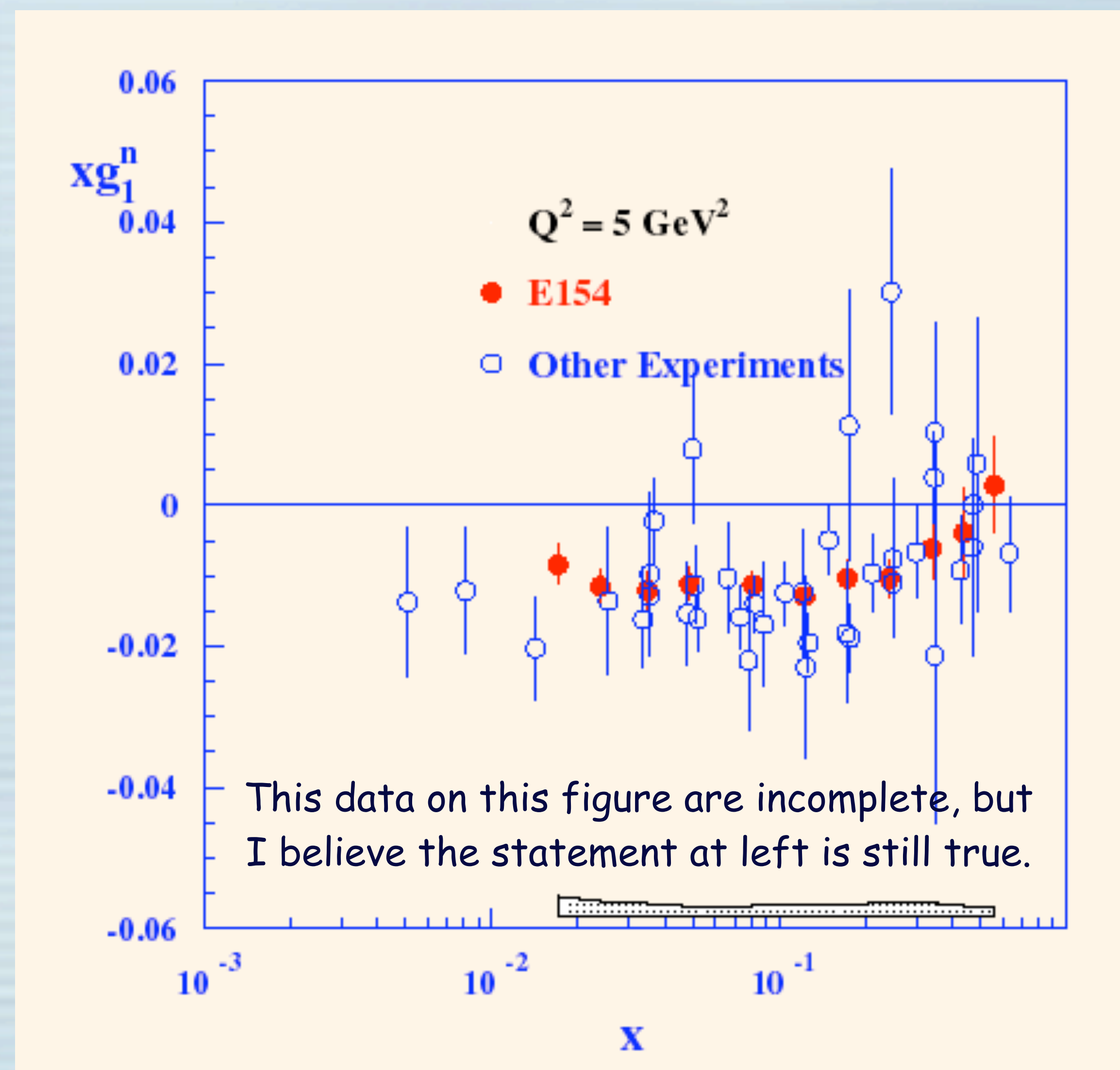
2. noble-gas nuclei are polarized through spin- exchange collisions



The first liter-sized polarized ^3He targets were developed to study the spin structure of the neutron at SLAC

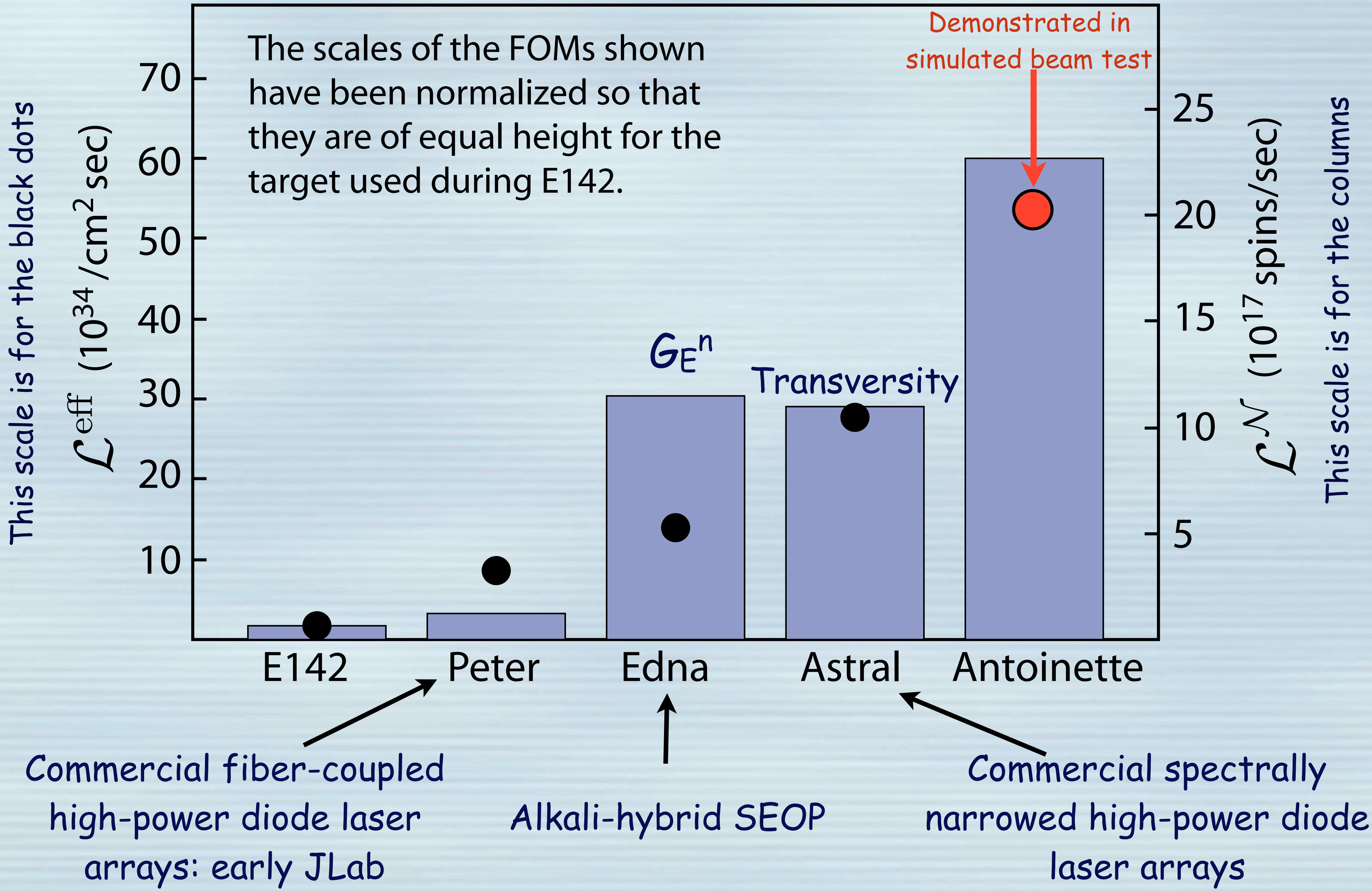


With volumes of 150-200 cc's and nearly 10 atmospheres, these targets contained 1-2 STP liters of gas.



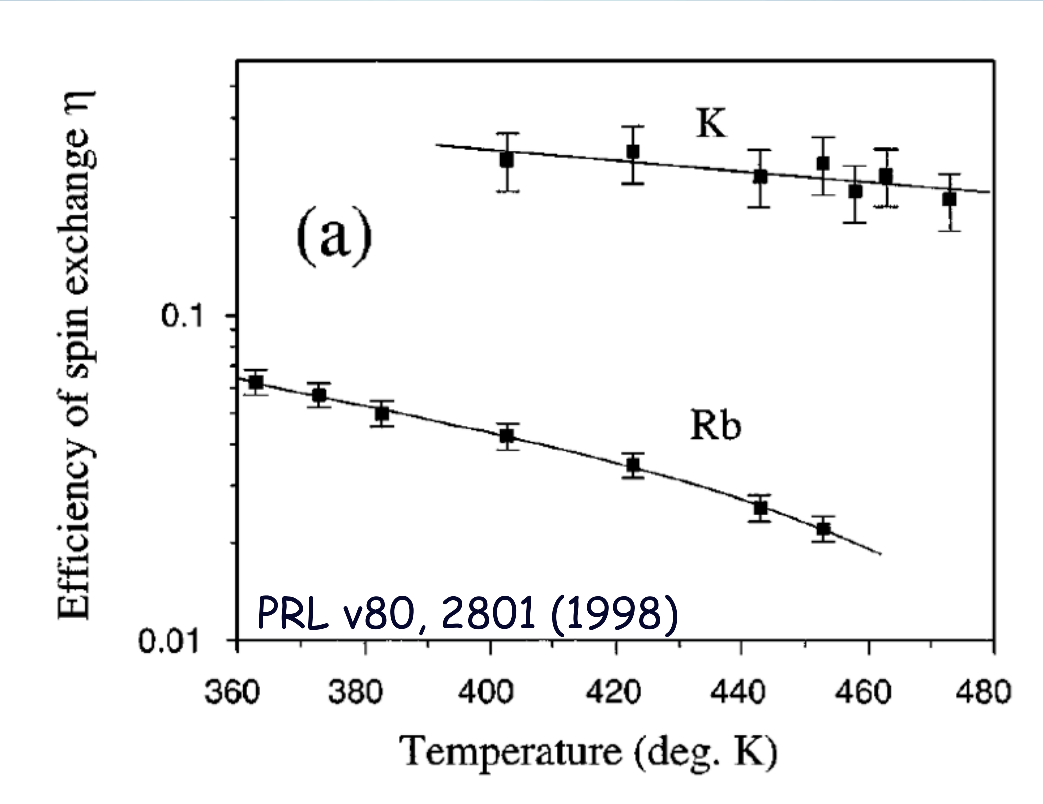
To this day, the data from E142 and E154 provide the most accurate data on the spin structure functions of the neutron over the kinematic range studied.

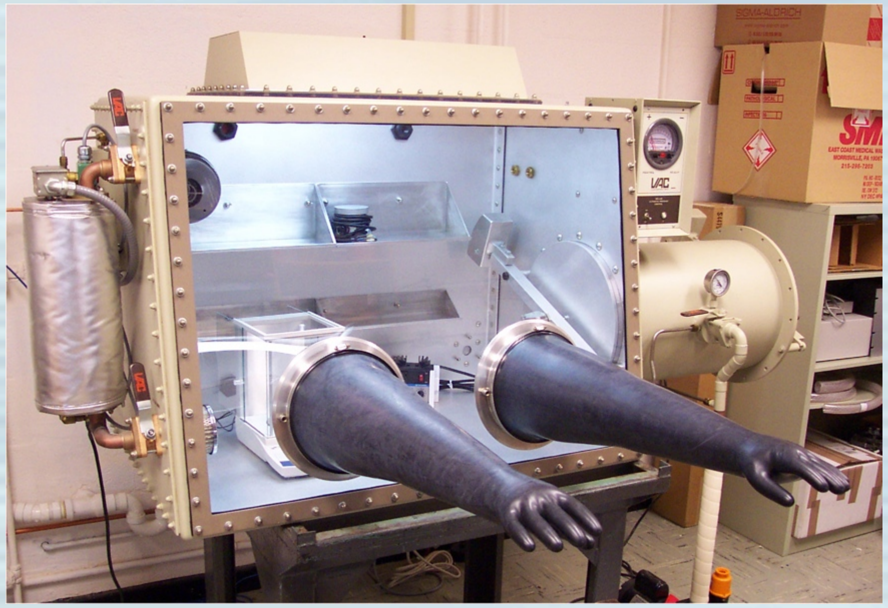
The performance of polarized ^{3}He targets have increased by roughly a factor of 30 since SLAC E142



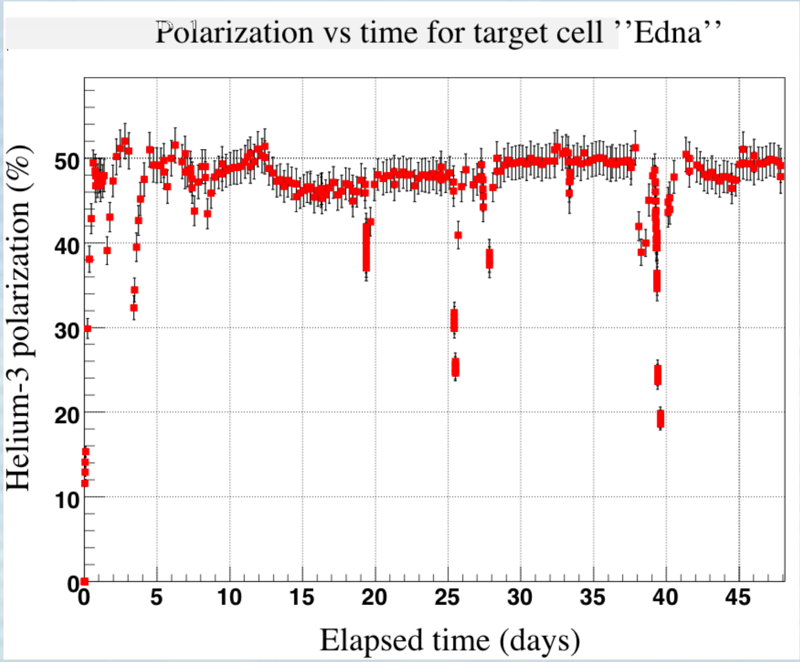
One big step: Hybrid mixtures of Rb and K to greatly improve efficiency of spin transfer

- 1997 - ^{3}He-K spin relaxation predicted to be weaker than for ^{3}He-Rb: Walker, Thywissen and Happer, PRA vol. 56, pg 2090 (1997).
- 1998 - ^{3}He-K spin-exchange shown to be more efficient: Baranga et al. (incl. Romalis), PRL vol 80, 2801 (1998).
- 2001 - alkali-hybrid spin-exchange optical pumping suggested: Happer, Cates, Romalis, Erickson, U.S. Patent 6318092 (2001).
- 2003 - alkali-hybrid spin-exchange optical pumping demonstrated; Babcock, Nelson, Kadlecek, Driehuys, Anderson, Hersman and Walker, PRL vol 91, 123003 (2003)



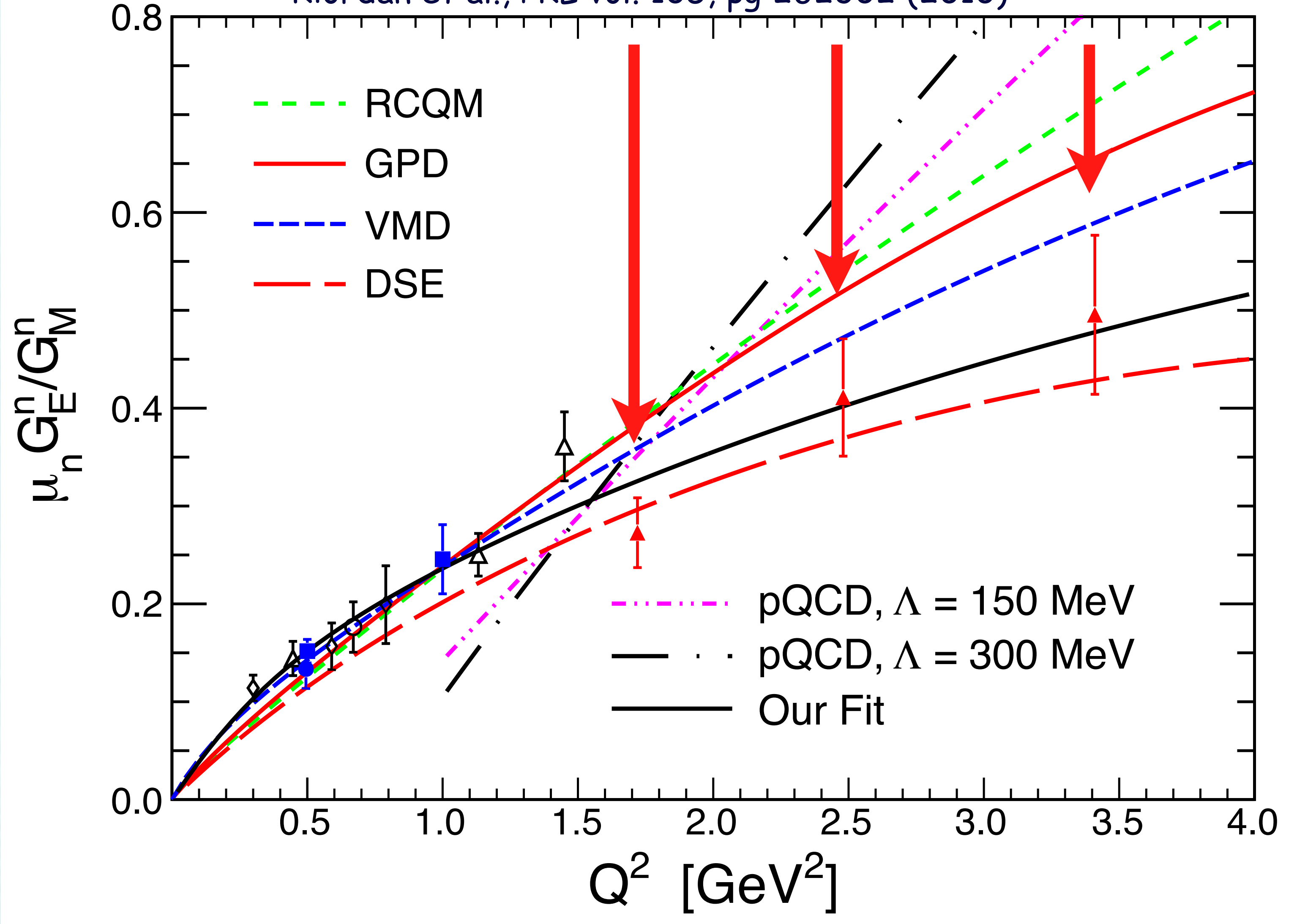


Alkali-hybrid SEOP polarized ^{3}He targets produce large gains, ~50% polarization, for E02-013, which measured GEn in Hall A



The alkali-hybrid SEOP polarized ^{3}He targets were critical to studying the electric form factor of the neutron at high Q^2 (JLab E02-013, Hall A, w BigBite)

Riordan et al., PRL vol. 105, pg 262302 (2010)

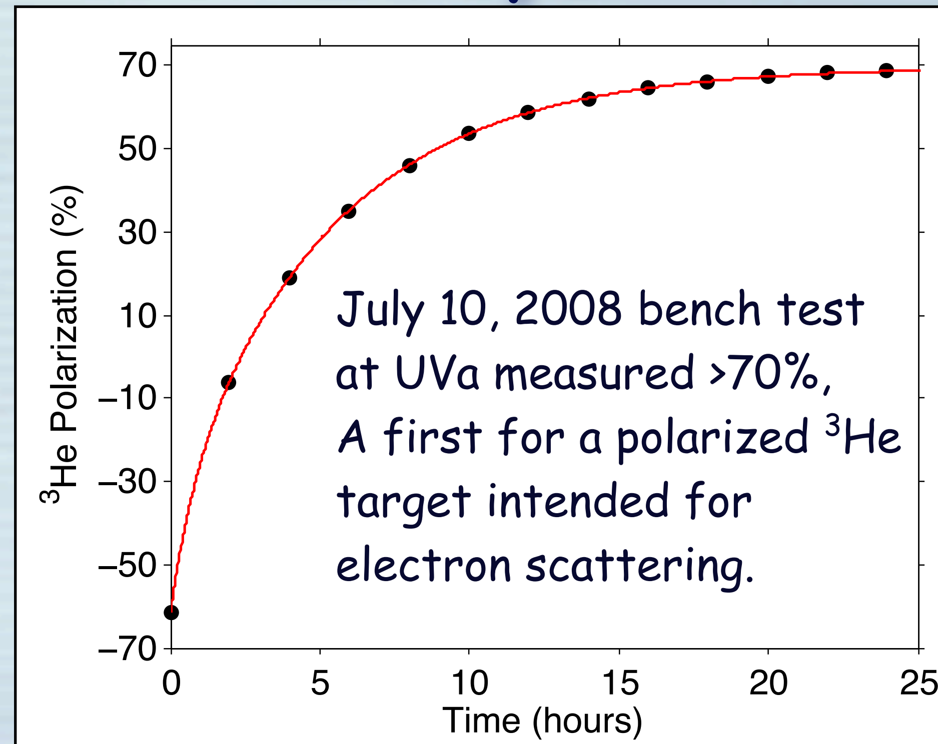


- More than doubled the Q^2 range over which GEn was known.
- Provide the first coverage of the regime in which the surprising proton results had been seen.
- The experiment relied critically on on high luminosity and the large solid angle provided by the BigBite spectrometer (first developed at NIKEF)

Has also led to flavor-separated form factors at high Q^2 which provide evidence for the importance of diquark degrees of freedom, but that is a different story ....

Polarized ^{3}He SEOP targets top 70% for the first time using commercial spectrally-narrowed high-power diode-laser arrays

We had purchased four "Comet" lasers for a ^{3}He polarizer for medical imaging, and decided to test them on our targets.



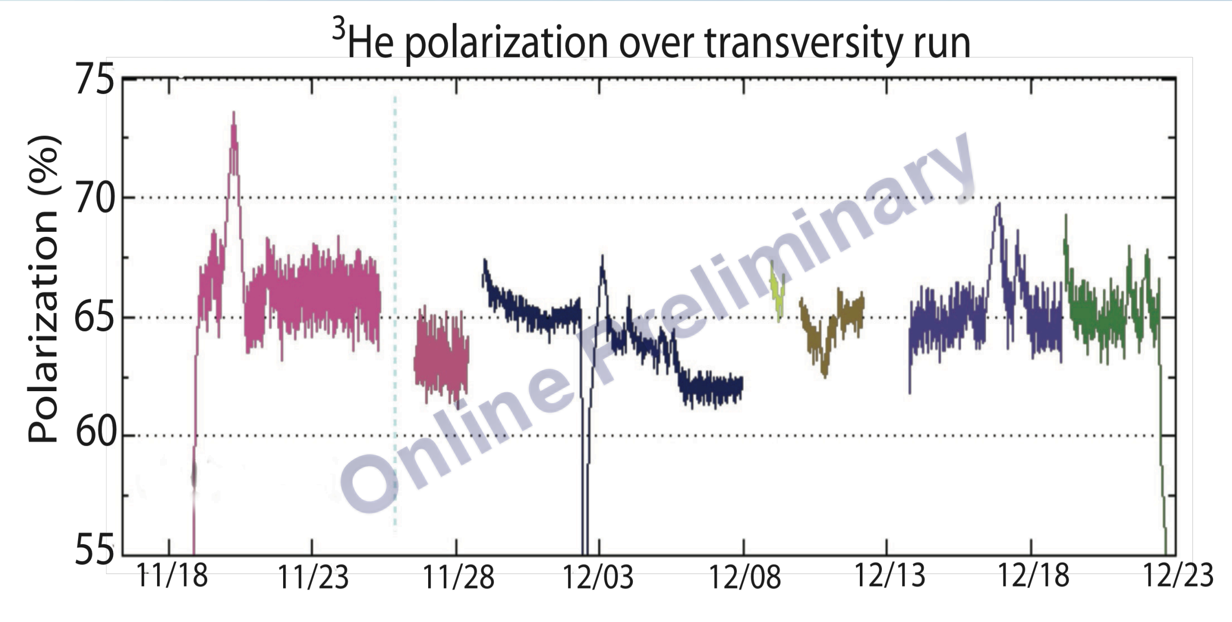
From: Gordon D. Cates <cates@virginia.edu>
Subject: **Comet lasers**
Date: July 10, 2008 9:30:32 PM EDT
To: Xiaodong Jiang <jiang@jlab.org>, Jian-Ping Chen <jpchen@jlab.org>, Todd Averett <tdaver@wm.edu>
Cc: Kees DeJager <kees@jlab.org>, Larry Cardman <cardman@jlab.org>
Bcc: Jaideep Singh <js7uq@mail.phys.virginia.edu>, Vladimir Nelyubin <vvn2c@galileo.phys.virginia.edu>, Al Tobias <wat4y@virginia.edu>, Peter Dolph <pad8c@tetra.mail.virginia.edu>, Karen Mooney <mooney@virginia.edu>

Dear Xiaodong, Jian-Ping and Todd,

Having heard that input is being sought on budget stuff for transversity, I wanted to pass along to you the latest result from our lab. Fortuitously, we had a group meeting earlier today at which we agreed upon numbers that we could release quasi-publicly.

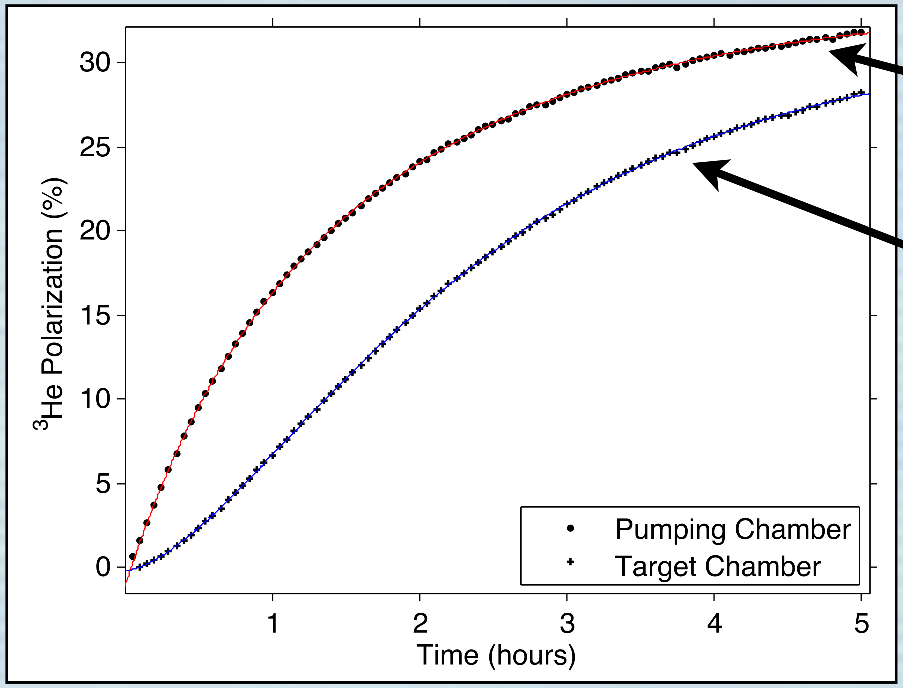
We have just completed measurements on the transversity cell Samantha. Using Comet lasers, which are spectrally narrowed, we achieved a polarization of 70.3 +/- 3.5%. This confirms our belief that a "good" cell would break 70% in polarization. The pump-up time constant was also extremely short, I believe something like around 4 hours, but don't quote me on that. You may recall that a few months ago Simone, a "fair" GEN cell that had never previously broken something like 45% achieved 62% using Comets.

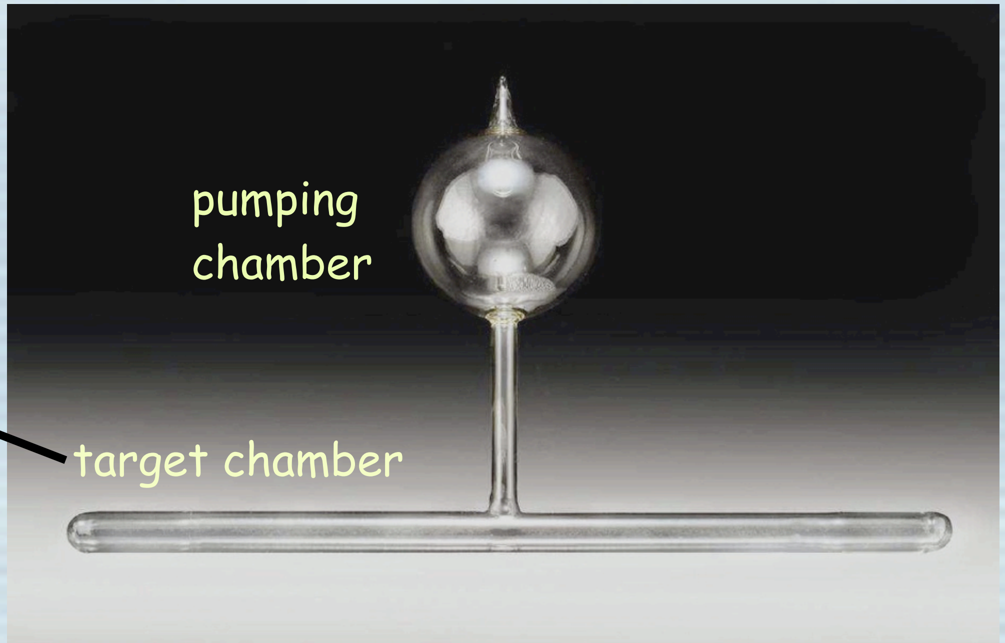
Polarizaton Gradients



Despite polarizations (measured in the pumping chamber) hovering around 65% in beam, the published target polarization was 55.4% +/- 2.8%

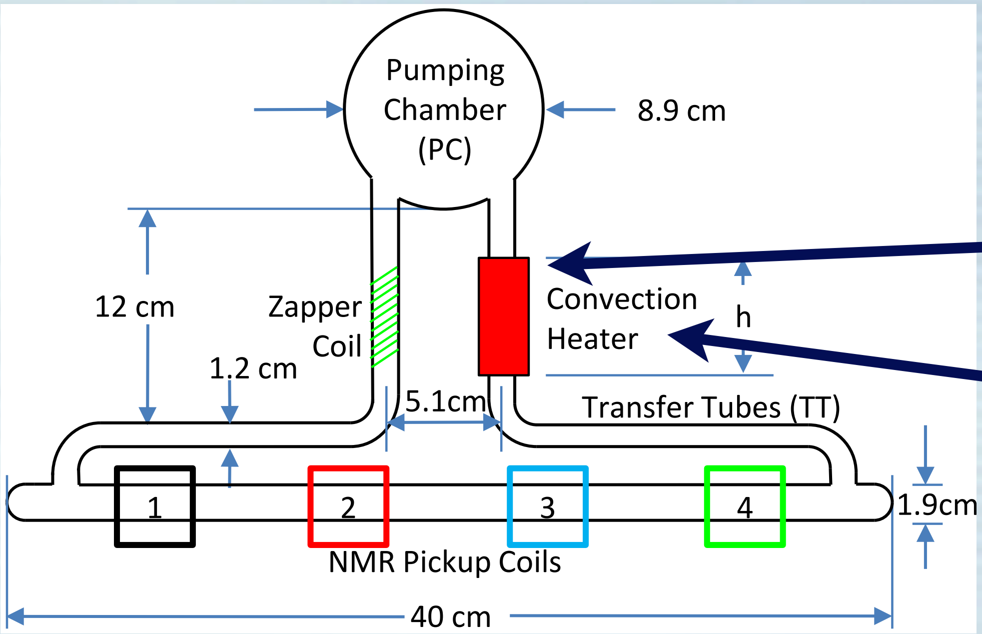
Why the big difference?



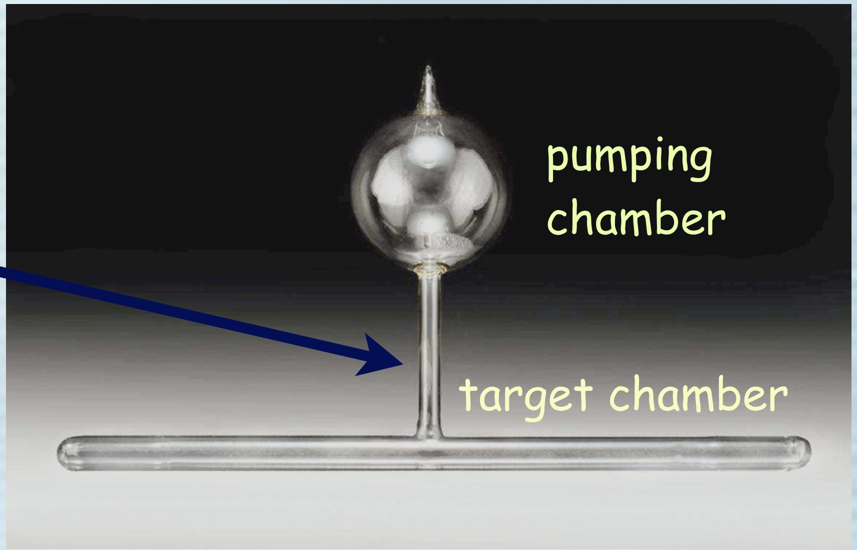


Diffusion limits mixing between the pumping and target chambers.
This problem could be crippling with the high-luminosity experiments planned for 12 GeV

Convection-based target cells



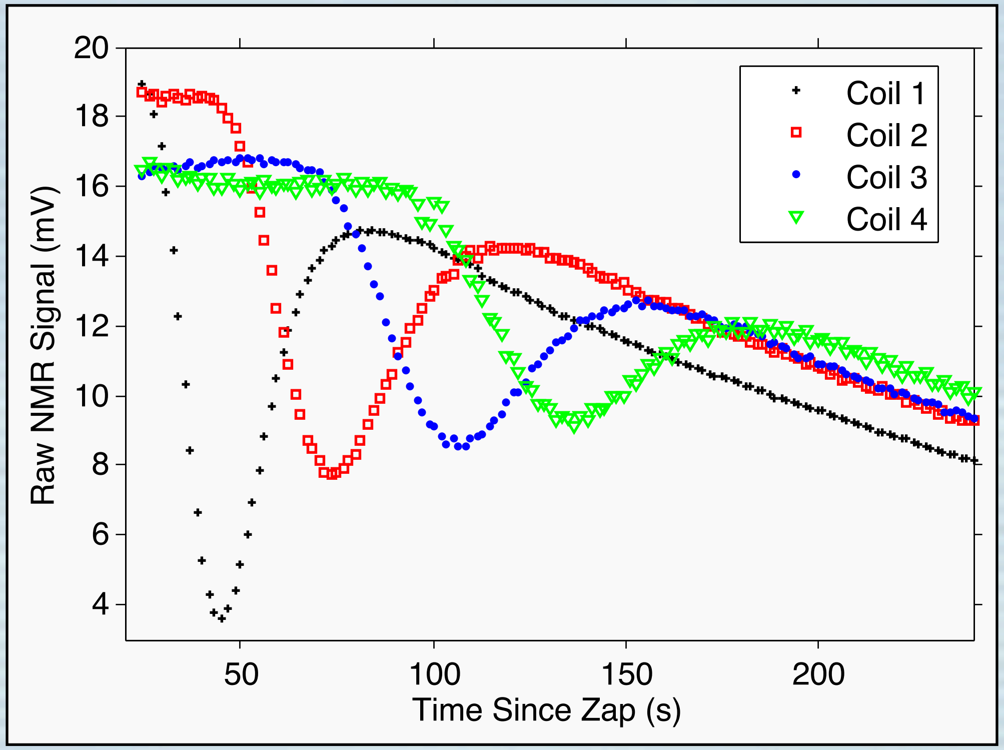
The convection-style cells have two transfer tubes instead of one.



A small heater on one transfer tube creates a buoyancy force that induces convection

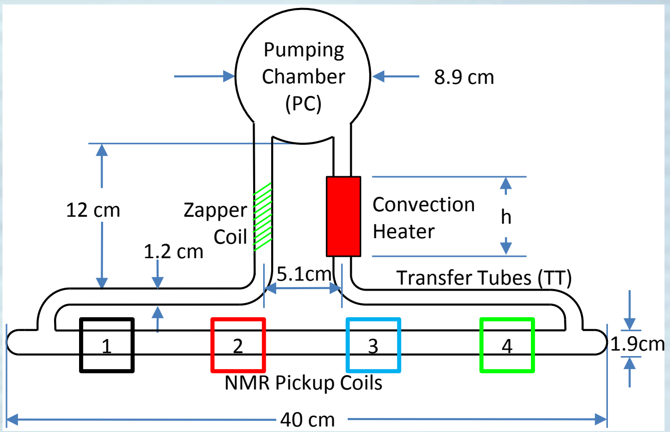
Measuring the gas speed

A "Zapper coil" is used to produce a depolarized slug of gas. Four NMR pickup coils register the passage of the slug of gas as a function of time.

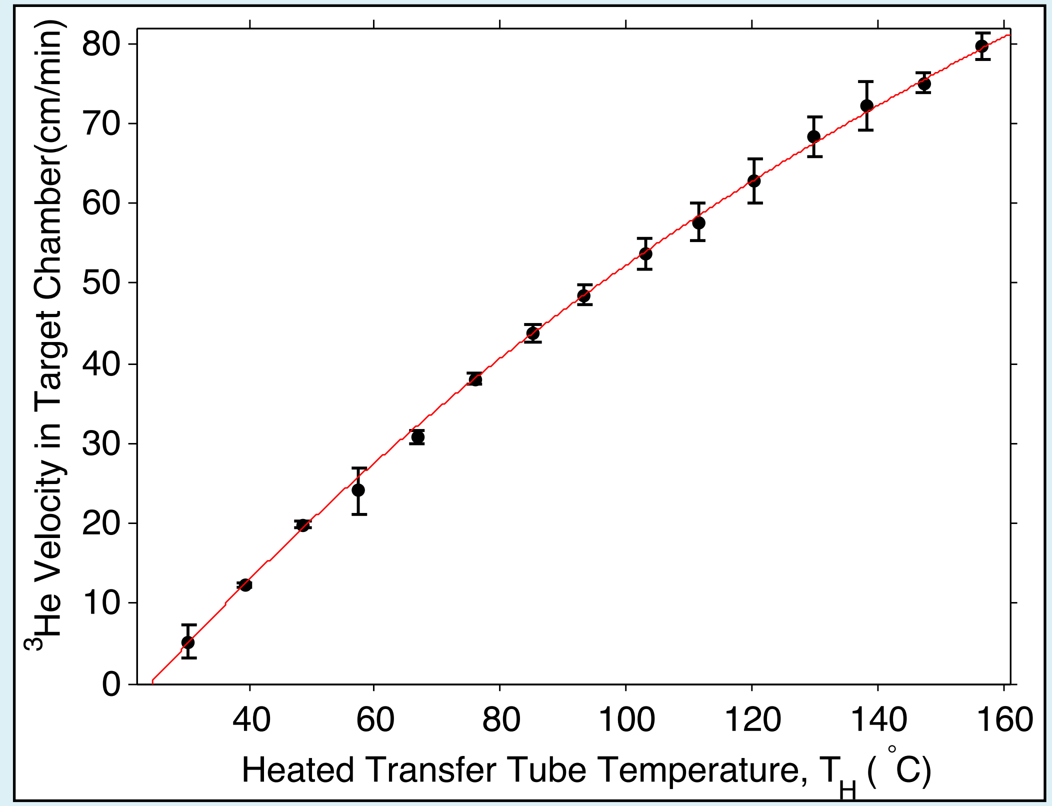


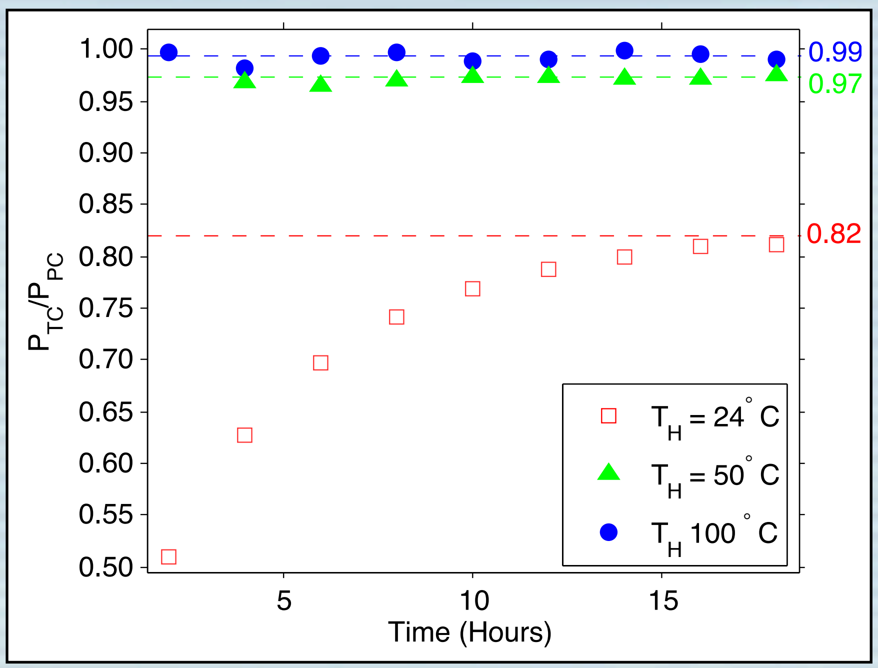
Dolph, Singh, Averett, Kelleher, Mooney, Nelyubin, Tobias Wojtsekhowski and Cates, PRC vol 84, pg 065201 (2011)

Eliminating polarization graadients



With convection-style cells, the velocity of the gas traveling through the target chamber can be easily controled from a few cm/min up to around 80 cm/min.





Polarization gradient: $$\frac{P^{\infty}_{\rm tc}}{P^{\infty}_{\rm pc}} = \frac{1}{1+\Gamma_{\rm tc}/d_{\rm tc}}$$

With V_{gas} = 6 cm/min,
$P_{tc}/P_{pc} > 0.98$ with beam, and
$P_{tc}/P_{pc} > 0.99$ with no beam.

With V_{gas} = 60 cm/min, $P_{tc}/P_{pc} > 0.999$!!!

Thus, convection also has implications for polarimetry

Why isn't P_{He} > 70%? -- The "X-factor"

The so-called X-factor characterizes a poorly understood temperature-dependent spin-relaxation mechanism that limits the maximum polarization of the target.

Babcock, Chann, Walker, Chen and Gentile
PRL vol. 96, pg. 083003 (2006)

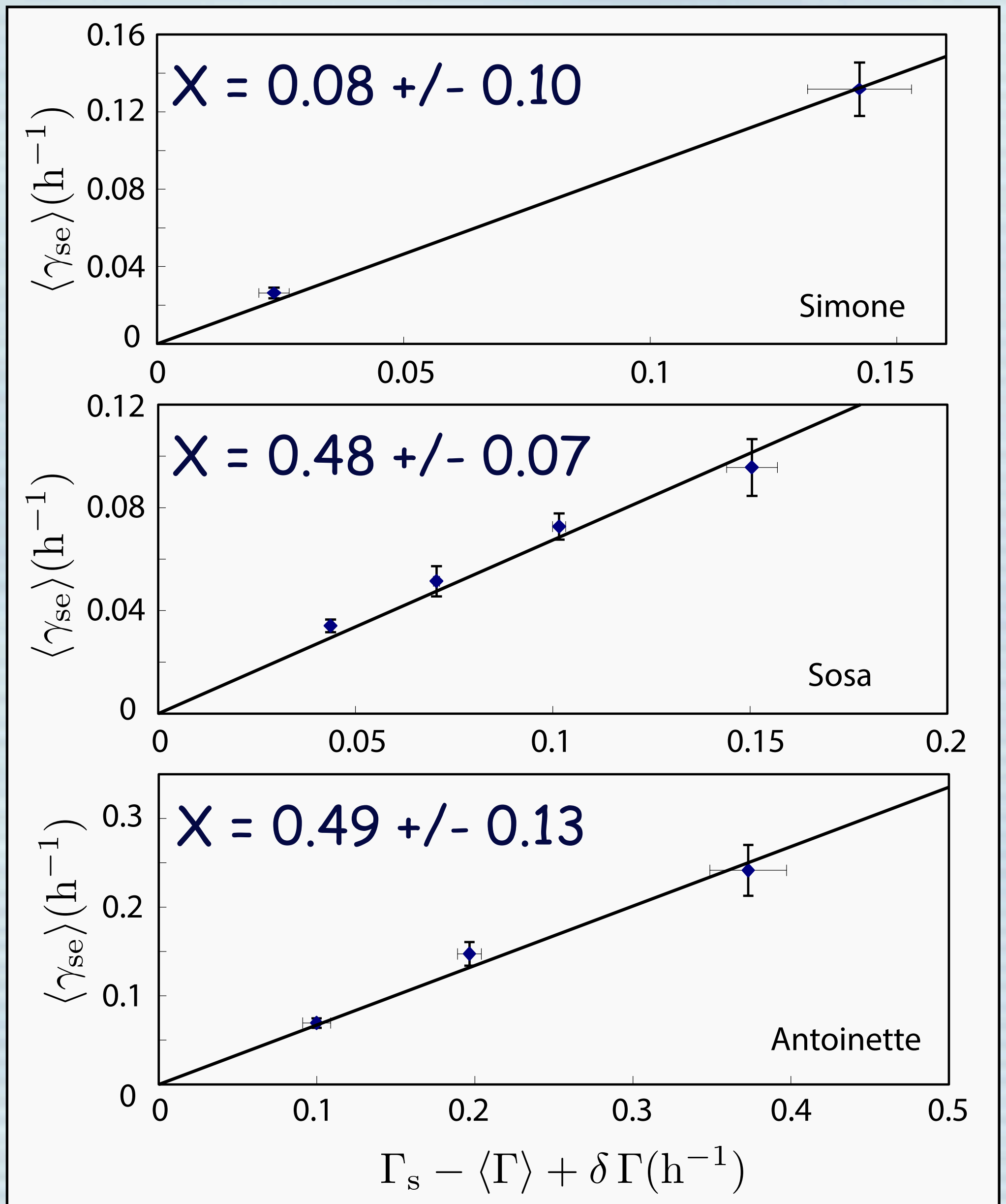
$$\lim_{\gamma_{\rm se}\to\infty} P_{\rm He} = \lim_{\gamma_{\rm se}\to\infty} \frac{\langle P_{\rm A}\rangle\langle\gamma_{\rm se}\rangle}{\langle\gamma_{\rm se}\rangle(1+X)+\langle\Gamma_{\rm He}\rangle} = \frac{\langle P_{\rm A}\rangle}{1+X}$$

The new relaxation mechanism has been observed to be roughly proportional to the spin-exchange rate, so it cannot be overwhelmed by running the target "harder".

Indeed, the highest polarization reported in the PRL mentioned above is 79%, and there are VERY few examples in the literature claiming anything higher.

The X-factor

One way of measuring X-factors is by looking at spin-relaxation rates at different temperatures (and thus alkali densities).



These quantities are determined by looking at "spin-ups" and cold "spin downs"

$$\langle\gamma_{se}\rangle = \frac{\Gamma_s - \langle\Gamma\rangle + \delta\Gamma}{(1+X)}$$

The expected spin-exchange rat is determined by measuring the alkali densities and using known spin-exchange coefficients

$$\gamma_{se} = k_{se}^{Rb}[Rb] + k_{se}^{K}[K]$$

The X-factor

X-factors can also be measured at a single temperature. We did so in a manner that overdetermined the X-factors, allowing both a better determination, as well as a check of internal consistency.

Cell	T(C)	X_1	X_2	X_3	X_4	X_{12}/X_{1234}
Sim.	215	-0.02(12)	-0.10(14)	-	-	-0.04(12)
	255	0.13(08)	0.08(09)	-	-	0.11(06)
Sosa	160	0.22(07)	0.28(09)	0.32(15)	0.18(09)	$0.24(06)^{\dagger}$
	170	0.24(07)	0.37(15)	-	-	0.27(06)
	180	0.45(08)	0.40(09)	0.50(17)	0.45(09)	$0.43(06)^{\dagger}$
	190	0.59(16)	0.57(17)	-	-	0.58(12)
Boris	235	0.21(14)	0.31(14)	-	-	0.26(10)
Sam.	235	0.08(06)	0.22(09)	-	-	0.12(05)
Alex	235	0.34(09)	0.35(09)	0.63(20)	0.29(10)	$0.34(06)^{\dagger}$
Astral	235	0.15(07)	0.22(10)	0.20(14)	0.14(07)	$0.17(05)^{\dagger}$
Steph.	235	0.31(17)	0.31(10)	-	-	0.31(08)
Brady	235	0.13(07)	0.15(09)	0.23(14)	0.11(07)	$0.14(05)^{\dagger}$
Antoinette	215	0.27(09)	0.44(17)	0.30(19)	0.25(11)	$0.28(08)^{\dagger}$
	235	0.20(09)	0.34(12)	0.36(17)	0.15(09)	$0.24(07)^{\dagger}$
	255	0.55(26)	0.54(16)	0.50(30)	0.56(26)	$0.55(13)^{\dagger}$

The X-factor

We see evidence suggesting there may be temperature dependence in the X-factor, a possibility explicitly mentioned by Babcock et al.

Cell	T(C)	X_1	X_2	X_3	X_4	X_{12}/X_{1234}
Sim.	215	-0.02(12)	-0.10(14)	-	-	-0.04(12)
	255	0.13(08)	0.08(09)	-	-	0.11(06)
Sosa	160	0.22(07)	0.28(09)	0.32(15)	0.18(09)	0.24(06)†
	170	0.24(07)	0.37(15)	-	-	0.27(06)
	180	0.45(08)	0.40(09)	0.50(17)	0.45(09)	0.43(06)†
	190	0.59(16)	0.57(17)	-	-	0.58(12)
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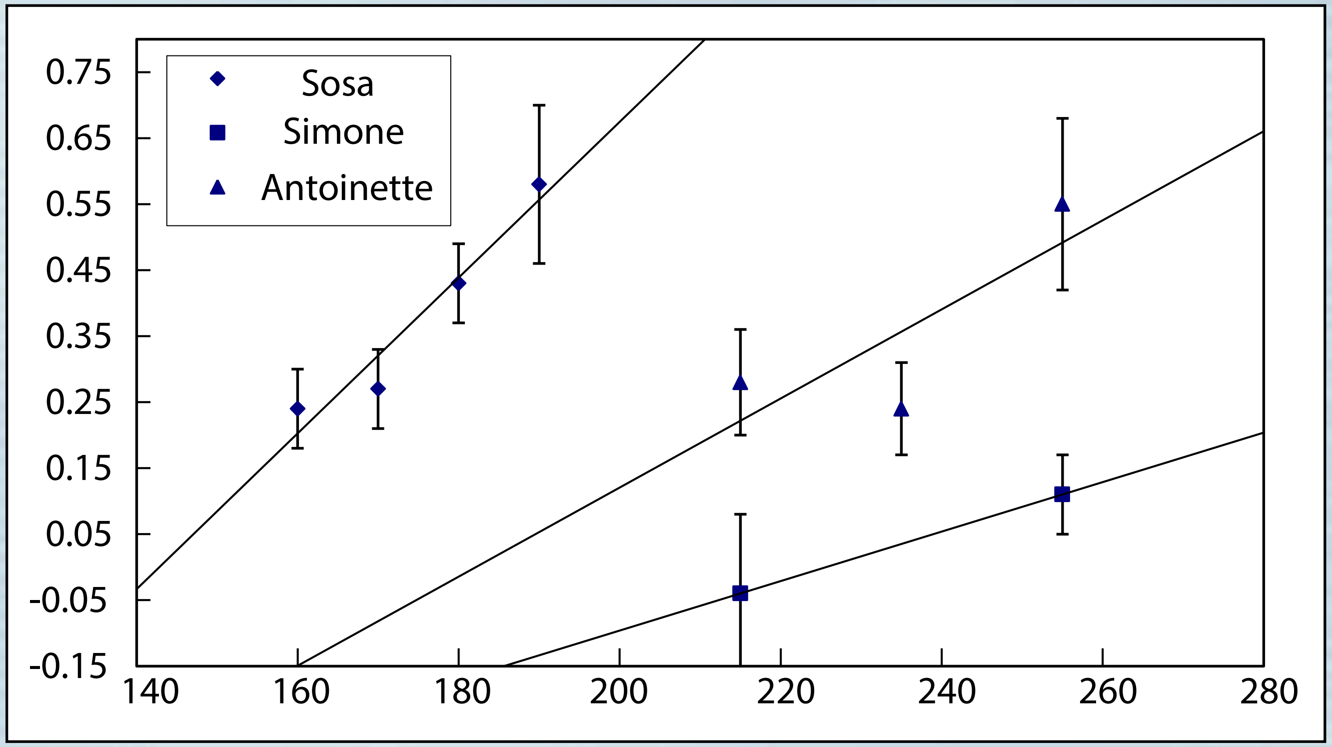
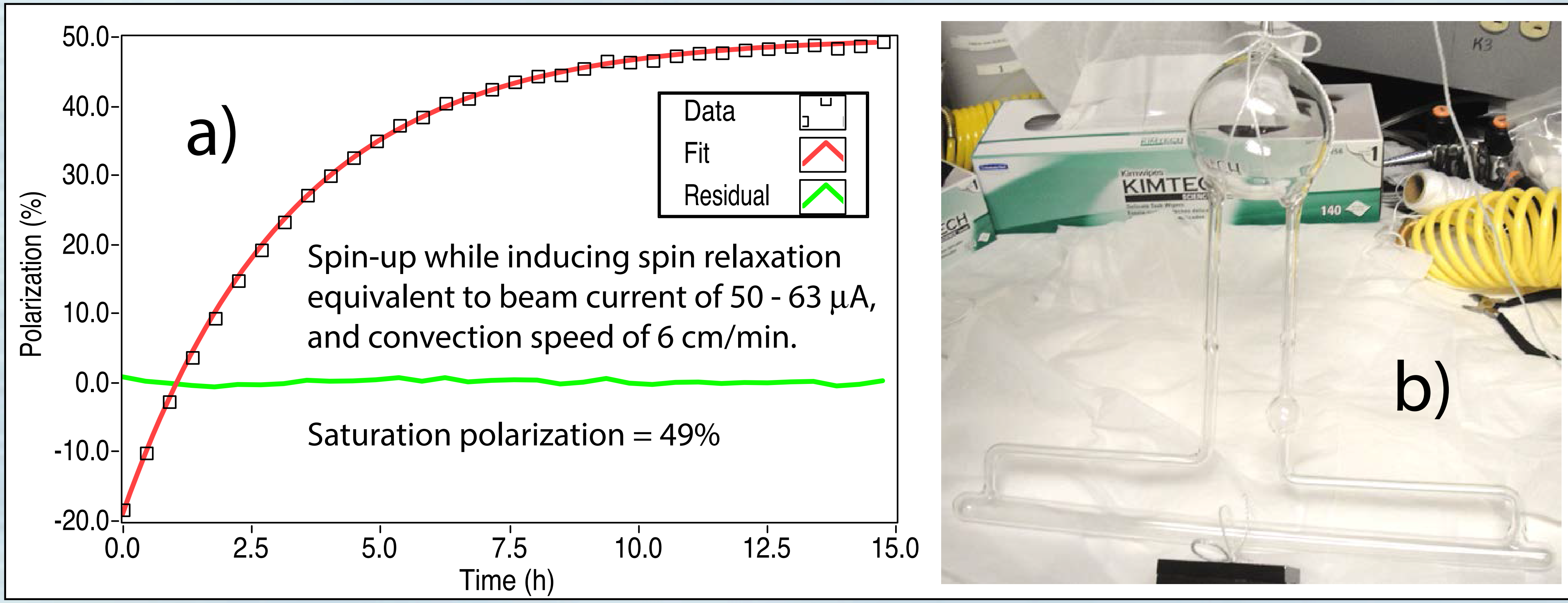
Astral	235	0.15(07)	0.22(10)	0.20(14)	0.14(07)	0.17(05)†
Steph.	235	0.31(17)	0.31(10)	-	-	0.31(08)
Brady	235	0.13(07)	0.15(09)	0.23(14)	0.11(07)	0.14(05)†
Antoinette	215	0.27(09)	0.44(17)	0.30(19)	0.25(11)	0.28(08)†
	235	0.20(09)	0.34(12)	0.36(17)	0.15(09)	0.24(07)†
	255	0.55(26)	0.54(16)	0.50(30)	0.56(26)	0.55(13)†



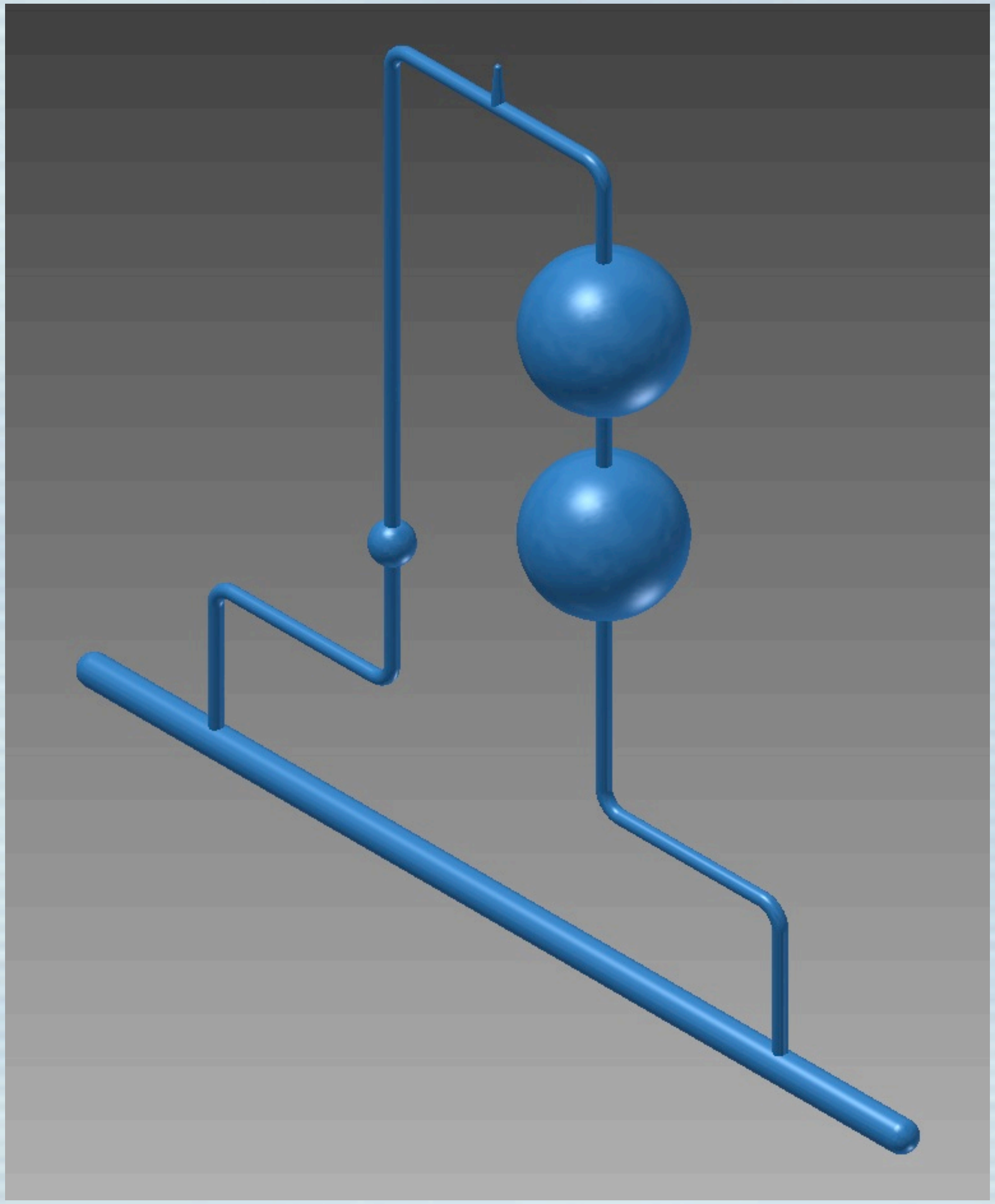
If true, X factors may represent an even more limiting ceiling on the polarization of SEOP ^3He targets

The first prototype quasi-next-generation polarized ^3He target



- Simulated beam test: P_{He} > 49% with 45 μA beam current.
- P_{He} ~ 67% with no convection (and no simulated beam).
- P_{He} ~ 61% with convection (and no simulated beam).
- P_{He} likely around 55-60%, with 30 μA beam current for actual target cell under full operating conditions.

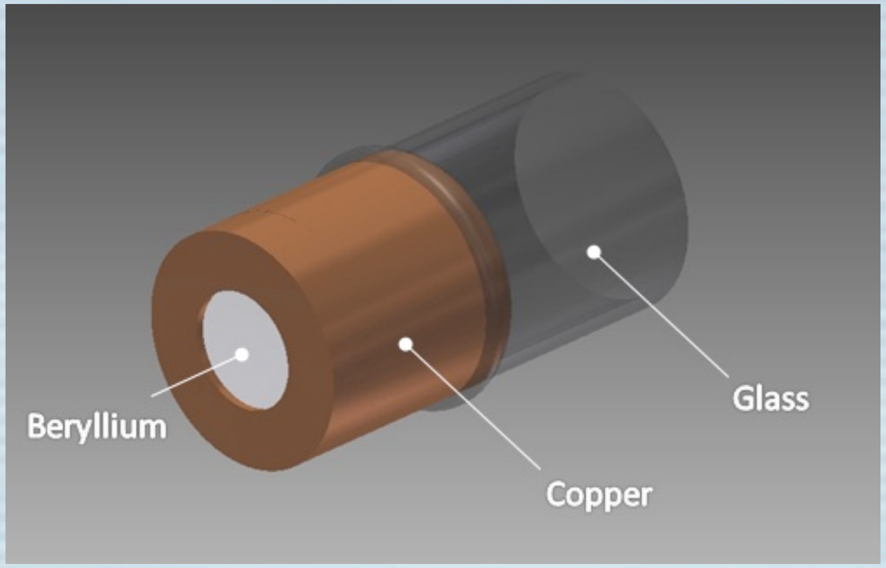
True next-generation polarized ^{3}He target



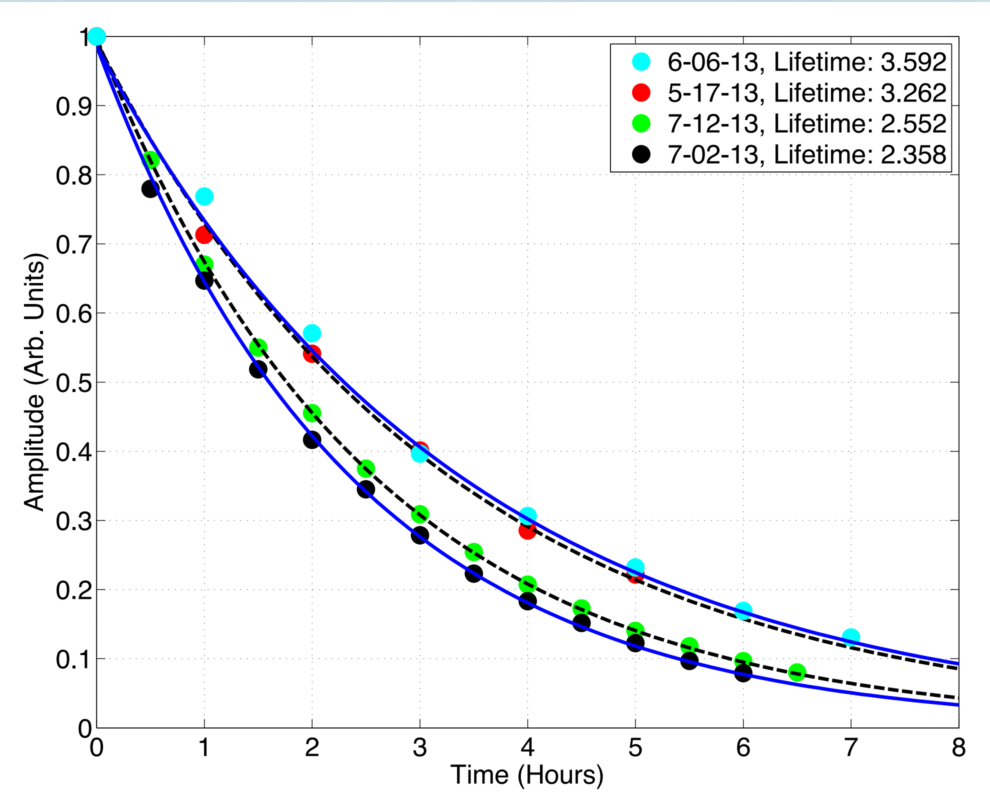
- Capable of Luminosity ~ 1 x 10^{37} $cm^{-2}s^{-1}$ (more than four times higher than Transversity).
- Double pumping chamber
- Target chamber 60 cm instead of 40 cm.
- P_{He} 60-65%
- Would probably need metal end windows.

One design is ready to roll

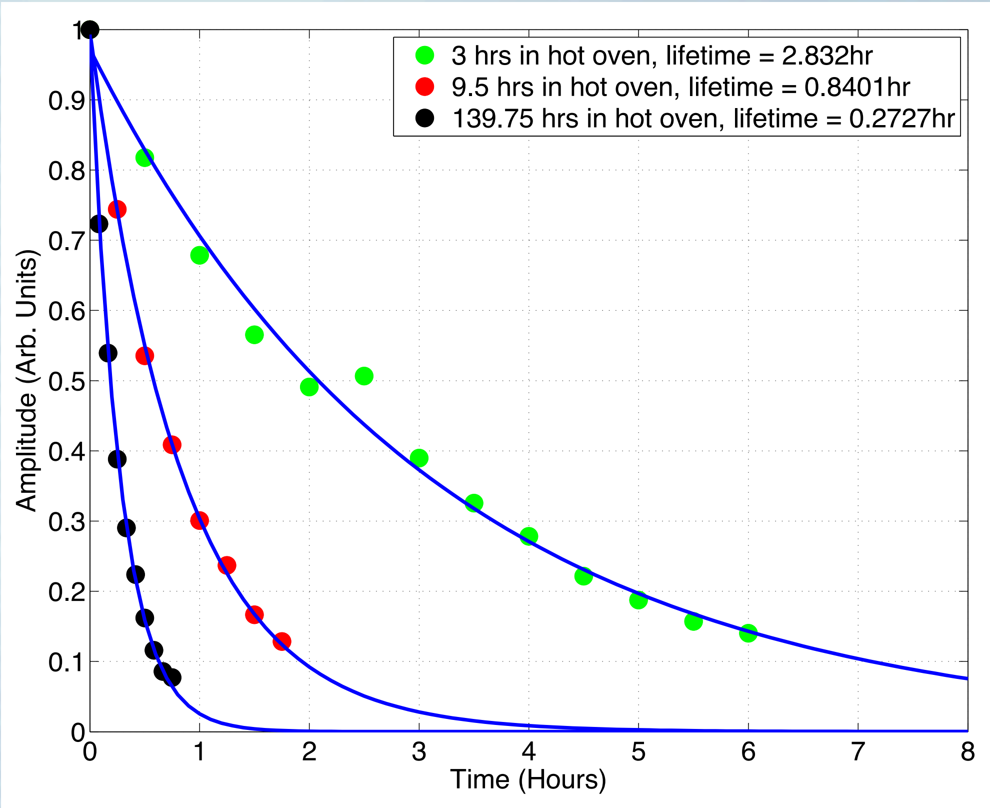
- Berylium window mounted on OFHC copper frame
- Inner surface of of OFHC copper coated with gold
- Glass-to-aluminosilicate glass seal
- Gold shown at Mainz to have ~22 spin-relaxation time for ^{3}He target, more than good enough.
- Mainz tests involved NO ALKALI metals .....



Tests show two surfaces get worse with exposure to Rb



Gold electroplated onto OFHC copper



Electropolished OFHC copper

Conclusion - metal parts may need to be protected against exposure to alkali vapor

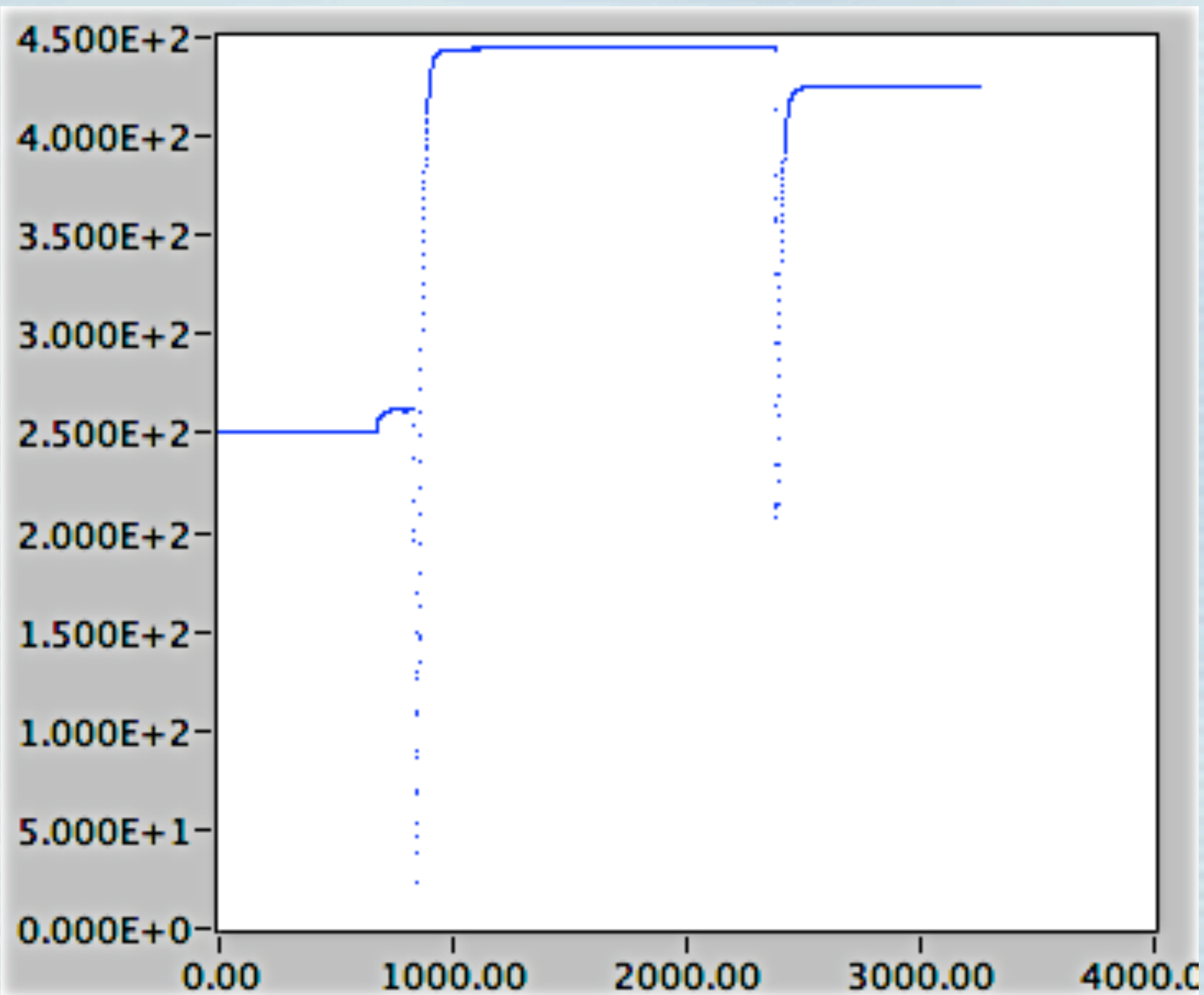
Summary

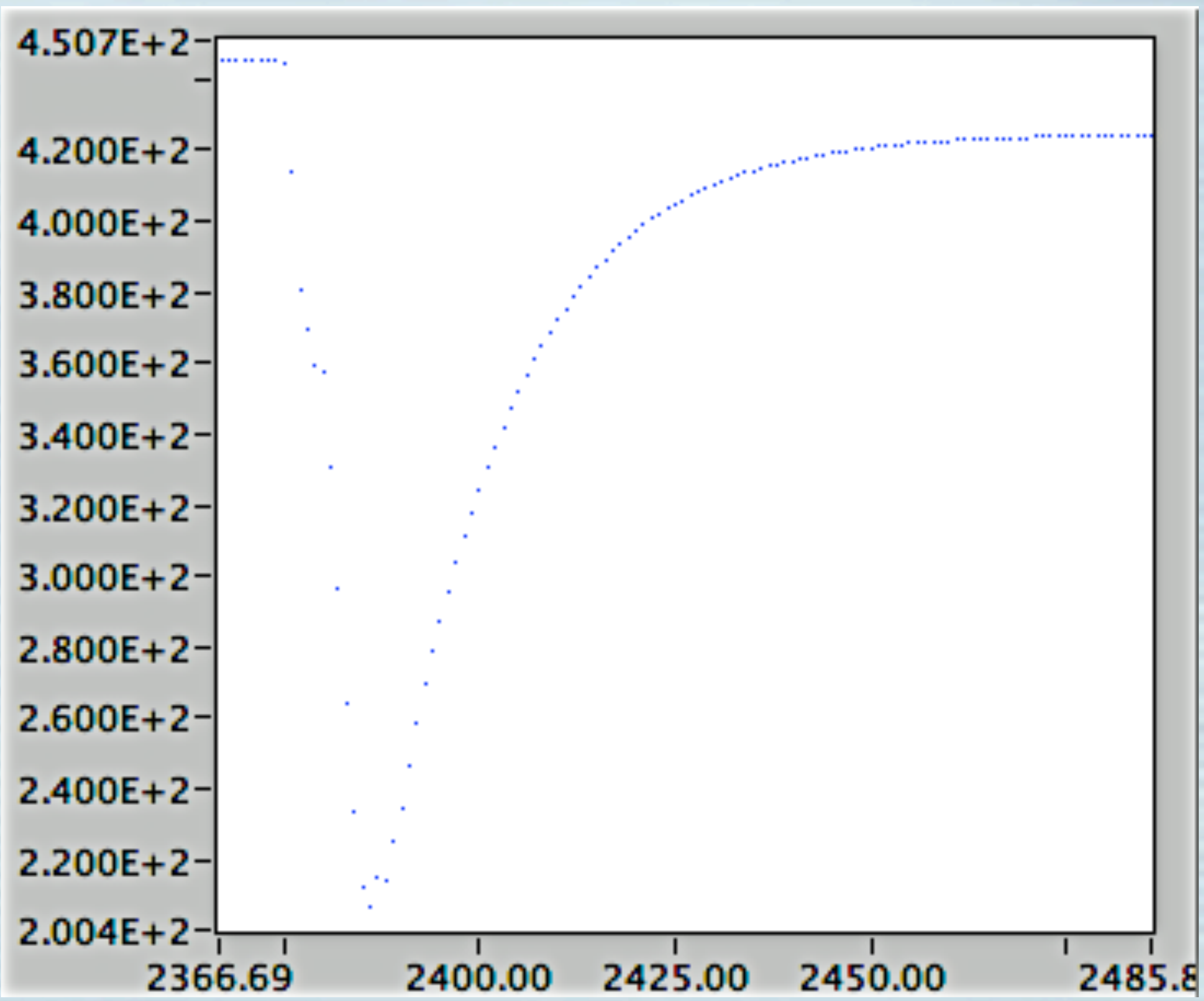
- SEOP Polarized ^{3}He targets have figures of merit that have climbed by x30 since E142 and E154 at SLAC
- We expect the improvement to be X120 (compared to E142) with the next generation of targets.
- Even larger gains are almost certainly possible.
- Polarized ^{3}He continues to broaden our reach in terms of physics.

AFP Measurement from Goldfinger

Several features to notice in measurement:

- Large shifts in baseline
- Very large apparent losses.
- Asymmetric line shape.
- Regardless of messed-up signal, excellent signal-to-noise. Made us wonder if the cell was better when we first started our tests.



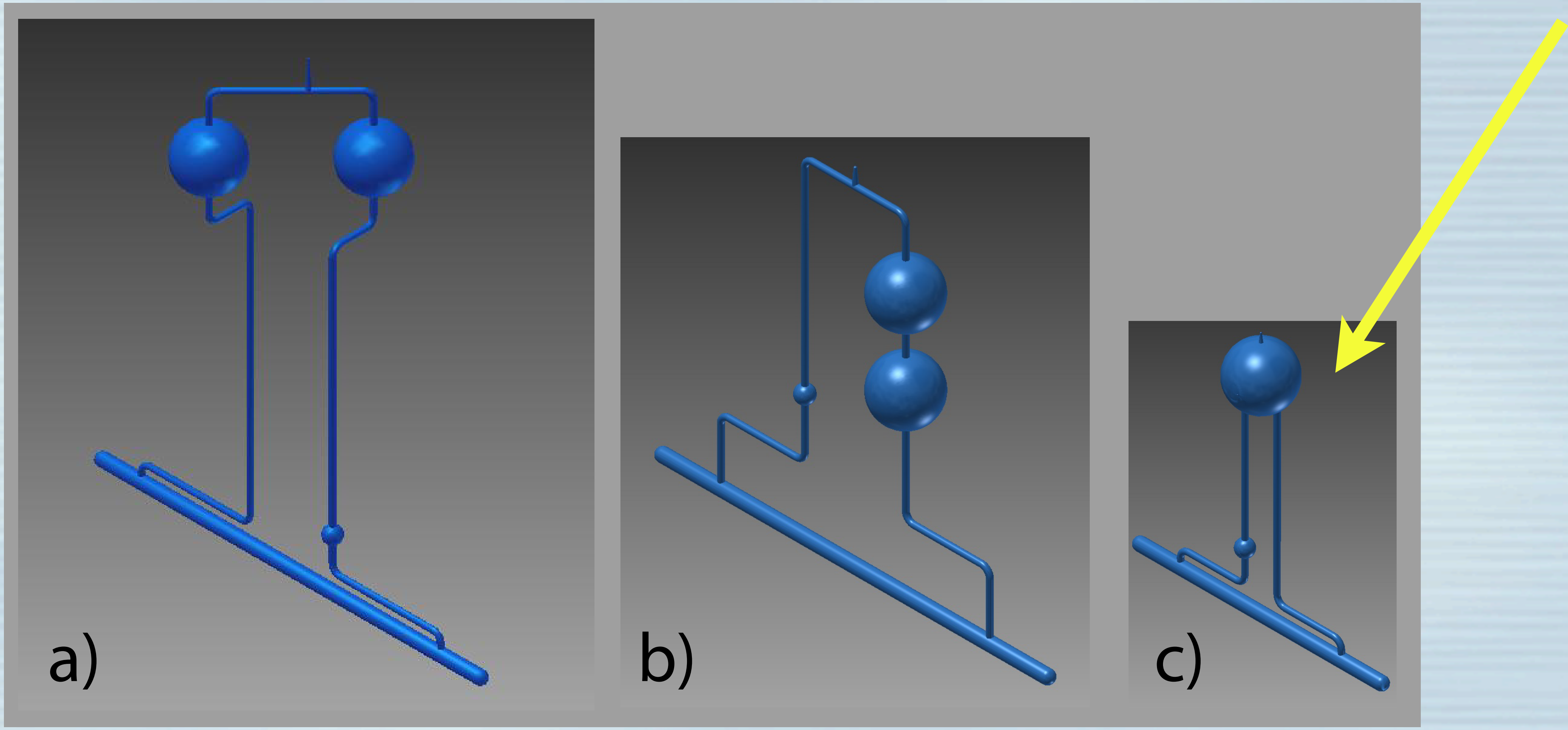


Next test: valved gold-coated cell

- If gold is a good surface before being exposed to Rb, we should get good lifetimes if we never allow the gold to see any Rb.
- With a valve, we can isolate the gold portion of the cell until the pumping chamber is cold.
- If the results are favorable, we may well be able to design a target in which the Rb reaching the gold is minimized.

We also have cells in the pipeline with both titanium as well as non-magnetic stainless steel.

The choice of the cell design



- Currently, our magnetic-field studies are of option a).
- Our design of choice would probably be option b).
- The current plan is option c). This is essentially the design of Protovec-I, which has already been bench tested.

EXP	Cell	Lasers	I_0 W/cm^2	T_{pc}^{set} °C	P_{pc}^{∞}	Γ_s^{-1} hrs	$\langle\Gamma\rangle^{-1}$ hrs	$\frac{\langle P^A \rangle}{P^A_{line}}$	P^A_{line}	D_{fr}	D_{pb}	$[Rb]_{fr}$ 10^{14}/cm^3	ΔT_{Rb} °C	ΔT_{He} °C	X
saGDH	Proteus	3B	3.8	180	0.46	27	74	-	-	0	0	-	-	-	-
	Priapus	3B	3.8	180	0.44	21	56	-	-	0	0	-	-	-	-
	Penelope	3B	3.8	180	0.39	18	46	-	-	0	0	-	-	-	-
	Powell	3B	3.8	180	0.38	13	25	-	-	0	0	-	-	-	-
	Prasch	3B	3.8	180	0.33	13	33	-	-	0	0	-	-	-	-
GEN	Al	2.5B	3.2	235	0.53(03)	7.86(05)	27.42(1.37)	-	-	-	4.53(25)	-	-	-	-
		5B	6.1	235	0.54(03)	6.73(18)	27.42(1.37)	-	-	-	4.53(25)	-	-	-	-
	Barbara	2.5B	1.6	235	0.37(02)	5.50(08)	42.95(2.15)	-	-	-	4.80(25)	-	-	-	-
		5B	3.1	235	0.57(03)	4.76(63)	42.95(2.15)	-	-	-	4.80(25)	-	-	-	-
	Gloria	3B	1.7	235	0.60(03)	6.13(04)	38.29(1.91)	-	-	-	7.20(40)	-	-	-	-
	Anna	1B	0.6	235	0.33(02)	5.60(34)	11.38(57)	-	-	-	9.64(57)	-	-	-	-
		1.5B	1.0	235	0.39(02)	5.37(08)	11.38(57)	-	-	-	9.64(57)	-	-	-	-
	Dexter	1.5B	1.5	235	0.47(02)	7.58(17)	18.45(92)	-	-	-	-	-	-	-	-
		5B	6.1	235	0.49(02)	6.63(12)	18.45(92)	-	-	-	-	-	-	-	-
	Edna	3B	2.4	235	0.56(03)	5.71(02)	27.42(1.37)	-	-	-	3.63(20)	-	-	-	-
	Dolly	3B	1.0	235	0.43(02)	6.16(03)	35.24(1.76)	-	-	-	20(1.3)	-	-	-	-
		1N1B	1.4	235	0.62(03)	5.79(07)	35.24(1.76)	-	-	-	20(1.3)	-	-	17(10)	-
	Simone	2N1B	3.8	215	0.31(01)	14.08(06)	22.87(1.14)	0.947(020)	0.91(05)	10.66(54)	8.89(45)	0.20(02)	-7(3)	-	-0.04(12)*
		2N1B	3.8	240	0.48(02)	6.89(20)	22.87(1.14)	-	-	-	9.76(49)	-	-	-	-
		2N1B	3.8	255	0.58(02)	6.45(10)	22.87(1.14)	0.929(023)	0.92(05)	12.48(83)	10.3(52)	0.90(09)	-4(5)	-	0.11(06)*
	Sosa	2N1B	1.9	160	0.57(02)	16.69(09)	73.68(3.68)	0.966(020)	1.00(03)	0	0	1.97(13)	4(1)	30(7)	0.24(06)†
		2N1B	1.9	170	0.61(03)	11.67(04)	73.68(3.68)	0.964(020)	0.98(03)	0	0	3.00(33)	3(3)	38(14)	0.27(06)*
		2N1B	1.9	180	0.55(02)	8.79(09)	73.68(3.68)	0.954(022)	0.97(03)	0	0	4.30(27)	1(2)	47(7)	0.43(06)†
		2N1B	1.9	190	0.40(02)	6.39(22)	73.68(3.68)	0.854(075)	0.82(03)	0	0	5.69(63)	-2(3)	48(20)	0.58(12)*
		2N1B	1.9	200	0.26(01)	5.04(17)	73.68(3.68)	-	-	0	0	-	-	43(18)	-
Transversity	Boris	3B	1.8	235	0.42(02)	6.25(04)	23.74(1.19)	0.871(050)	0.79(07)	1.96(18)	2.45(23)	2.19(34)	-8(7)	-	0.26(10)*
	Samantha	3B	1.8	235	0.50(02)	6.30(13)	36.51(1.83)	-	-	-	4.34(23)	-	-	-	-
		3N	2.6	235	0.68(03)	4.62(03)	22.13(1.11)	0.956(020)	0.99(03)	4.37(10)	4.34(23)	1.80(10)	7(2)	21(10)	0.12(05)*
	Alex	2N1B	2.6	235	0.59(03)	4.81(02)	32.96(1.65)	0.942(042)	0.99(03)	1.37(08)	1.19(07)	4.08(36)	0(4)	42(10)	0.34(06)†
	Moss	1N1B	1.8	235	0.62(03)	5.35(04)	33.00(1.65)	-	0.95(09)	-	2.40(13)	-	-	29(8)	-
	Tigger	1N1B	1.8	235	0.51(02)	4.89(05)	12.62(63)	-	0.95(09)	-	-	-	-	23(9)	-
	Astral Weeks	2N1B	2.6	235	0.69(03)	6.57(12)	48.90(2.45)	0.954(020)	0.99(03)	7.09(55)	6.21(56)	0.97(09)	3(5)	25(4)	0.17(05)†
	Stephanie	3N	2.6	235	0.63(03)	4.55(09)	48.35(2.42)	0.929(114)	0.99(03)	1.39(11)	1.50(10)	5.08(58)	7(5)	54(6)	0.31(08)*
	Brady	1N	0.9	235	0.62(03)	4.82(1.08)	33.50(1.68)	-	0.95(03)	-	2.36(24)	-	-	14(9)	-
		2N	1.8	235	0.68(03)	5.52(70)	33.50(1.68)	-	0.99(03)	-	2.36(24)	-	-	25(8)	-
		3N	2.6	235	0.70(03)	5.30(01)	33.50(1.68)	0.956(021)	0.99(03)	2.60(20)	2.36(24)	2.86(30)	6(5)	39(9)	0.14(05)†
	Maureen	3N	2.6	235	0.66(03)	5.42(12)	29.21(1.46)	-	0.97(09)	-	4.42(55)	-	-	32(12)	-
	Antoinette	3N	1.7	215	0.49(02)	6.63(37)	20.93(1.05)	0.958(020)	0.99(03)	2.85(13)	-	0.96(07)	0(3)	16(8)	0.28(08)†
		3N	1.7	235	0.61(03)	4.18(10)	20.93(1.05)	0.936(043)	0.99(03)	3.32(27)	-	1.83(20)	0(5)	20(10)	0.24(07)†
		3N	1.7	255	0.41(02)	2.66(11)	20.93(1.05)	0.776(099)	0.93(10)	3.57(23)	-	2.88(39)	-5(6)	33(9)	0.55(13)†