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1 OF 1

CALIBRATION OF THE FERMILAB E-704 POLARIZED TARGET*

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A. Summary

Table 1 lists the final, best estimate of the target polarization P_T as a function of time for all of the periods during which scattering data were (or may have been) collected. The information under "RUN" refers to $\Delta\sigma_L$ -runs. The notation "sfs" stands for "start of frozen spin," "efs" for "end of frozen spin," " $\rightarrow la$ " for "go to large-aperture" target magnet position, and "nla" for "not large-aperture" position, i.e., the target magnet is in "polarizing" position. Where the "NOTE" column is blank it means that all standard frozen-spin conditions were in effect: the target temperature was reduced and the magnet was in large-aperture position. The timing marks were developed on the basis of three criteria: (1) the availability of direct NMR data, (2) the inclusion of major Target and Run boundaries, and (3) the arbitrary inclusion of enough "minor" Run boundaries to shorten large timing gaps.

The *sign* of the P_T -values is given in the NMR convention: (+) corresponds to predominant occupation of the Zeeman ground state (the "thermal" NMR-signals are considered positive). Since the target magnet field pointed upstream, (+) corresponds to target spin *antiparallel* to the beam momentum.

The estimated uncertainty on P_T is $\pm 6.5\%$ (2σ), and the estimated uncertainty on the *ratio* of values for the two signs of polarization, $P_T(+)/P_T(-)$, is $\pm 4.3\%$ (2σ).

B. Corrections to the thermal equilibrium NMR data

The main tasks in establishing the target calibration are the consideration of potential systematic errors of the thermals measurements and the correction of such errors, where possible. This section describes systematics that have been identified as correctable offline.

A very large systematic effect was present during the first two days of two-spin running. This was caused by a major readjustment that was made to the NMR system on 6-May-90 (increased damping of the tank circuits). A new set of thermals was taken on 13-May, and this information has been used to back-calibrate the online P_T -values for 11,12-May.

The online program that was used to convert the resistance thermometer readings to a temperature value used straight-line interpolation between the reference

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Table 1: Target polarization summary.

DATE-TIME	RUN	P _T	NOTE	DATE-TIME	RUN	P _T	NOTE
11-May-0430		-.784	sfs	18-May-2340	188 end	+.737	
1230	125 start	-.784		19-May-0340	191 start	+.735	
1540	127 end	-.784	efs	0850	195 end	+.732	
1920		+.622	nla	1240	198 end	+.730	
1940	129 start	+.657	nla	1400	199 start	+.729	
1950		+.668	nla	1640	200 start	+.727	
2010		+.685	nla	2230	203 end	+.724	
2040	129 end	+.684	sfs	20-May-0600	208 start	+.720	
2120	130 start	+.677		1430	213 end	+.715	
12-May-0250	135 end	+.675		1630	215 start	+.714	
1000	141 start	+.673		1830	216 end	+.713	efs
1710	143 end	+.671		1840	217 start	+.713	nla
1800	144 start	+.671		1930	218 start	+.729	nla
2140	146 end	+.670		2240	219 end	+.777	nla
2330		+.669	efs	2320	220 start	+.780	sfs
15-May-1620		-.829	sfs	21-May-0200	223 start	+.771	
1650		-.821		0830	228 start	+.769	
2330	147 start	-.796		1420	231 end	+.767	efs
16-May-0650	153 end	-.793		22-May-0240		-.466	nla
1330	156 start	-.790		0300	234 start	-.549	nla
1930	160 start	-.788		0430	235 start	-.747	nla
17-May-0220	165 start	-.785		0600	235 end	-.806	nla
0850	169 end	-.782		0720	236 end	-.836	sfs
0920		-.782	efs	0730	237 start	-.831	
1650	170 start	+.759	nla	1240	239 end	-.827	
1720	170 end	+.759	sfs(nla)	1320	240 start	-.827	
1810	171 end	+.758	nla	1940	243 start	-.824	
2300		+.751	nla	23-May-0200	247 end	-.821	
2340	172 start	+.751	nla	0800	251 end	-.818	efs
18-May-0200	175 start	+.749	nla	5-Jun-0230	252 start	+.776	nla
0310		+.748	nla	0330		+.784	sfs(nla)
0440		+.750	nla	0350	252 end	+.784	nla
0750		+.751	nla	0520	253 end	+.785	nla
1010		+.748	nla	1150		+.789	nla
1150		+.744	nla	1450	254 start	+.783	nla
1650	185 start	+.743	nla	1700	255 end	+.776	nla
2150	188 start	+.738	nla	1810		+.772	nla
2230		+.738	→la	1930	256 start	+.782	nla

DATE-TIME	RUN	P _T	NOTE	DATE-TIME	RUN	P _T	NOTE
5-Jun-2020	256 end	+.782	nla	11-Jun-2100	343 end	-.780	
2130		+.782	→la	12-Jun-0200	348 end	-.779	
6-Jun-0110	257 start	+.781		0440	349 start	-.778	
0550	259 end	+.780		0650	350 end	-.777	
0640	"547" end	+.780		1140		-.775	
1200	261 start	+.779		2000		-.772	
1710	265 start	+.779		13-Jun-0400		-.769	
1840	266 end	+.778		1200		-.766	
2100	267 start	+.778		2000		-.764	
7-Jun-0200	270 start	+.777		14-Jun-0400		-.761	
0840	273 end	+.776		1120	351 start	-.758	
1410	277 end	+.775		1850	355 end	-.755	
1650		+.775	efs	15-Jun-0010	359 start	-.754	
1920		-.707	nla	0550	362 end	-.752	
2010	279 start	-.768	nla	0630	363 start	-.751	
2120	280 start	-.800	sfs	1430	369 end	-.748	
2200		-.794		1500	370 end	-.748	
8-Jun-0450	285 start	-.790		1540		-.748	nla
1310	289 end	-.785		1720	371 start	-.746	nla
2010	297 end	-.781		2000	373 end	-.742	nla
9-Jun-0350	302 end	-.776		2330		-.737	efs
0520	303 start	-.776		16-Jun-0250	374 start	+.805	nla
1200	308 start	-.772		0310	375 start	+.805	sfs
1620	310 end	-.769		0340	377 start	+.799	
1650	311 end	-.769	efs	0850	380 end	+.795	
10-Jun-0550		+.751	nla	1430	383 end	+.790	
0640	319 start	+.765	nla	1810	384 start	+.787	
0710		+.772	nla	17-Jun-0030	387 end	+.781	
0740		+.774	sfs	0730	392 start	+.775	
0800	320 start	+.774		1210		+.771	
1450	325 start	+.774		1350	395 end	+.770	efs
2240	328 end	+.774		1810	399 start	-.801	sfs
11-Jun-0010	329 end	+.774	efs	1820		-.798	
0120	330 start	-.722	nla	2150	400 start	-.792	
0150	330 end	-.784	nla	18-Jun-0310	402 end	-.790	
0210	331 start	-.793	sfs	0840	405 end	-.787	
0225		-.792		1210	407 end	-.785	
0720	336 start	-.785		2000		-.781	
1410	339 end	-.783		19-Jun-0400		-.776	
1530	340 start	-.782		1220		-.772	
				1800		-.769	efs

DATE-TIME	RUN	P _T	NOTE
20-Jun-0310		+ .721	nla
0450	408 start	+ .759	nla
0610	408 end	+ .770	sfs
0700	409 start	+ .764	
0900		+ .762	(nla)
1400	412 start	+ .761	
1910	415 end	+ .759	
2120	416 start	+ .758	
21-Jun-0210	418 end	+ .757	
0730	422 end	+ .755	
0930	424 start	+ .754	
1740	428 end	+ .751	
1810		+ .751	efs
23-Jun-0930	450 start	- .356	nla
1100	451 start	- .512	nla
1240	452 start	- .603	nla
1320	453 start	- .616	nla
1420	454 start	- .640	nla
1530		- .662	nla
1600	454 end	- .672	sfs
1620	455 start	- .660	
2140	458 start	- .657	
24-Jun-0430	462 start	- .654	
1200	465 end	- .650	
1830	469 end	- .647	
2140		- .645	
25-Jun-0000	472 end	- .644	efs
0040	473 start	- .724	nla
0210	473 end	- .809	sfs
0350	474 end	- .799	
0520	475 end	- .797	efs
0600	476 start	- .230	nla
0720	477 start	- .604	nla
0810		- .751	nla
0840	478 start	- .795	nla
1000	479 end	- .824	sfs
1130	480 start	- .819	
1520	485 end	- .817	
1540	486 start	- .817	
2310	490 start	- .813	

DATE-TIME	RUN	P _T	NOTE
26-Jun-0750	494 end	- .809	
1300		- .806	
1810	495 start	- .804	
27-Jun-0150	499 end	- .800	
1040	506 end	- .796	
1210	507 start	- .795	
1440	508 end	- .794	
1950	509 start	- .791	
2200	510 end	- .790	
2220		- .790	efs
2350	511 start	+ .275	nla
28-Jun-0200		+ .760	nla
0210	511 end	+ .761	nla
0230	512 start	+ .764	nla
0300	513 start	+ .765	sfs
0310		+ .762	
0350		+ .753	
1140	518 end	+ .750	
1230	519 start	+ .750	
1820	522 start	+ .747	
29-Jun-0020	526 start	+ .745	
0750	530 end	+ .743	
1240	531 start	+ .741	
1930	536 start	+ .738	
30-Jun-0200	539 end	+ .736	
0300	540 start	+ .736	
0800	542 end	+ .734	
0920	543 start	+ .734	
1120	545 start	+ .733	
1300	546 start	+ .732	
1840	546 end	+ .730	
1-Jul-0230	551 end	+ .727	
0910	554 end	+ .725	
1200	556 end	+ .724	efs
1510		- .798	sfs
1530	557 start	- .794	
2010	559 start	- .793	
2-Jul-0220	560 end	- .787	
0810	562 end	- .782	
0820		- .782	efs

points of the lookup table. Offline curve fitting of the table shows that the online temperature values used in conjunction with the thermals should be reduced by typically 1-2%, depending on the exact temperature. This correction has been applied to each set of thermals data.

On a few occasions during the two-spin runs, gross instabilities and offsets were observed in the thermometer readout system. Eventually it was noticed that these periods of instability were invariably associated with times of very high humidity in the experimental hall. It appeared that if the ambient humidity rose above some threshold value the readout became unreliable. By the end of the two-spin running period the problem had been traced to some sensitive element(s) on the thermometry amplifier board, and a solution was found, which consisted of spraying the board with a sealant. This solution came too late, however, to ensure the integrity of any of the E-704 thermals data. As will be seen in Sec. C, the sets of thermals taken at various times are mutually consistent, except for the set of 19-June. For this set, the size of the thermal NMR signals was reasonable but the indicated temperature of the beads was higher than normal by $>10\%$. There was no known reason for the dilution refrigerator to equilibrate at a different temperature on this occasion. This, and other internal evidence, strongly suggested that the thermometry was subject to a "humidity error" during that set, and that set of thermals was not used for the online running. It will also be excluded in the final offline analysis, although the data are included in the next section for completeness.

In an unrelated development, by the time that the final set of thermals data was taken on 2-July, a problem with temperature "bursts" of the dilution refrigerator had become so severe that there was concern that a reliable value of temperature could not be assigned for that set. Offline modelling of the spin dynamics shows that this error is very unlikely to be $>1\%$, and a small ($+0.87\%$) temperature correction has been applied to that set for this effect. Also, it should be noted that the thermometry system was recalibrated on 21-June. Because of a different setting of the "offsets," a different algorithm has been used to obtain the offline estimate of the temperature for the 2-July thermals.

Finally, there is a question about the possible heating effect of noise and pickup currents in the thermometer resistors. During the running period, tests suggested that the "beads" thermometer was reading as much as 100% high during the frozen-spin periods i.e., ≈ 100 mK instead of ≈ 50 mK) owing to heating from spurious ac currents. There is no particular reason to believe that these pickup currents were not also present during thermals measurements. However, since the thermals were taken at temperatures near 1 K, and since it is well known that the thermal boundary resistance (Kapitsa effect) is a steep function of temperature (boundary resistance $\propto T^{-n}$, where $n \geq 3$), it is clear that the heating effect for the thermals data is $\ll 1$ mK and is thus entirely negligible.

C. Thermals data

The calibration coefficient for P_T is inversely proportional to a quantity AT , where A is the integrated surface area of the thermal NMR signal and T is the bead temperature during the thermals measurement. Table 2 lists the thermals data acquired online, along with the offline values resulting from the above systematic corrections. The Signal Area values are labeled with NMR coil numbers. Coil No. 1 is at the upstream end of the target, No. 3 at the downstream end. (A coil provided at the middle of the target was inoperative.) Note that the statistical error corresponds to a 2σ value.

Table 2: Thermal equilibrium data.

Date	Online Data		Offline Values		
	Signal Area	T (K)	T (K)	AT	Statistical Error (2σ)
6-May	$A_1=17\ 416$	0.998			
	$A_3=14\ 974$	0.998			
	(used until 13-May)				
	(new damping)				
13-May	$A_1=6271$	1.049	1.038	6509	25
	$A_3=4183$	1.049	1.038	4342	28
	(retune)				
	$A_1=6278$	1.047	1.036	6504	50
	$A_3=4164$	1.047	1.036	4314	75
	(used until 31-May)				
	(retune)				
31-May	$A_1=6183$	1.065	1.040	6430	65
	$A_3=4017$	1.065	1.040	4178	81
	(used until 2-July)				
19-June	$A_1=6053$	1.228	1.192	7215	78
	$A_3=4015$	1.228	1.192	4786	71
	(not used)		(not used)		
2-July	$A_1=5864$	1.057	1.104	6471	60
	$A_3=3883$	1.042	1.089	4230	89

Examination of the offline-corrected values of AT leads one to the conclusion that, with the exception of the 19-June thermals already noted previously, the NMR system was reasonably stable over the two-spin running period. The extent to which

Table 3: Offline correction coefficients for P_T .

Dates applicable	Offline multiplier
11-May to 13-May	$M_1 = 0.998(17416)/[1.038(6271)] = 2.670 \pm 0.010$ $M_3 = 0.998(14974)/[1.038(4183)] = 3.442 \pm 0.022$
13-May to 31-May	$M_1 = 1.047/1.036 = 1.011 \pm 0.008$ $M_3 = 1.047/1.036 = 1.011 \pm 0.018$
31-May to 19-June	$M_1 = 1.065/1.040 = 1.024 \pm 0.010$ $M_3 = 1.065/1.040 = 1.024 \pm 0.020$
19-June to 2-July	$M_1 = 1.065(6183)/[1.104(5864)] = 1.018 \pm 0.009$ $M_3 = 1.065(4017)/[1.089(3883)] = 1.011 \pm 0.021$

some of the error bars do not overlap is fairly typical of the "drift" experienced with this type of system for these kinds of time intervals.

Using the information in Table 2, the offline correction coefficients (multipliers, M_i) for the online P_T -values are developed in Table 3. The information from the thermals sets of 13-May (second set) and 31-May has been used directly for the respective subsequent running periods. The information from 13-May (first set, before the NMR retune) has been used retrospectively for the earliest runs, and the information from 2-July has been used retrospectively back to 19-June. The 19-June data have been rejected both online and offline, as noted in Sec. B. With the exception of the first two days of data-taking, there are only modest deviations from unity. For a major part of the running time (13-May to 19-June), the only correction applied is that for the "curvature" of the thermometer lookup table. The only uncertainties included here on the M_i are the 2σ sampling errors carried forward from Table 2.

D. Maximum polarizations

Examination of the maximum polarizations attained for each NMR coil, on various occasions, can give some idea of the overall relative consistency of the results and also of the uniformity of the polarization within the target. Table 4 lists the values of polarization attained in both coils at the beginning of selected frozen-spin series. The online values have been corrected with the M_i of Table 3. The following conclusions can be drawn from these data:

1. There are no evident gross trends as a function of time. The fluctuations among the values corresponding to different occasions are probably mainly due to such factors as differences in the times allotted for the polarization

Table 4: Maximum attained polarizations for each coil.

DATE	P_1	P_3
11-May	-.788	-.781
14	+.801	+.809
15	-.835	-.822
17	+.751	+.767
20	+.774	+.787
22	-.840	-.831
5-June	+.780	+.788
7	-.823	-.777
10	+.778	+.770
11	-.798	-.787
16	+.798	+.813
17	-.807	-.796
20	+.778	+.763
25	-.822	-.826
28	+.766	+.764
1-July	-.797	-.800

buildup, differing degrees of experience of the target operators, and differing degrees of “plugging” of the refrigerator.

2. The mean value for negative P_T is $\langle P(-) \rangle = -0.808 \pm 0.005$, and for positive, $\langle P(+) \rangle = +0.780 \pm 0.005$, where the uncertainties are 1σ . The difference is consistent with our online experience that slightly greater negative values could be attained for a given amount of effort.
3. The mean absolute value for coil 1 is $\langle |P_1| \rangle = 0.796 \pm 0.006$, and for coil 3, $\langle |P_3| \rangle = 0.793 \pm 0.006$. Thus, there is no significant difference between the target ends, on the whole. However, there are individual instances where the end-values were significantly different, such as on 7-June and on 23-June (the latter case has not been included in Table 4).

E. Treatment of frozen-spin data from coil 1

The online P_T -information has two general deficiencies. First, NMR signals from both coils were not always taken at the end of frozen-spin running, after returning the target magnet to the n/a position. On some occasions, neither coil was registered. Second, examination of the complete data set indicates that a measurable fraction of

the P_T -decay during frozen-spin usually occurred right at the beginning, i.e., while the dilution refrigerator was cooling down. These deficiencies are partially offset by the fact that coil-1 data were taken at fairly regular intervals during the frozen-spin condition. (Since the magnet z-offset was ≈ 15 cm, coil 1, but not coil 3, remained in a reasonably uniform field during frozen-spin.) In principle, these data can be used to help fill in the missing records, but it is necessary to ascertain that there is no systematic discrepancy between the two types of coil-1 data.

The online record does contain a number of instances in which, near the end of a frozen-spin period, proximate data were taken for both frozen-spin (la) and polarizing (nla) positions, for coil 1. Averages of these cases give the following results:

$$\begin{aligned}\langle P_1(\text{la})/P_1(\text{nla}), (-) \rangle &= 1.0036 \pm 0.0028, \\ \langle P_1(\text{la})/P_1(\text{nla}), (+) \rangle &= 1.0035 \pm 0.0024, \\ \langle P_1(\text{la})/P_1(\text{nla}), \text{all} \rangle &= 1.0036 \pm 0.0017,\end{aligned}$$

where the uncertainties are 1σ . The ratio does not depend on the sign of the polarization and is barely significantly different from unity.

F. Comparison of overall decay rates for the two coils

The online record has several instances in which coil 3 was not registered at the end of frozen-spin. Since the best estimate of P_T is the mean of the two end-values, it is desirable to see if the missing coil-3 records can be estimated from the available coil-1 data combined with the coil-3 measurements taken at the start of frozen-spin. The basic issue here is the relationship between the polarization decay rates for the two coils.

Table 5 lists the ten instances throughout E-704 in which NMR data for both coils is available for both sfs and efs. The time interval between sfs and efs is Δt . The polarization decay rate for each coil is estimated as the logarithmic derivative. Although there is a lot of scatter in the rates, it is clear by inspection that there is a fair degree of correlation between the rates for the two coils. Furthermore, the mean rates for the two coils do not differ significantly: $\langle -\Delta P_1/P_1 \Delta t \rangle = 2.03 \pm 0.41$ %/day, and $\langle -\Delta P_3/P_3 \Delta t \rangle = 2.01 \pm 0.38$ %/day, where the uncertainties are 1σ and the two cases with $\Delta t < 0.7$ day have been excluded. The implication is that the decay rate observed for coil 1 is a good predictor of the coil-3 rate. This is actually a bit surprising, if true, since the "holding" fields at the ends of the target differ substantially (2.5 T at coil 1 vs ≈ 2.0 T at coil 3), and the decay rate is expected to be approximately inversely proportional to the field at these temperatures. Of course, this expected dispersion could easily be masked by the uncertainties.

If it is assumed that the data for the two coils can be binned together, the combined mean decay rate is $\langle -\Delta P_T/P_T \Delta t \rangle = 2.02 \pm 0.26$ %/day.

Table 5: Polarization decay rates based on sfs, efs measurements.

DATE	P_1		P_3		Δt (days)	$-\Delta P_1/P_1 \Delta t$ (%/day)	$-\Delta P_3/P_3 \Delta t$ (%/day)
	sfs	efs	sfs	efs			
11-May	-.788	-.782	-.781	-.781	0.465	1.64	0.00
11-12-May	+.684	+.673	+.685	+.664	1.118	1.44	2.74
15-17-May	-.835	-.791	-.822	-.773	1.708	3.09	3.49
5-7-June	+.780	+.772	+.788	+.778	2.555	0.40	0.50
10-11-June	+.778	+.776	+.770	+.771	0.688	0.37	-0.19
11-15-June	-.798	-.746	-.787	-.750	4.563	1.43	1.03
16-17-June	+.798	+.760	+.813	+.779	1.444	3.30	2.90
25-27-June	-.822	-.788	-.826	-.793	2.514	1.65	1.59
28-June-							
1-July	+.766	+.725	+.764	+.724	3.375	1.59	1.55
1-2-July	-.797	-.778	-.800	-.787	0.715	3.33	2.27

G. Frozen-spin polarization decay rates for coil 1

As mentioned previously, it appears that there was a measurable transient decay at the onset of frozen-spin conditions. It is of interest to derive decay rates from the post-sfs data taken at various intervals for coil 1, selecting only data points taken ≈ 20 min or more after the establishment of frozen-spin. The result of such an exercise is shown in Table 6. The decay rate is obtained by a linear regression analysis on the indicated number of points n for each case. Here, again, Δt is the total time spanned. The mean values are:

$$\text{decay rate } (-) = 1.61 \pm 0.18 \text{ \%/day,}$$

$$\text{decay rate } (+) = 1.37 \pm 0.33 \text{ \%/day,}$$

$$\text{decay rate (all)} = 1.51 \pm 0.16 \text{ \%/day,}$$

where the uncertainties are 1σ and the two cases with $\Delta t < 0.7$ day have again been excluded. The $(-, +)$ rates do not differ significantly. The combined mean decay rate is significantly smaller than the rates derived in Sec. F, which included the effect of initial transients.

Comparison of this decay rate with previously published values is made difficult by the fact that there are very few examples of frozen-spin at 2.5 T. The measurement by de Boer and Niinikoski [NIM 114, (1974) 495] would give the above decay rate at a temperature of 50–60 mK, but that is for a propanediol target. Bernard *et al.* [NIM A249, (1986) 176] have measured 1-pentanol (the same material as for E-704) up to fields of ≈ 0.5 T. Plausible extrapolation of their values would yield

Table 6: Coil-1 polarization decay rates excluding the initial transient.

Date (efs)	Target sign	n	Δt (days)	Correlation coefficient	Decay rate (%/day)
12-May	+	7	1.090	0.907	1.11
17	-	7	1.410	0.989	1.21
20	+	18	2.813	0.980	1.79
21	+	3	0.514	0.9995	1.02
23	-	6	1.020	0.947	1.32
7-June	+	15	2.208	0.533	0.47
9	-	9	1.784	0.930	1.74
11	+	4	0.674	-0.429	-0.73
15	-	21	4.347	0.965	1.09
17	+	8	1.423	0.936	2.58
19	-	8	1.840	0.979	1.61
21	+	10	1.465	0.941	1.12
25	-	7	1.319	0.997	1.86
27	-	14	2.452	0.993	1.44
1-July	+	18	3.340	0.993	1.13
2	-	5	0.701	0.983	2.61

a temperature of 110 mK or higher for the above decay rate. It is worth noting that the entries of 15-June and 1-July in Table 6, which are potentially the most accurate owing to the long times spanned, have rates that are noticeably less than the global mean.

H. Workup of the best estimates of P_T

Table 7 shows the worksheet for P_T . For ease of analysis, time-of-day has been converted to a decimal value "DAYS." The mean result for the two coils (the best estimate of P_T) is tabulated here as " $\langle P_1, P_3 \rangle_{av}$ " and is the value that appears in the summary, Table 1. The "NOTE" column contains some supplemental information that does not appear in Table 1.

In Table 7, the P_i -values that are not enclosed in delimiters are the online values, corrected by the M_i of Table 3. The P_1 -values enclosed in "(...)" are the online $1a$ -values corrected by the combined factor $M_1/1.0036$ (see Sec. E). Where online efs -data for coil 3 are lacking, the P_3 -values enclosed in "{...}" have been estimated from the corresponding sfs -data by assuming the same relative amount of decay as measured on coil 1 (see Sec. F). In a few instances during the polarization buildups, the P_3 -values enclosed in "{{...}}" have been inferred from the NMR chart-

Table 7: Target polarization worksheet.

DATE-TIME	DAYS	RUN	CORR. P ₁	CORR. P ₃	(P ₁ , P ₃) _{av}	NOTE
11-May-0430	11.188		-.788	-.781	-.784	sfs
1230	11.521	125 start			(.784)	
1540	11.653	127 end	-.782	-.781	-.784	efs
1920	11.806		+.611	+.633	+.622	nla
1940	11.819	129 start	.654		(.657)	nla
1950	11.826		.668	.668	.668	nla
2010	11.840		.681	.688	.685	nla
2040	11.861	129 end	.684	.685	.684	sfs
2120	11.889	130 start	(.681)		[.677]	
12-May-0250	12.118	135 end	(.676)		[.675]	
1000	12.417	141 start	(.674)		[.673]	
1710	12.715	143 end	(.672)		[.671]	
1800	12.750	144 start	(.672)		[.671]	
2140	12.903	146 end	(.671)		[.670]	
2330	12.979		+.673	+.664	+.669	efs
15-May-1620	15.681		-.835	-.822	-.829	sfs
1650	15.701		(.827)		(.821)	(high temperature)
2330	15.979	147 start	(.805)		[.796]	
16-May-0650	16.285	153 end	(.802)		[.793]	
1330	16.563	156 start	(.800)		[.790]	
1930	16.813	160 start	(.797)		[.788]	
17-May-0220	17.097	165 start	(.796)		[.785]	
0850	17.368	169 end	(.791)		[.782]	
0920	17.389		-.791	-.773	-.782	efs
1650	17.701	170 start	+.751	+.767	+.759	nla
1720	17.722	170 end	.751	.767	.759	sfs(nla)
1810	17.757	171 end			(.758)	nla
2300	17.958		.737	.764	.751	nla
2340	17.986	172 start			(.751)	nla
18-May-0200	18.083	175 start			(.749)	nla
0310	18.132		.735	.761	.748	nla
0440	18.194		.735	.764	.750	nla
0750	18.326		.737	.764	.751	nla
1010	18.424		.734	.761	.748	nla
1150	18.493		.731	.757	.744	nla
1650	18.701	195 start	.733	.753	.743	nla (replaced
2150	18.910	188 start		.743	[.738]	nla H4P1
2230	18.938			.745	[.738]	→la membranes)
2340	18.986	188 end	(.723)		[.737]	
19-May-0340	19.153	191 start	(.717)		[.735]	
0850	19.368	195 end	(.715)		[.732]	
1240	19.528	198 end	(.716)		[.730]	
1400	19.583	199 start	(.716)		[.729]	
1640	19.694	200 start	(.715)		[.727]	
2230	19.938	203 end	(.714)		[.724]	
20-May-0600	20.250	208 start	(.707)		[.720]	
1430	20.604	213 end	(.705)		[.715]	

DATE-TIME	DAYS	RUN	CORR. P ₁	CORR. P ₃	(P ₁ , P ₃) _{av}	NOTE
20-May-1630	20.688	215 start	(.703)		[.714]	
1830	20.771	216 end	(+.702)	{+.725}	[+.713]	efs
1840	20.778	217 start	+.706		(+.713)	nla
1930	20.813	218 start	.722		(.729)	nla
2240	20.944	219 end	.770	.785	.777	nla
2320	20.972	220 start	.774	.787	.780	sfs
21-May-0200	21.083	223 start	(.765)		[.771]	
0830	21.354	228 start	(.763)		[.769]	
1420	21.597	231 end	+.761	{+.774}	[+.767]	efs
22-May-0240	22.111		-.471	-.461	-.466	nla
0300	22.125	234 start	.554		(.549)	nla
0430	22.188	235 start	.751		(.747)	nla
0600	22.250	235 end	.810	.802	.806	nla
0720	22.306	236 end	.840	.831	.836	sfs
0730	22.313	237 start	(.835)		(.831)	
1240	22.528	239 end	(.829)		[.827]	
1320	22.556	240 start	(.829)		[.827]	
1940	22.819	243 start	(.826)		[.824]	
23-May-0200	23.083	247 end	(.825)		[.821]	
0800	23.333	251 end	(-.822)	{-.813}	[-.818]	efs
5-Jun-0230	5.104	252 start	+.774	+.778	+.776	nla
0330	5.146		.780	.788	.784	sfs(nla)
0350	5.160	252 end			(.784)	nla
0520	5.222	253 end			(.785)	nla
1150	5.493		.785	.793	.789	nla
1450	5.618	254 start	.779	.786	.783	nla
1700	5.708	255 end			(.776)	nla
1810	5.757		.769	.775	.772	nla
1930	5.813	256 start			[.782]	nla
2020	5.847	256 end		.791	[.782]	nla
2130	5.896		(.783)		[.782]	→la
6-Jun-0110	6.049	257 start	(.777)		[.781]	
0550	6.243	259 end	(.776)		[.780]	
0640	6.278	"547" end	(.776)		[.780]	
1200	6.500	261 start	(.779)		[.779]	
1710	6.715	265 start	(.777)		[.779]	
1840	6.778	266 end	(.776)		[.778]	
2100	6.875	267 start	(.767)		[.778]	
7-Jun-0200	7.083	270 start	(.771)		[.777]	
0840	7.361	273 end	(.773)		[.776]	
1410	7.590	277 end	(.775)		[.775]	
1650	7.701		+.772	+.778	+.775	efs
1920	7.806		-.740	-.673	-.707	nla
2010	7.840	279 start	.794		(.768)	nla
2120	7.889	280 start	.823	.777	.800	sfs
2200	7.917		(.818)		[.794]	
8-Jun-0450	8.201	285 start	(.812)		[.790]	
1310	8.549	289 end	(.812)		[.785]	

DATE-TIME	DAYS	RUN	CORR. P ₁	CORR. P ₃	(P ₁ , P ₃) _{av}	NOTE
8-Jun-2010	8.840	297 end	(.800)		[.781]	
9-Jun-0350	9.160	302 end	(.795)		[.776]	
0520	9.222	303 start	(.795)		[.776]	
1200	9.500	308 start	(.801)		[.772]	
1620	9.681	310 end	(.792)		[.769]	
1650	9.701	311 end	(-.791)	{-.747}	[-.769]	efs
10-Jun-0550	10.243		+.745	+.756	+.751	nla
0640	10.278	319 start	.766		(.765)	nla
0710	10.299		.776	.767	.772	nla
0740	10.319		.778	.770	.774	sfs
0800	10.333	320 start	(.769)		[.774]	
1450	10.618	325 start	(.768)		[.774]	
2240	10.944	328 end	(.767)		[.774]	
11-Jun-0010	11.007	329 end	+.776	+.771	+.774	efs
0120	11.056	330 start	-.737	{{-.707}}	(-.722)	nla
0150	11.075	330 end	.799	{{.769}}	(.784)	nla
0210	11.090	331 start	.798	.787	.793	sfs
0225	11.101		(.797)		(.792)	
0720	11.306	336 start	(.785)		[.785]	
1410	11.590	339 end	(.781)		[.783]	
1530	11.646	340 start	(.780)		[.782]	
2100	11.875	343 end	(.776)		[.780]	
12-Jun-0200	12.083	348 end	(.772)		[.779]	
0440	12.194	349 start	(.769)		[.778]	
0650	12.285	350 end	(.768)		[.777]	
1140	12.486		(.766)		[.775]	
2000	12.833		(.763)		[.772]	
13-Jun-0400	13.167		(.760)		[.769]	
1200	13.500		(.769)		[.766]	
2000	13.833		(.765)		[.764]	
14-Jun-0400	14.167		(.758)		[.761]	
1120	14.472	351 start	(.756)		[.758]	
1850	14.785	355 end	(.751)		[.755]	
15-Jun-0010	15.007	359 start	(.749)		[.754]	
0550	15.243	362 end	(.745)		[.752]	
0630	15.271	363 start	(.745)		[.751]	
1430	15.604	369 end	(.742)		[.748]	
1500	15.625	370 end	(.742)		[.748]	
1540	15.653		.746	.750	.748	nla
1720	15.722	371 start			(.746)	nla
2000	15.833	373 end			(.742)	nla
2330	15.979		-.733	-.741	-.737	efs
16-Jun-0250	16.118	374 start	+.798	+.813	+.805	nla
0310	16.132	375 start			(.805)	sfs
0340	16.153	377 start	(.789)		[.799]	
0850	16.368	380 end	(.785)		[.795]	
1430	16.604	383 end	(.777)		[.790]	
1810	16.757	384 start	(.765)		[.787]	

DATE-TIME	DAYS	RUN	CORR. P ₁	CORR. P ₃	(P ₁ , P ₃) _{av}	NOTE
17-Jun-0030	17.021	387 end	(.767)		[.781]	
0730	17.313	392 start	(.761)		[.775]	
1210	17.507		(.761)		[.771]	
1350	17.576	395 end	+.760	+.779	+.770	efs
1810	17.757	399 start	-.807	-.796	-.801	sfs
1820	17.764		(.804)		(.798)	
2150	17.910	400 start	(.798)		[.792]	
18-Jun-0310	18.132	402 end	(.792)		[.790]	
0840	18.361	405 end	(.788)		[.787]	
1210	18.507	407 end	(.788)		[.785]	
2000	18.833		(.781)		[.781]	(replaced H4P2 membrane)
19-Jun-0400	19.167		(.779)		[.776]	
1220	19.514		(.774)		[.772]	
1800	19.750		-.774	{-.763}	[-.769]	efs
20-Jun-0310	20.132		+.708	+.734	+.721	nla
0450	20.201	408 start	.768		(.759)	nla
0610	20.257	408 end	.778	(.763)	(.770)	sfs
0700	20.292	409 start	(.773)		[.764]	
0900	20.375		.770	.755	.762	(brief nla)
1400	20.583	412 start	(.769)		[.761]	
1910	20.799	415 end	(.769)		[.759]	
2120	20.889	416 start	(.767)		[.758]	
21-Jun-0210	21.090	418 end	(.765)		[.757]	
0730	21.313	422 end	(.767)		[.755]	
0930	21.396	424 start	(.763)		[.754]	
1740	21.736	428 end	(.760)		[.751]	
1810	21.757		+.757	+.745	+.751	efs
23-Jun-0930	23.396	450 start	-.411	{{-.301}}	(-.356)	nla
1100	23.458	451 start	.567		(.512)	nla
1240	23.528	452 start	.658		(.603)	nla
1320	23.556	453 start	.671		(.616)	nla
1420	23.597	454 start	.695		(.640)	nla
1530	23.646		.717	.607	.662	nla
1600	23.667	454 end	.722	.622	.672	sfs
1620	23.681	455 start	(.710)		[.660]	
2140	23.903	458 start	(.706)		[.657]	
24-Jun-0430	24.188	462 start	(.703)		[.654]	
1200	24.500	465 end	(.699)		[.650]	
1830	24.771	469 end	(.696)		[.647]	
2140	24.903		(.693)		[.645]	
25-Jun-0000	25.000	472 end	-.692	{-.596}	[-.644]	efs
0040	25.028	473 start	-.753		(-.724)	nla
0210	25.090	473 end	.818	.800	.809	sfs
0350	25.160	474 end	(.808)		[.799]	
0520	25.222	475 end	(-.806)	{-.788}	[-.797]	efs
0600	25.250	476 start	-.233		(-.230)	nla
0720	25.306	477 start	.612		(.604)	nla

DATE-TIME	DAYS	RUN	CORR. P ₁	CORR. P ₃	(P ₁ , P ₃) _{av}	NOTE
25-Jun-0810	25.340		.761	.741	.751	nla
0840	25.361	478 start	.798		(.795)	nla
1000	25.417	479 end	.822	.826	.824	sfs
1130	25.479	480 start	(.816)		[.819]	
1520	25.639	485 end	(.814)		[.817]	
1540	25.653	486 start	(.814)		[.817]	
2310	25.965	490 start	(.807)		[.813]	
26-Jun-0750	26.326	494 end	(.805)		[.809]	
1300	26.542		(.804)		[.806]	
1810	26.757	495 start	(.803)		[.804]	
27-Jun-0150	27.076	499 end	(.796)		[.800]	
1040	27.444	506 end	(.793)		[.796]	
1210	27.507	507 start	(.792)		[.795]	
1440	27.611	508 end	(.790)		[.794]	
1950	27.826	509 start	(.787)		[.791]	
2200	27.917	510 end	(.786)		[.790]	
2220	27.931		-.788	-.793	-.790	efs
2350	27.993	511 start	+.274		(+.275)	nla
28-Jun-0200	28.083		.757	.763	.760	nla
0210	28.090	511 end	.759		(.761)	nla
0230	28.104	512 start	.765		(.764)	nla
0300	28.125	513 start	.766	.764	.765	sfs
0310	28.132		(.763)		(.762)	
0350	28.160		(.758)		[.753]	
1140	28.486	518 end	(.753)		[.750]	
1230	28.521	519 start	(.753)		[.750]	
1820	28.764	522 start	(.751)		[.747]	
29-Jun-0020	29.014	526 start	(.748)		[.745]	
0750	29.326	530 end	(.746)		[.743]	
1240	29.528	531 start	(.744)		[.741]	
1930	29.813	536 start	(.742)		[.738]	
30-Jun-0200	30.083	539 end	(.740)		[.736]	
0300	30.125	540 start	(.739)		[.736]	
0800	30.333	542 end	(.738)		[.734]	
0920	30.389	543 start	(.737)		[.734]	
1120	30.472	545 start	(.737)		[.733]	
1300	30.542	546 start	(.737)		[.732]	
1840	30.778	546 end	(.736)		[.730]	
1-Jul-0230	1.104	551 end	(.732)		[.727]	
0910	1.382	554 end	(.729)		[.725]	
1200	1.500	556 end	+.725	+.724	+.724	efs
1510	1.632		-.797	-.800	-.798	sfs
1530	1.646	557 start	(.793)		(.794)	
2010	1.840	559 start	(.786)		[.793]	
2-Jul-0220	2.097	560 end	(.783)		[.787]	
0810	2.340	562 end	(.777)		[.782]	
0820	2.347		-.778	-.787	-.782	efs

recorder trends. The values of $\langle P_1, P_3 \rangle_{av}$ enclosed in "[...]" were derived by back-extrapolating the efs-value using the slope of decay exhibited by the corresponding P_1 -measurements (see Table 6). The remaining values of $\langle P_1, P_3 \rangle_{av}$ enclosed in "<...>" are interpolations of the surrounding data, mainly nla-measurements taken during the buildups.

I. Error estimates

The estimated total uncertainty on the polarization is $\pm 6.5\%$, consisting of the following contributions:

a) Temperature of thermals	4.5%
b) Statistical uncertainties of thermals	1.5%
c) NMR background	1.0%
d) Spatial uniformity of polarization	3.0%
e) NMR nonlinearity	1.0%
f) Residual NMR drift	2.2%
g) Errors of interpolation/extrapolation	2.0%

These contributions are (mostly) symmetric and uncorrelated, so they have been added in quadrature. Contribution (a) arises from uncertainty in the thermometer lead resistance and calibration of the thermometry software. Contribution (b) is typical for the 2σ errors of Table 2. Contribution (c) is based on past experience with clean target-holder structures made of Teflon. Concerning contribution (d), as was seen in Sec. D, the global averages of the peak polarizations measured on the two end coils are in close agreement, $\langle |P_1| \rangle = 0.796 \pm 0.006$ vs $\langle |P_3| \rangle = 0.793 \pm 0.006$. Differences of 10% or more between the two coils were sometimes seen during buildups, however, these observable differences are accounted for in Table 1 by the averaging of the results for the two coils. The additional allowance of 3% is included above mainly in consideration of the fact that data from the center NMR coil were unavailable. Contribution (e) is known to be typical for NMR detectors of the Liverpool type. Contributions (f) and (g) are estimated from the levels of internal consistency of the results.

Note that the first three contributions are pure *scaling* errors on P_T . Therefore, at least for the purpose of comparisons within a given "thermals" period, and to a considerable extent even globally, these uncertainties do not contribute to the error analysis for measurements that depend only on the ratio of the two signs of polarization, $P_T(+)/P_T(-)$. The estimated total uncertainty on the ratio is thus $\pm 4.3\%$.

It should be stressed that all of the above uncertainties are considered to be " 2σ " estimates, i.e., they represent the maximum likely excursions.

END

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