G_E^n Cell Inventory

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Abstract

This is a cell inventory for G_E^n. It includes everything[1].

Contents

1 Introduction

These cells are filled with ^{3}He, N_2, and an alloy of Rb and K.

Typical parameters for a cell were chosen along time ago by someone. Typical cells from SLAC and JLAB will be used as a benchmark for comparison. The parameters for an "average" cell of each type is listed in table blah. Note that we strictly define room temperature as 23 °C = 296.15 K.

We fill the cell with as much ^{3}He as we can. The limit is for the most part one of mechanical strength of the cell. We know from historical experience that there is a strong correlation between the operating cell pressure and the in beam explosion probability. The traditional goal is about 8.75 amg for a 2.5 in diameter pumping chamber, 40 cm long cell that will be operated at a gas temperature of 220 °C $\pm$ 30 °C. Note that this corresponds to a operating cell pressure of about 13 atm.

We fill the cell with N_2:

1. A greater N_2 density results in increased nonradiative quenching. In theory, this is desirable for improving the optical pumping process.

2. A greater N_2 density results in more background and/or dilution. In theory, this is undesirable for the nuclear physics.

[1]only in the Breit Frame

Parameter	SLAC-E154	JLAB-E94010	$\mathbf{JLAB - A_n^1}$	units
^{3}He density	8.83 ± 0.06	9.62 ± 1.08	8.69 ± 0.43	amagat
N_2 density	0.0776 ± 0.0017	?	0.0824 ± 0.0104	amagat
Goal N_2 pressure	60(0.0723)	80(0.0964)	70(0.0844)	torr at 23°C (amagat)
Total Volume	185.4 ± 4.7	202.5 ± 10.5	172.6 ± 1.0	cc
PC outer diameter	1.45 ± 0.03	2.50 ± 0.13	2.65 ± 0.08	inches
PC max path length	3.47 ± 0.25	2.46 ± 0.05	2.53 ± 0.03	inches
PC volume	75.0 ± 5.9	106.5 ± 8.6	116.4 ± 0.3	cc
PC gas temperature	191.7 ± 7.5	219.3 ± 8.5	231.7 ± 8.0	°C
PC ^{3}He density	7.31 ± 0.07	7.85 ± 1.25	7.49 ± 0.52	amagat
PC N_2 density	0.0642 ± 0.0020	0.0787 ± 0.003	0.0711 ± 0.0127	amagat
TC length	29.8 ± 0.3	39.6 ± 0.6	25.6 ± 0.4	cm
TC volume	106.0 ± 4.9	89.9 ± 4.8	52.3 ± 1.2	cc
TC gas temperature	69.9 ± 4.4	57.1 ± 5.0	60.0 ± 5.0	°C
TC ^{3}He density	9.91 ± 0.09	11.7 ± 1.86	11.4 ± 0.8	amagat
TC N_2 density	0.0871 ± 0.0027	0.117 ± 0.004	0.108 ± 0.008	amagat
Operating Pressure	12.5 ± 0.2	14.3 ± 2.3	14.0 ± 1.0	atm
Radiative Decay	6.05%	4.86%	5.96%	pct of all decays
N_2 Fraction	0.871%	1.00%	0.948%	pct of total atoms

Table 1: Typical Parameters for past cells. Data taken from theses of M. Romalis, S. Jensen, I. Kominis, K. Kramer, and X. Zheng

3. A greater N_2 density results in greater suppression of one form of beam induced depolarization. In theory, this is desirable for the nuclear physics.

The standard balance struck between the above considerations is to fill the cell with about 70 torr of N_2 at room temperature. This corresponds to a density of 0.0844 amg. Under these conditions, the fraction of Rb atoms that decay through radiation is about 6%.

2 Cell History

With the exception of Panache, large PC cells with be given names that have been traditionally considered female. Small PC cells with be given names that have been generally considered male. With the exception of Panache, cells will be named in alphabetical order.

2.1 Panache

This our first hybrid large PC cell.

2.2 Anna

This is our second hybrid large PC cell.

2.3 Barbara

This is our third hybrid large PC cell.

Cell	Fill Date	Polarization	Lifetime	^{3}He	N_2	K:Rb	Glassblower	Filler
		(max EPR)	(hrs)	(amg)	(amg)	(solid)		
Panache	12/19/04	43	55/35	8.02	0.0857	1.00%	Mike	UVa
Anna	03/24/05	-	-	8.05	0.0880	-	Mike	UVa
Barbara	04/09/05	-	-	7.61	0.1110	-	Mike	UVa

Table 2: Main Summary

Cell	T2P	PCV	PCH	TTL	TTD	PC2TC	TCL	TCD
Panache								
Anna								
Barbara								

Table 3: External Dimensions

3 Data

3.1 Summary

3.2 Dimensions

3.3 Volumes

3.4 ^{3}He Pressures and Densities

Ignoring the transfer tube, the total number of atoms in the pumping chamber (subscript p) and the target chamber (subscript t) can be written as the following (using the ideal gas law):

$$n_p V_p + n_t V_t = n\left(V_p + V_t\right) \tag{1}$$

When the two chambers are at equilibrium, the pressure throughout the cell is constant:

$$P = n_p R T_p = n_t R T_t \tag{2}$$

Using these two formulas, the densities in the two chambers $n_{\mathrm{p,t}}$ can be calculated:

$$\frac{n_p}{n} = \left[1 + \frac{V_t}{V_p + V_t}\left(\frac{T_p}{T_t} - 1\right)\right]^{-1} \tag{3}$$

$$= \left[\frac{T_p}{T_t} + \frac{V_p}{V_p + V_t}\left(1 - \frac{T_p}{T_t}\right)\right]^{-1} \tag{4}$$

$$\frac{n_t}{n} = \left[1 + \frac{V_p}{V_p + V_t}\left(\frac{T_t}{T_p} - 1\right)\right]^{-1} \tag{5}$$

$$= \left[\frac{T_t}{T_p} + \frac{V_t}{V_p + V_t}\left(1 - \frac{T_t}{T_p}\right)\right]^{-1} \tag{6}$$

where n is the density throughout the cell at a uniform temperature.

Cell	Win	Win	Wall	Wall	Wall	Wall	Wall	Wall	Wall	Wall	Wall	Wall
	Dot		A	B	C	D	E	F	G	H	I	J
Panache												
Anna												
Barbara												

Table 4: Cell Thickness Data

Cell	Archimedes	Gas System	Ext Dim	PC	TT	TC
Panache		399.1	406.8	321.9	5.08	79.8
Anna		384.8	413.2	325.9	4.67	82.6
Barbara		391.3	416.6	326.6	5.00	85.0

Table 5: Internal Cell Volumes

Temp °C	Room	Room	215	215	215	235	235	235	255	255	255
Cell	dens	press	press	PC	TC	press	PC	TC	press	PC	TC
Panache	8.02	8.65	13.2	7.40	10.5	13.6	7.32	10.8	14.0	7.24	11.1
Anna	8.06	8.73	13.3	7.42	10.6	13.7	7.34	10.9	14.0	7.26	11.2
Barbara	7.61	8.23	12.5	7.00	9.95	12.9	6.92	10.3	13.2	6.85	10.5

Table 6: Cell pressures (press in atm) and densities (in amg) in the pumping chamber (PC) and target chamber (TC) at different temperatures

3.5 N_2 Nonradiative Quenching and Densities

From Happer's Optical Pumping RMP review paper, the cross sections for nonradiative decay for Rb by N_2 are:

$$\sigma_{\mathrm{D1}} = 58 \times 10^{-20}\ \mathrm{m}^2 \tag{7}$$

$$\sigma_{\mathrm{D2}} = 42.5 \times 10^{-20}\ \mathrm{m}^2 \tag{8}$$

The propbability of decay per unit time is given by:

$$\Gamma_{\mathrm{q}} = [\mathrm{N}_2]\sigma_{\mathrm{q}} \langle v_{\mathrm{rel}} \rangle \tag{9}$$

where mean relative thermal velocity is:

$$\langle v_{\mathrm{rel}} \rangle = \sqrt{\frac{8kT}{\pi\mu}} \tag{10}$$

$$\frac{1}{\mu} = \frac{1}{m_{\mathrm{N}_2}} + \frac{1}{m_{\mathrm{Rb}}} \tag{11}$$

This calculation assumes that the cross section is independant of temperature. Under typical conditions, $\langle v_{\mathrm{rel}} \rangle \approx 700\ \frac{\mathrm{m}}{\mathrm{s}}$ and $\Gamma_{\mathrm{q}} \approx 2$ ns. The spontaneous radiation decay lifetime from NIST Atomic Spectra Database for Rb are:

$$\Gamma^{-1}_{\mathrm{D1-spontaneous}} = 27.70\ \mathrm{ns} \tag{12}$$

$$\Gamma^{-1}_{\mathrm{D2-spontaneous}} = 26.25\ \mathrm{ns} \tag{13}$$

$$\tag{14}$$

The fraction of Rb atoms that decay by radiative transitions:

$$f_r = \frac{\Gamma_{\mathrm{spontaneous}}}{\Gamma_{\mathrm{spontaneous}} + \Gamma_{\mathrm{q}}} \tag{15}$$

I am assuming that the stimulated emission rate is negligible. Since collisions mix the exited P states, the average of the radiative fraction for the D1 and D2 transitions is quoted.

3.6 Alkali Content

To estimate the vapor ratio of an alkali alloy, we'll use Raoult's law. This says that vapor pressure for an element in a uniform and homogenous mixture, p_a, is equal to the mole fraction of the element in the mixture, f_a, times the vapor pressure for the pure element, p_a^0:

$$p_a = f_a p_a^0 \tag{16}$$

Cell	% N2	Room	215	215	235	235	255	255
		Press (torr)	% Rad	amg	% Rad	amg	% Rad	amg
Panache	1.06	70.4	4.86	0.0791	4.82	0.0783	4.78	0.0774
Anna	1.08	72.5	4.75	0.0810	4.71	0.0802	4.67	0.0793
Barbara	1.44	91.3	3.81	0.1021	3.78	0.1010	3.75	0.0999

Table 7: Radiative decay fractions and N_2 densities in the pumping chamber at different temperatures

Element	A	B
Na	4.704	5377 K
K	4.402	4453 K
Rb	4.312	4040 K

Table 8: Vapor pressure coefficients (above liquid) for selected alkali metals from 1995 CRC

This gives a vapor density ratio of:

$$D = \frac{n_a}{n_b} = \frac{\frac{p_a}{RT}}{\frac{p_b}{RT}} = \frac{p_a}{p_b} = \frac{f_a p_a^0}{f_b p_b^0} = \left(\frac{1-f_b}{f_b}\right)\frac{p_a^0}{p_b^0} = \left(\frac{1}{f_b} - 1\right) D_0 \tag{17}$$

If f_b is the mole fraction of Rb in the solid alloy and D_0 is the K:Rb pure vapor ratio, the D is the vapor density ratio of K:Rb. The pure vapor pressure above a liquid:

$$\log_{10}\left(\frac{p}{1 \text{ atm}}\right) = A - \frac{B}{T} \tag{18}$$

where A and B are taken from the CRC. The number density can be obtained from:

$$\log_{10}\left(\frac{nRT}{1 \text{ atm}}\right) = A - \frac{B}{T} \tag{19}$$

For a K:Rb alloy:

$$\log_{10} D_0 = \log_{10} p_{\mathrm{K}} - \log_{10} p_{\mathrm{Rb}} \tag{20}$$

$$= (A_{\mathrm{K}} - A_{\mathrm{Rb}}) - \frac{(B_{\mathrm{K}} - B_{\mathrm{Rb}})}{T} \tag{21}$$

$$= 0.09 - \frac{413 \text{ K}}{T} \tag{22}$$

which gives the following estimate for the vapor density ratio of K:Rb at some temperature T (must be above the melting points of K):

$$D = \left(\frac{1}{f_{\mathrm{Rb}}} - 1\right) 1.23 \times 10^{\frac{-413 \text{ K}}{T}} \tag{23}$$

3.7 Performance

Temp °C	(solid)	125	150	175	215	235	255
Panache	1.00%	11.2 (0.030)	12.9 (0.130)	14.6 (0.474)	17.4 (2.83)	18.7 (6.22)	20.1 (12.9)
Anna							
Barbara							

Table 9: Theoretical K:Rb ratios (K number densities in 10^{14} cm^{-3}) at different temperatures

Cell	Polarization	Lifetime	215	215	235	235	255	255
	(max EPR)		Pol	γ_{su}	Pol	γ_{su}	Pol	γ_{su}
Panache	43	55/35		-	-	-		
Anna		-	-	-	-	-		
Barbara		-	-	-	-	-		

Table 10: Maximum measured cell polarization, lifetime, and spin-up time constants at different temperatures