Recent Advances in Laser-Polarized He-3 Targets for Electron Scattering at JLab

Jaideep Singh



Physics & Applications of Polarized Noble Gases (an informal workshop w/ bagels)





























What can you learn from electron scattering?

 $p_{\rm f} = {\rm final \ electron \ momentum}$

 $p_{\rm i} = {\rm initial \ electron \ momentum}$

 N_e = number of scattered electrons $q = (p_f - p_i)$, momentum transfer















What can you learn from electron scattering?

accounts for imperfect electron & target polarizations

calculated from well-understood theory and/or measured from high precision experiments

$$\frac{\text{difference}}{\text{sum}} = \frac{N_e^{\rightarrow} - N_e^{\leftarrow}}{N_e^{\rightarrow} + N_e^{\leftarrow}} = F(q) \times \begin{pmatrix} \text{stuff we know} \\ \text{from QED} \end{pmatrix} \times \begin{pmatrix} \text{dilution} \\ \text{factors} \end{pmatrix}$$

accounts for imperfect electron & target polarizations

 $\begin{pmatrix} \text{dilution} \\ \text{factors} \end{pmatrix}$

calculated from well-understood theory and/or measured from high precision experiments unitless quantity that encodes deviations from simple "point"-like structure

 $\frac{\text{difference}}{\text{sum}} = \frac{N_e^{\rightarrow} - N_e^{\leftarrow}}{N_e^{\rightarrow} + N_e^{\leftarrow}} = F(q) \times \begin{pmatrix} \text{stuff we know} \\ \text{from QED} \end{pmatrix} \times$

F(q) = constant independent of q for a simple point particle



F(q) = constant independent of q for a simple point particle for quasi-elastic scattering from He-3

 $F(q) = G_E^n(q)$ = electric form factor of the neutron



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 $F(q) = ext{constant}$ independent of q for a simple point particle for quasi-elastic scattering from He-3 $F(q) = G_E^n(q) = ext{electric}$ form factor of the neutron



Form Factors from Electron Scattering *in the appropriate framework*, a form factor is **the Fourier Transform of a spatial distribution**

 $F(q) = G_E^n(q)$ = electric form factor of the neutron



The Charge Distribution of the Neutron

electric form factor <----> charge distribution

 $F(q) = G_E^n(q)$ = electric form factor of the neutron









Polarized Noble Gases Workshop (pre-DAMOP 2009) - UVa - Charlottesville, Va - May 19, 2009

How do you build an effective polarized neutron target?

Free Neutron Target?

n

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.0086649156 \pm 0.0000000006$ u Mass $m = 939.56536 \pm 0.0008$ MeV ^[a] $m_n - m_p = 1.2933317 \pm 0.0000005$ MeV $= 0.0013884487 \pm 0.000000006$ u Mean life $\tau = 885.7 \pm 0.8$ s $c\tau = 2.655 \times 10^8$ km Magnetic moment $\mu = -1.9130427 \pm 0.0000005 \ \mu_N$ Electric dipole moment $d < 0.29 \times 10^{-25} \ e \text{ cm}$, CL = 90%

HTTP://PDG.LBL.GOV PDG, Rev. of Particle Physics [C. Amsler et al., Phys. Lett. B667, 1 (2008)]

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HTTP://PDG.LBL.GOV PDG, Rev. of Particle Physics [C. Amsler et al., Phys. Lett. B667, 1 (2008)]

too short for precision electron scattering measurements! (...but great for graduate students...)
How do you build an effective polarized neutron target? 1. Polarized Deutron - solid target group (D. Crabb et. al) at UVa



S(88%) D(10%) S'(1.5%)

B. Blankleider & R. M. Woloshyn, Phys. Rev. C 29, 538 - 552 (1984)

- 1. Polarized Deutron solid target group (D. Crabb et. al) at UVa
- 2. Polarized He-3 what we (Cates Group) do



B. Blankleider & R. M. Woloshyn, Phys. Rev. C 29, 538 - 552 (1984)

Ground state of the He-3 wave function is dominated by S state, **due to Pauli Exclusion Principle**



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Ground state of the He-3 wave function is dominated by S state, *due to Pauli Exclusion Principle* small admixture of other states



B. Blankleider & R. M. Woloshyn, Phys. Rev. C 29, 538 - 552 (1984)

Ground state of the He-3 wave function is dominated by S state, *due to Pauli Exclusion Principle*

Bag of "free" nucleons



B. Blankleider & R. M. Woloshyn, Phys. Rev. C 29, 538 - 552 (1984)



How do you polarized He-3?

Metastability Exchange Optical Pumping (MEOP)
 Spin Exchange Optical Pumping (SEOP)

PHYSICAL REVIEW

VOLUME 132, NUMBER 6

15 DECEMBER 1963

Polarization of He³ Gas by Optical Pumping

F. D. COLEGROVE, L. D. SCHEARER,* AND G. K. WALTERS* Texas Instruments Incorporated, Dallas, Texas (Received 5 August 1963)

The process of He³ nuclear polarization by metastability exchange with optically pumped metastable He³ atoms is described and experimental details given. Phenomenological theories are presented which explain the optical signals and the time variation of the polarization. The polarization is measured both optically and by nuclear magnetic resonance. Relaxation of the nuclear spins by diffusion through magnetic field gradients is discussed. When gradients are small, nuclear relaxation times as long as 4000 sec have been measured. The maximum polarization achieved was $40\pm5\%$ in He³ gas at a pressure of one mm Hg.



How do you polarized He-3? 1. Metastability Exchange Optical Pumping (MEOP) **2. Spin Exchange Optical Pumping (SEOP)** PHYSICAL REVIEW LETTERS **OCTOBER** 15, 1960 VOLUME 5, NUMBER 8 NUCLEAR POLARIZATION IN He³ GAS INDUCED BY OPTICAL PUMPING AND DIPOLAR EXCHANGE* M. A. Bouchiat,[†] T. R. Carver,[‡] and C. M. Varnum Palmer Physical Laboratory, Princeton University, Princeton, New Jersey (Received September 26, 1960) 373

How do you polarized He-3?

1. Metastability Exchange Optical Pumping (MEOP)

2. Spin Exchange Optical Pumping (SEOP)



How do you polarized He-3?

- 1. Metastability Exchange Optical Pumping (MEOP)
- 2. Spin Exchange Optical Pumping (SEOP)



A Target Cell



A Target Cell































He-3 Polarization in Double Chambered Cells $P_{\rm pc}$ $1 + \langle \Gamma_{\rm He} \rangle / \langle \gamma_{\rm se} \rangle$ $P_{\rm A} =$ alkali polarization $\langle \Gamma_{\rm He} \rangle$ = volume-averaged He-3 relaxation rate $\langle \gamma_{\rm se} \rangle$ = volume-averaged spin-exchange rate

$$P_{\rm tc} = \frac{P_{\rm pc}}{1 + d_{\rm tc}/\Gamma_{\rm tc}}$$

 $d_{\rm tc} =$ fraction of nuclei exiting the t.c. per unit time $\Gamma_{tc(pc)} = \text{He-3 relaxation rate in the target (pumping) chamber}$

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He-3 Relaxation in Target Cells






He-3 Relaxation in Target Cells

He-3 relaxation mechanism

formula/range

typical

X-factor 0.

$$0.1 \le X \le (0.4 \text{ cm}) \frac{S}{V}$$

expected to be 0.25 ± 0.15

Babcock et. al, PRL 96, 083003 (2006)

Beam

1 cm^2	$n_a I$	
$105 \ \mu \mathrm{A} \cdot \mathrm{hr}$	$\overline{A_{ m tc}}$	

1/(50 hr)

Bonin et. al, PRA 38(9), 4481-7 (1988)

Wall

1/(20 hr) to 1/(200 hr)

1/(70 hr)

What is the required spin-exchange rate?

$$\begin{split} \left< \Gamma_{\rm He}^{0} \right> \approx \frac{1}{30 \text{ hr}} \\ \left< \gamma_{\rm Se} \right> = f_{\rm pc} k_{\rm Se} \left[A \right]_{\rm Se} \\ f_{\rm pc} = \text{fraction of nuclei in the p.c.} \approx 0.5 \\ k_{\rm se} = \text{spin-exchange rate constant} \approx \frac{10^{-14} \text{ cm}^3}{45 \text{ hr}} \\ \left[A \right]_{\rm se} = \text{alkali number density} \\ \left< \Gamma_{\rm He}^{0} \right> / \left< \gamma_{\rm se} \right> = 0.2 \Rightarrow \left[A \right]_{\rm se} \approx 15 \times 10^{14} \text{ cm}^{-3} \end{split}$$

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Alkali Polarization $P_{\text{light}}(\vec{r})$ $P_{\mathrm{A}}(ec{r})$ $\overline{1 + X_{\alpha} + \Gamma_{\rm A} / \left(2\Lambda R(\vec{r})\right)}$ $P_{\text{light}} = \text{light polarization at position } \vec{r}$ $R = optical pumping rate at position \vec{r}$ $\Gamma_{\rm A}$ = alkali spin relaxation rate $\Lambda =$ probability of decay to opposite state ($\neq 1/2$?) $X_{\alpha} =$ light intensity dependent alkali relaxation mechanism? inadvertent pumping of D2 and other unwanted transitions, skew pumping, reabsorption of D1/D2 fluorescence, fine structure mixing Polarized Noble Gases Workshop (pre-DAMOP 2009) - UVa - Charlottesville, Va - May 19, 2009

Alkali Polarization $P_{\text{light}}(\vec{r})$ $\overline{1 + X_{\alpha} + \Gamma_{A} / (2\Lambda R(\vec{r}))}$ $P_{\text{light}} = \text{light polarization at position } \vec{r}$ $R = optical pumping rate at position \vec{r}$ $\Gamma_{\rm A}$ = alkali spin relaxation rate $\Lambda = \text{probability of decay to opposite state } (\neq 1/2?)$ $X_{\alpha} =$ light intensity dependent alkali relaxation mechanism? inadvertent pumping of D2 and other unwanted transitions, skew pumping, reabsorption of D1/D2 fluorescence, fine structure mixing

$$\frac{1}{\phi} \frac{\partial \phi(\vec{r}, \nu)}{\partial z} = -\sigma(\nu) [A]_{\text{abs}} \left(1 - P_{A}(\vec{r}) + X_{\gamma}\right)$$

 $\phi(\vec{r},\nu) =$ photon flux per unit frequency bin

 $\sigma(\nu)$ = unpolarized absorption cross section

 $[A]_{abs} = absorbing alkali number density$

 $X_{\gamma} = \text{extra light absorption mechanism?}$

inadvertent pumping of D2 and other unwanted transitions, skew pumping, fine structure mixing

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Please don't laugh, this how we do it in the "nuclear world."

Alkali Polarization "Profile", Broadband Laser, Pure Rb

Alkali Polarization "Profile", Broadband Laser, Pure Rb

back end of cell

Alkali Polarization "Profile", Broadband Laser, Pure Rb

back end of cell

Path Length Variation for a Spherical Pumping Chamber

Laser Intensity Spatial Distribution for a Gaussian Beam

Line Averaged Alkali Polarization Across the Pumping Chamber

Alkali Hybrid SEOP

United States Patent Happer, et al.		6,318,092 November 20, 2001				
Alkali metal hybrid spin-exchange optical pumping						
Abstract						
Methods of hyperpolarizing a noble gas by spin-exchange optical pumping use an alkali metal hybrid comprising a primary alkali metal and an auxiliary alkali metal to effectuate spin transfer interaction among the primary alkali metal, the auxiliary alkali metal, and the noble gas.						
Inventors:	Happer; William (Princeton, NJ), Cates, Jr.; Gordon D. (Skillman, NJ), Romalis; Mikhail V. (Seattle, WA), Erickson; Christopher J. (Princeton, NJ)					
Assignee:	The Trustees of Princeton University (Princeton, NJ)					
Appl. No.:	09/485,833					
Filed:	February 15, 2000					
PCT Filed:	ed: August 17, 1998					
PCT No.:	PCT/US98/17030					
371 Date:	February 15, 2000					
102(e) Date:	Date: February 15, 2000					
PCT Pub. No.:	PCT Pub. No.: WO99/08766					
PCT Pub. Date: February 25, 1999						
Current U.S. Class: 62/55.5 ; 6		62/55.5 ; 62/637				
Current International Class:		G01R 33/28 (20060101); B01D 008/00 ()				
Field of Search:		62/55.5.637.925				

Alkali Hybrid SEOP

VOLUME 91, NUMBER 12

PHYSICAL REVIEW LETTERS

week ending 19 SEPTEMBER 2003

Hybrid Spin-Exchange Optical Pumping of ³He

Earl Babcock,¹ Ian Nelson,² Steve Kadlecek,² Bastiaan Driehuys,² L.W. Anderson,¹ F.W. Hersman,³ and Thad G. Walker¹

¹Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin 53706, USA ²Amersham Health, 2500 Meridian Parkway, Suite 150, Durham, North Carolina 27713, USA ³Department of Physics, University of New Hampshire, Durham, New Hampshire 03824, USA (Received 16 May 2003; published 16 September 2003)

We demonstrate spin-exchange optical pumping of ³He using a "hybrid" K-Rb vapor mixture. The Rb atoms absorb light from a standard laser at 795 nm, then collisionally polarize the potassium atoms. Spin-exchange collisions of K and ³He atoms then transfer the angular momentum to the ³He with much greater efficiency than Rb-³He. For a K-rich vapor, the efficiency of the hybrid spin-exchange collisions approaches 1/4, an order of magnitude greater than achieved by pure Rb pumping. We present the first measurements of actual photon efficiencies (polarized nuclei produced per absorbed photon), and show that a new parasitic absorption process limits the total efficiencies for both hybrid and pure Rb pumping.

DOI: 10.1103/PhysRevLett.91.123003

PACS numbers: 32.80.Bx, 03.75.Be, 29.25.Pj, 67.65.+z

Alkali Hybrid SEOP					
$\langle \gamma_{\rm se} \rangle = f_{\rm pc} k_{\rm se} [{\rm Rb}] \left(1 + D \cdot k_{\rm se}' / k_{\rm se} \right)$					
$D = \frac{[K]}{[Rb]}$	$P_{\rm A} = P_{\rm Rb} = F$	$P_{\rm K} \ (D \ll 1000)$			
effective alkali number density	spin exchange	light absorption			
pure Rb	[Rb]	[Rb]			
hybrid K/Rb	$[\mathrm{Rb}]\left(1 + D \cdot k_{\mathrm{se}}'/k_{\mathrm{se}}\right)$	[Rb]			
Γ_{A} :	$= \Gamma_{\rm Rb} + D \left(\Gamma_{\rm K} + 2k_{\rm A} \right)^2$	Rb])			
This only works because $\Gamma_{\rm K} \ll \Gamma_{\rm Rb}$ under the same conditions.					
Polariz	ed Noble Gases Workshop (pre-DAMOP 2009)	- Uva - Charlottesville, Va - May 19, 2009			

Alkali Hybrid SEOP

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$D = \frac{[K]}{[Rb]}$	$P_{\rm A} = P_{\rm Rb} = P$	$P_{\rm K} \ (D \ll 1000)$			
effective alkali number density	spin exchange	light absorption			
pure Rb	[Rb]	[Rb]			
hybrid K/Rb	$[\mathrm{Rb}]\left(1+D\cdot k_{\mathrm{se}}'/k_{\mathrm{se}}\right)$	[Rb]			
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Polarized Noble Gases Workshop (pre-DAMOP 2009) - UVa - Charlottesville, Va - May 19, 2009					

Alkali Polarization "Profile", Broadband Laser, Hybrid

Alkali Polarization "Profile", Broadband Laser, Hybrid

back end of cell

Optical Pumping Rate

$$R(\vec{r}) = \int \phi(\vec{r},\nu)\sigma(\nu) \ d\nu$$

 $R(\vec{r}) = \int \left(\frac{\text{number of photons here}}{\text{unit time} \times \text{unit area} \times \text{unit frequency}}\right) \text{(absorption cross section) } d\nu$







This is the photon flux at the *front* of the cell.



This is the photon flux at the *front* of the cell. A line narrowed laser has a much *higher* optical pumping rate!

Alkali Polarization "Profile": Narrow vs. Broad



Alkali Polarization "Profile": Narrow vs. Broad $\Delta v = 0.2 \text{ nm}$ 1.0 Note the sharp transition 0.8 alkali polarization 0.6 0.4 Note the long tail $\Delta v = 2.0 \text{ nm}$

0.2

0.0

0

2

Polarized Noble Gases Workshop (pre-DAMOP 2009) - UVa - Charlottesville, Va - May 19, 2009

8

6

depth into cell (cm)

10

12





Polarized Noble Gases Workshop (pre-DAMOP 2009) - UVa - Charlottesville, Va - May 19, 2009









Best Performance w/ Hybrid Cell w/ Line Narrowed Lasers





As laser power increases, optimal ratio decreases.





from the stupid model, between 3 & 6

What is the optimal laser linewidth?





laser linewidth = absorption linewidth is "good enough"?

Now for Real Experiments!

Extraction of Helium-3 and Alkali Densities from Alkali D1
D2 pressure broadened spectroscopy

2. Helium-3 Polarimetry using NMR & EPR

3. Extracting Alkali Polarization & Density Ratios from Alkali EPR Spectroscopy

4. Extracting Absolute Alkali Densities using Faraday Rotation

5. Making Hybrid Mixes

6. Results

Experiment: Pressure Broadening of Alkali D1 & D2

FWHM gives He-3 density



Experiment: Pressure Broadening of Alkali D1 & D2

Ratio of areas gives Alkali Hybrid Ratio



Experiment: Pressure Broadening of Alkali D1 & D2

Pressure Broadening	Rb	K
Constant	M. V. Romalis, E. Miron, and G. D. Cates Phys. Rev. A 56, 4569 - 4578 (1997)	cross calibration
D1	18.7 ± 0.3	14.8 ± 0.5 preliminary!
D2	20.8 ± 0.2	20.3 ± 0.9 preliminary!

Experiment: NMR (Field Sweep AFP) Polarimetry



Experiment: Spin Up Time Constant, Diffusion Effects



Experiment: Spin Up Time Constant, Diffusion Effects



Experiment: EPR Frequency Shift Polarimetry

AFP



 B_0 B_{He}

Experiment: EPR Frequency Shift Polarimetry

AFP







Experiment: EPR Frequency Shift Polarimetry



Experiment: EPR Frequency Shift Polarimetry

This is interesting, ask me about it.









Experiment: Alkali Polarization vs. EPR RF Power



Experiment: Alkali Polarization vs. EPR RF Power


Experiment: Alkali Polarization vs. EPR RF Power



Experiment: Alkali Density from Faraday Rotation



E. Vliegen, et al Nucl. Instrum. Methods Phys. Res. A 460, 444 (2001)

Path Length "Measurement" **Probe Beam**

Experiment: Alkali Density from Faraday Rotation



Results: Hybrid Cells with Broadband Lasers		
Cell	D @ 235 C	Best Pol.
Boris	2.4	39%
Edna	3.5	54%
Samantha	4.1	53%
Al the Target Cell	4.4	54%
Barbara	4.8	53%
Gloria	6.9	58%
Anna	9.3	39%
Simone	9.6	45%
Dolly	21	42%
and the second second second second		

Results: Controlling the Hybrid Ratio			
Cell	Extrapolated from PB	Measured at temperature with FR	
Brady	2.2	2.7	
Samantha	4.1	4.3	
Astralweeks	6.2	7.1	
Simone	9.6	12	

PB: Measure the total absorption at low temperatureFR: Measure the Faraday Rotation of a linearly polarized probe beam at operating temperature

Results: Controlling the Hybrid Ratio



The initial solid mix is prepared in a glovebox. We measure the metals to 0.1 mg! Some unknown amount of the mix is then distilled into the cell using a hand torch. We believe that most of the variation in the final ratio comes from this last step.

Results: Controlling the Hybrid Ratio		
Desired ratio D @ 235 C	20	5
D @ 235 C for initial solid mix	19.1 ± 1.5	5.0 ± 1.5
D @ 235 C from PB inside the cell	9.2 ± 6.4	3.0 ± 1.6
number of cells with more Rb than desired	$5 ext{ of } 6$ $D_{\text{meas}} \leq 1$	6 of 7 $2 \times D_{\text{goal}}$
I claim: "Well enough!"		

Results: Hybrid Cells w/ Spectrally Narrow Lasers		
D @ 235 C	Best Pol. Broadband	Best Pol. Narrow
1.5		64%
2.2		73%
4.1	53%	<mark>→ 70</mark> %
6.2		70%
9.6	45%	→ 62%
	D @ 235 C 1.5 2.2 4.1 6.2 9.6	D @ 235 C Best Pol. Broadband 1.5 2.2 4.1 53% 6.2 9.6

What is "Quasi-masing"?

- 1. When in the low energy state, large AFP losses during NMR (>2%).
- 2. Much higher equilibrium polarization pumping to the low energy state than the high energy state, (upto a factor of 2!).
- 3. This effect can be suppressed using a gradient coil.
- 4. This effect appears to occur only in the pumping chamber, whether the cell is hot OR cold!
- 5. This effect does not appear to be a coupling between the He spins and any RF coil in the system (unlike "traditional" masing).
- 6. We've seen this effect for around 1/2 of the hybrid cells that we've tested.
- 7. When the gradient coil is turned off, when the spins are in the high energy state, the polarization drop in the pumping chamber is instantaneous!

Ref for "Traditional" Masing: M.V. Romalis and W. Happer Phys. Rev. A 60, 1385 (1999).

Varying the Gradient Coil Current, High Energy State

The low energy state is the -1/2 state for He-3. The high energy state is the +1/2 state for He-3.

The spin state can be switched by either: (1) reversing the polarity of the holding field (2) rotating the QWP by 90 deg

The "masing" threshold depends on the magnitude of the gradient.

The effect appears only to occur in the pumping chamber.







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This is a higher Helium polarization, with a faster time constant, and using *less laser power* than we have in the past!

Summary: What do I have to do to get really high polarization? 1. Use line narrowed lasers! They are now essentially turn-key off the shelf devices. Our experience has been (more or less) plug-and-play.

2. Use hybrid cells. The desired ratio of K to Rb is between 3 and 6. This is supported by the simulation, our results, and the results of *W.C. Chen et al., Phys. Rev. A* 75, 013416 (2007).

3. When making the hybrid mix, shoot for a ratio of 6. Our tests have shown that the final mix have a ratio of 6 or less.

4. Use both line narrowed lasers and hybrid cells, if possible!

5. Watch out for masing...use a gradient coil.

Thanks!

Gordon Cates (UVa) **Todd Averett (W+M)** Al Tobias (UVa) Vladimir Nelyubin (UVa) **Peter Dolph (UVa)** Karen Mooney (UVa) Aidan Kelleher (W+M)

- 1. It's analogous the AC Stark Effect.
- 2. It's a coupling between the NMR RF field used for AFP and the Alkali spins.
- **3.** The freq shift should have a quadratic NMR RF field dependence.
- 4. The freq shift should be essentially independent of the NMR RF frequency.

$$\left(\Delta\nu\right)_{\rm rf} = \frac{F(F+1) - m(m-1)}{4\nu_{\rm EPR}} \left[\frac{\partial\nu}{\partial B}B_{\rm rf}\right]^2$$







Results: Controlling the Hybrid Ratio Raoult's Law

$$\frac{f_{\rm Rb}}{f_{\rm K}} \approx \frac{1}{6.31 \cdot D_{\rm goal}} \times \left(\frac{[\rm K]_{\rm goal}}{10^{14} \ \rm cm^{-3}}\right)^{0.097} \qquad (\text{valid for } D_{\rm goal} \gg 0.2)$$

 f_A = mole fraction of **A**lkali in solid mix

 $D_{\text{goal}} = \text{desired K to Rb vapor ratio at operating temp}$ $[K]_{\text{goal}} = \text{desired K number density at operating temp}$

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