

Physics 451 Spring 2014: Introduction to Experiments

- Sonoluminescence
- Cavendish Balance—a study of gravity

- Nuclear Physics: Gamma Ray Spectroscopy & Muon Lifetime

- Photoelectric Effect and Determination of Plank's Constant
- Pulsed Nuclear Magnetic Resonance
- Optical Pumping
- Diode Laser Spectroscopy (Doppler-free Spectroscopy)

- Superfluidity of Liquid Helium-4
- Superconductivity and Superconducting Tunnel Junctions

Sonoluminescence

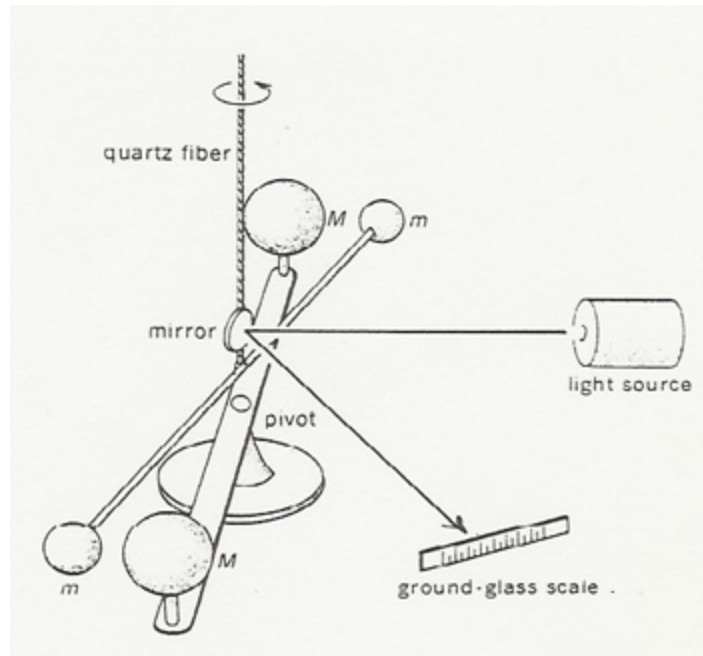
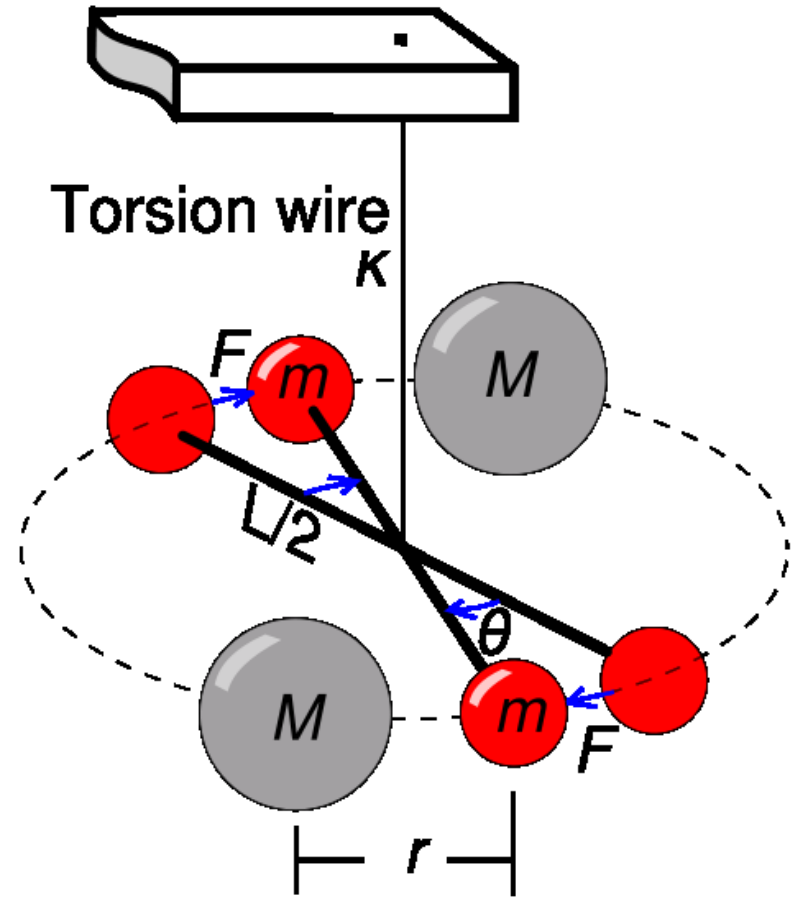
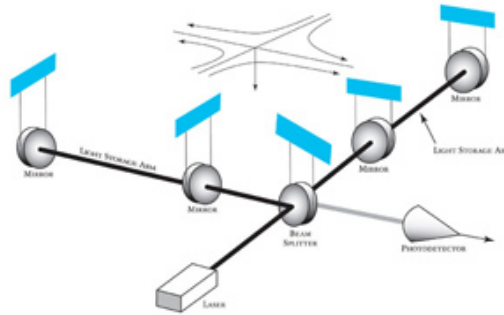
- Sonoluminescent bubble lighted with laser

<http://www.youtube.com/watch?v=3bfJploSBgM>

Ultrasonic levitation

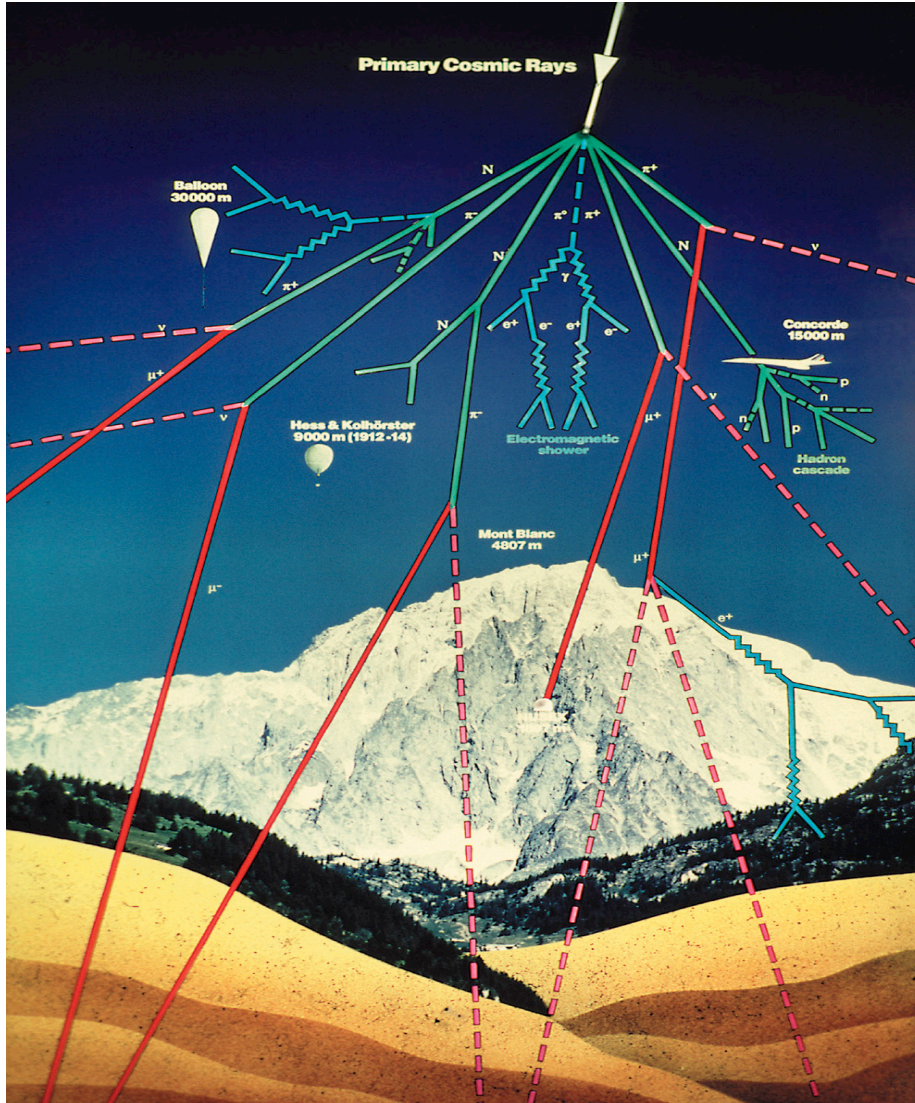
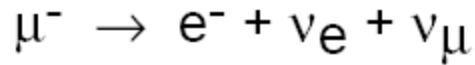
<http://www.youtube.com/watch?v=S4exO4CuoSU&feature=related>

Cavendish Balance

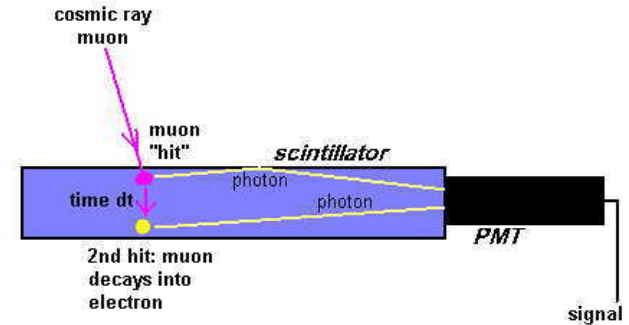


SYMMETRIC DIFFERENTIAL CAPACITIVE SENSORS (transducers)

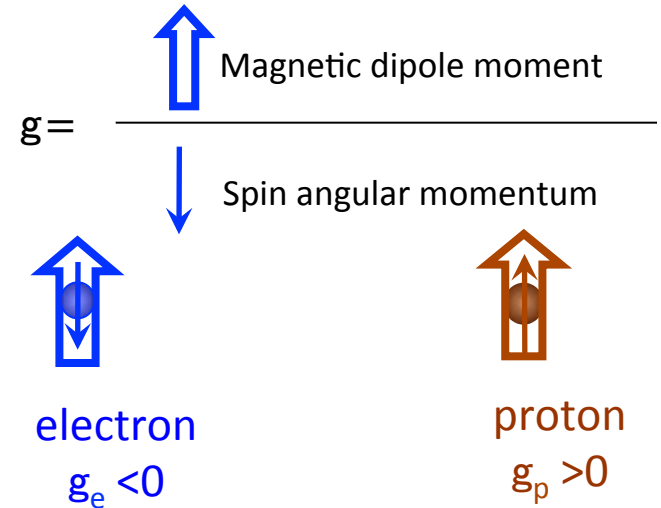
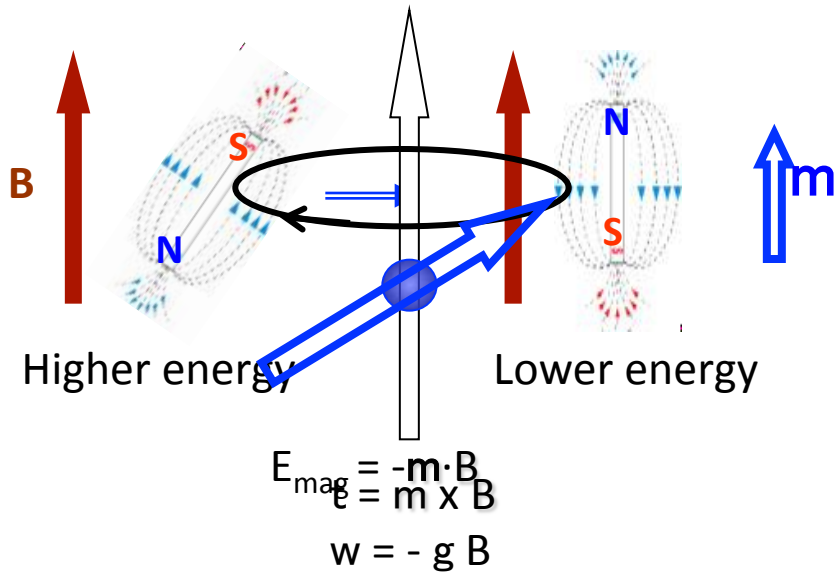
Nuclear Physics



Primary cosmic rays are particles such as protons and neutrons moving at high energies through the interstellar medium. Locally, many of these are ejecta from the sun. When these primary cosmic rays come toward earth they encounter atmospheric nuclei at around 30,000 m above the surface. The impacts cause nuclear reactions which produce pions. The pions decay into muons; this generally occurs at around 9000 m altitude. The muons rain down upon the surface of the earth, travelling at about 0.998c. Many decay on the way down while others reach the surface. A few of those will encounter Jeff and Ed's muon detector. These muons constitute "secondary cosmic rays" and have paths which are indicated by the red arrows on the diagram. Note that this diagram shows a "muon shower" on the Alps...such an event on the Rockies would look much the same!

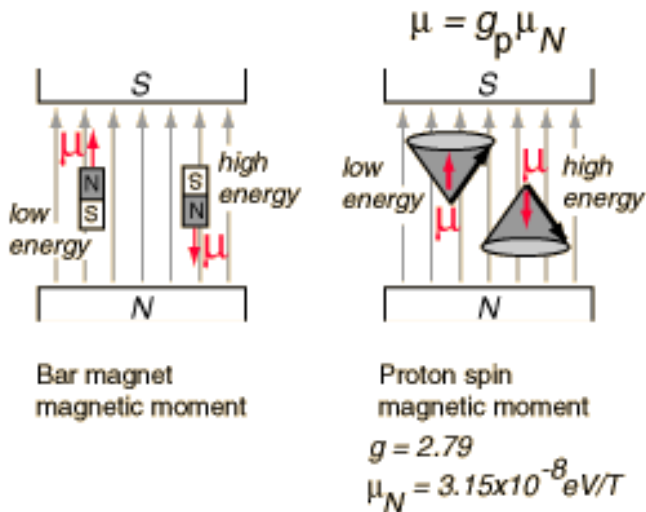


Nuclear Magnetic Resonance

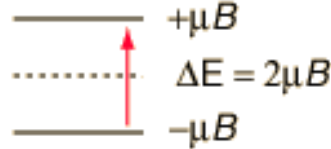


$$m_e = g_e S \sim 58 \text{ meV/T}$$

$$m_p = g_p I \sim 32 \text{ neV/T}$$



B=1Tesla



$$\Delta E = 2\mu B = 2g_p \mu_N B$$

$$\Delta E = 2 \cdot 2.79 \cdot 3.15 \times 10^{-8} \text{ eV/T} \cdot 1 \text{ T}$$

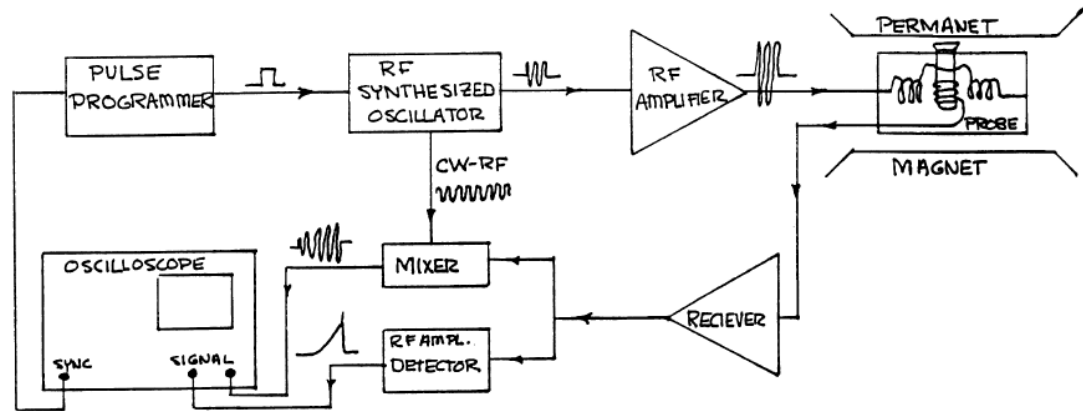
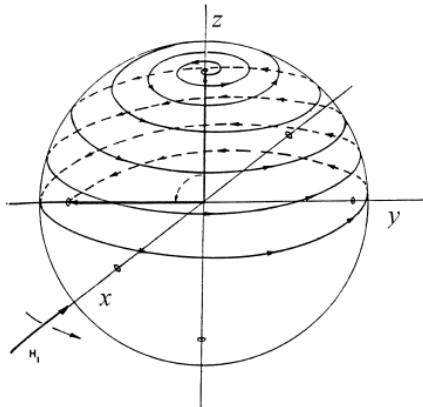
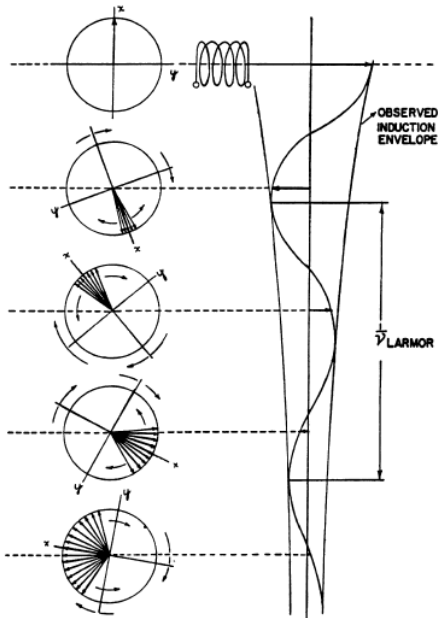
$$\Delta E = 1.76 \times 10^{-7} \text{ eV}$$

$kT \sim 25 \text{ meV} @ 300 \text{ K}$

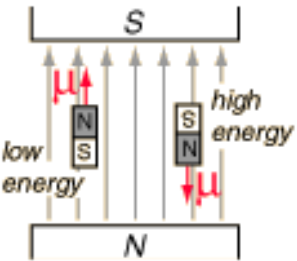
$$e^{-\frac{\Delta E}{kT}} \approx 1 - \frac{\Delta E}{kT} = 1 - \frac{1.76 \times 10^{-7}}{0.04} = 1 - 4.4 \times 10^{-6}$$

High field
Low temperature
Paramagnetic ions

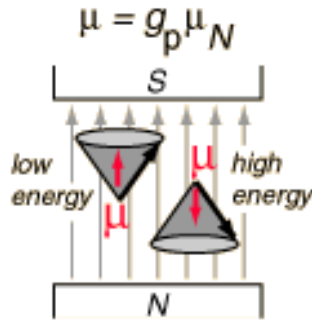
Pulse NMR Experiments



Nuclear spin and Hyperfine interaction



Bar magnet magnetic moment

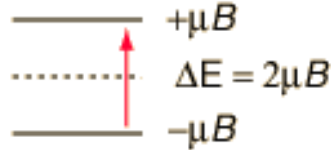


Proton spin magnetic moment

$$g = 2.79$$

$$\mu_N = 3.15 \times 10^{-8} \text{ eV/T}$$

$B = 1 \text{ Tesla}$



$$\Delta E = 2\mu B = 2g_p \mu_N B$$

$$\Delta E = 2 \cdot 2.79 \cdot 3.15 \times 10^{-8} \text{ eV/T} \cdot 1 \text{ T}$$

$$\Delta E = 1.76 \times 10^{-7} \text{ eV}$$

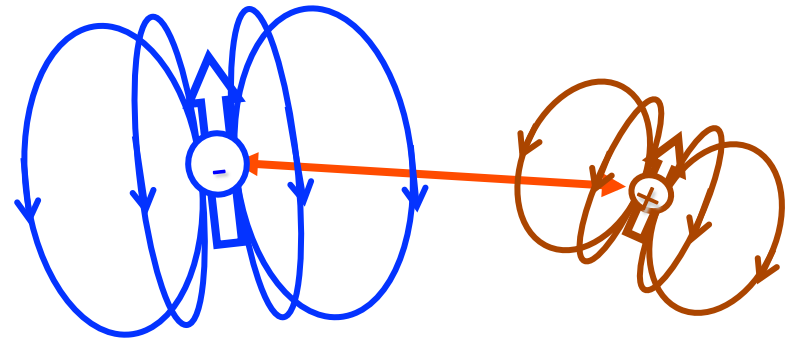
$kT \sim 25 \text{ meV} @ 300 \text{ K}$

$$e^{-\frac{\Delta E}{kT}} \approx 1 - \frac{\Delta E}{kT} = 1 - \frac{1.76 \times 10^{-7}}{0.04} = 1 - 4.4 \times 10^{-6}$$

**High field
Low temperature
Paramagnetic ions**

Isotope/Atom	^{85}Rb	^{87}Rb	^{23}Na
Natural abundance	72.2%	27.8	100
Nuclear spin	$I = 5/2$	$3/2$	$3/2$
Magnetic moment	$m_n = +1.35 m_p$	+2.75	+2.22

$$m_e/m_p \sim g_p/g_e \sim m_e/m_p \sim 10^3$$



Hyperfine interaction

What is optical pumping?

$$\frac{n_1}{n_2} = \exp\left(\frac{E_2 - E_1}{kT}\right)$$

$$k = 8.62 \times 10^{-5} \text{ eV K}^{-1}$$

$$kT \sim 0.03 \text{ eV @ } 300 \text{ K}$$

$$\text{First excited state} \sim 2 \text{ eV}$$

The Boltzmann factor is therefore which implies that only about one ϵ is in an excited state at any given m

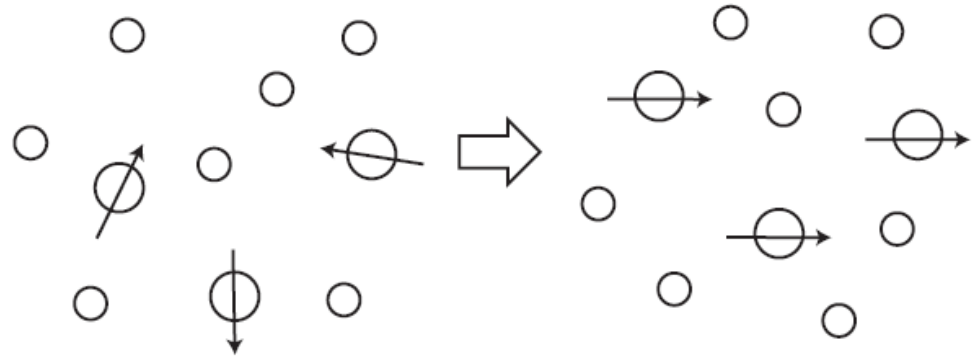


Figure 1: Optical pumping can be used to polarize a gas of atoms that have magnetic dipole moments. In practice, these atoms are often mixed with a nonpolar *buffer gas*, which helps keep the polarized atoms from touching with the walls of the container and losing their polarization.

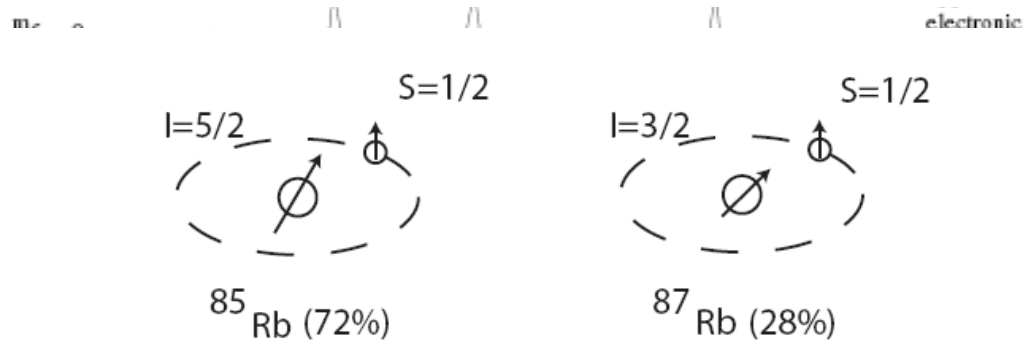
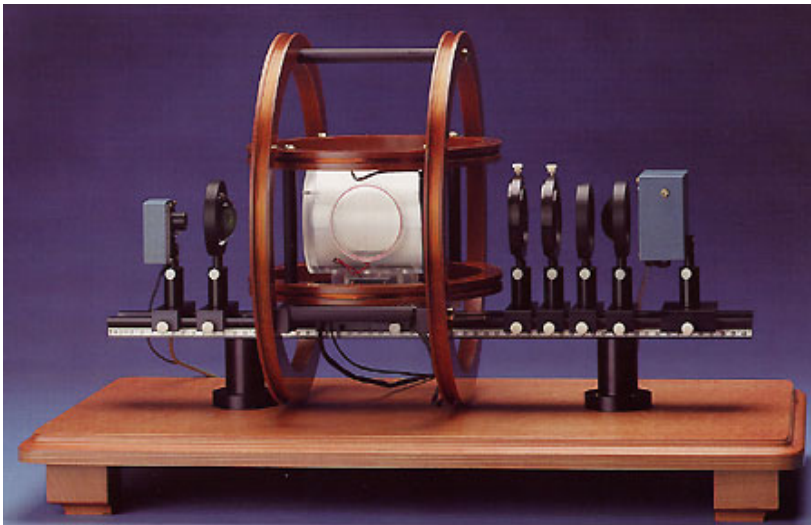


Figure 2: There are two commonly-occurring isotopes of Rubidium found in nature, ^{85}Rb and ^{87}Rb . Both have only one valence electron and can be approximated as one-electron atoms. The major difference between the isotopes is in the nuclear spin I .

Optical Pumping Instruments



PERIODIC TABLE
Atomic Properties of the Elements

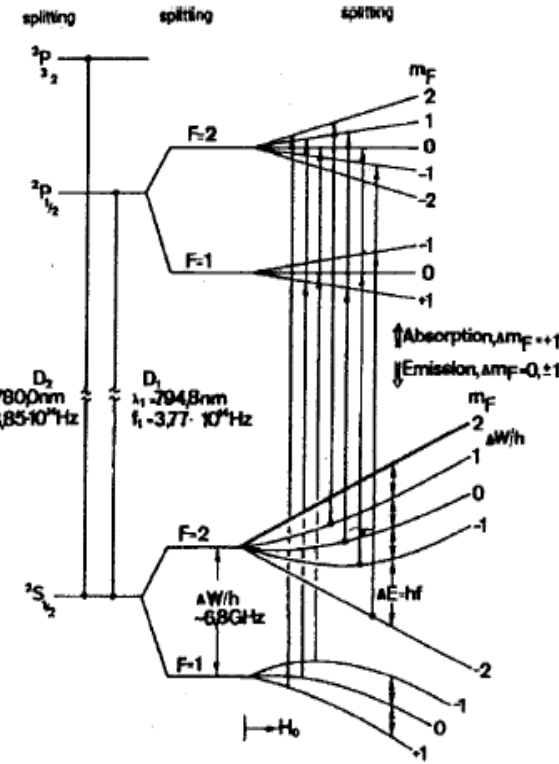
NIST
National Institute of Standards and Technology
Physics Laboratory
Standard Reference Data Group

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs
 speed of light in vacuum $c = 299\,792\,458\text{ m s}^{-1}$ (exact)
 Planck constant $h = 6.626\,070\,15 \times 10^{-34}\text{ J s}$ (exact)
 elementary charge $e = 1.602\,176\,634 \times 10^{-19}\text{ C}$ (exact)
 electron mass $m_e = 9.109\,383\,701 \times 10^{-31}\text{ kg}$
 proton mass $m_p = 1.672\,621\,923 \times 10^{-27}\text{ kg}$
 fine-structure constant $\alpha = 7.297\,352\,5698 \times 10^{-8}$
 Rydberg constant $R_\infty = 10\,973\,731.762\,178 \text{ m}^{-1}$
 Boltzmann constant $k_B = 1.380\,658 \times 10^{-23}\text{ J K}^{-1}$

Legend:
 Solids (blue)
 Liquids (green)
 Gases (yellow)
 Artificially Prepared (purple)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000
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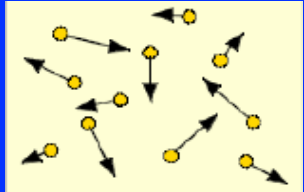


Properties of some liquids

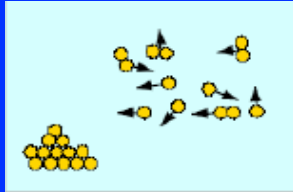
subst.	T_b (K)	T_m (K)	T_{tr} (K)	P_{tr} (bar)	T_c (K)	P_c (bar)	lat. heat, L (kJl ⁻¹)	vol% in air
H ₂ O	373.15	273.15	273.16	0.06*	647.3	220	2,252	–
Xe	165.1	161.3	161.4	0.82	289.8	58.9	303	0.1×10^{-4}
Kr	119.9	115.8	114.9	0.73	209.4	54.9	279	1.1×10^{-4}
O ₂	90.1	54.4	54.36	0.015	154.6	50.4	243	20.9
Ar	87.2	83.8	83.81	0.69	150.7	48.6	224	0.93
N ₂	77.2	63.3	63.15	0.13	126.2	34.0	161	78.1
Ne	27.1	24.5	24.56	0.43	44.5	26.8	103	18×10^{-4}
<i>n</i> -D ₂	23.7	18.7	18.69	0.17	38.3	16.6	50	–
<i>n</i> -H ₂	20.3	14.0	13.95	0.07	33.2	13.2	31.8	0.5×10^{-4}
⁴ He	4.21	–	–	–	5.20	2.28	2.56	5.2×10^{-4}
³ He	3.19	–	–	–	3.32	1.15	0.48	–

What's cool about "cold" and "absolute zero"?

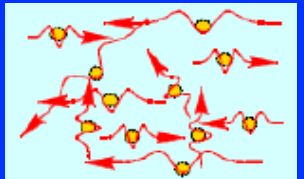
Quantum fluid and many-body effects



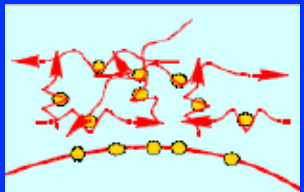
Cooling @
high density



Cooling @ low density



$T_{\text{three-body}} > t_{\text{therm}}$



$$\lambda_{dB} = \frac{h}{p} = \frac{h}{\sqrt{2\pi m^* k_B T}}$$

Single free particle

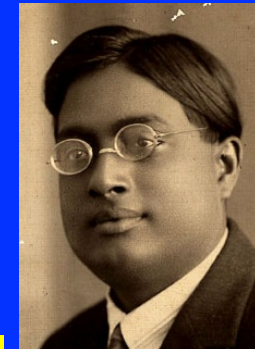


Many-body collective effects

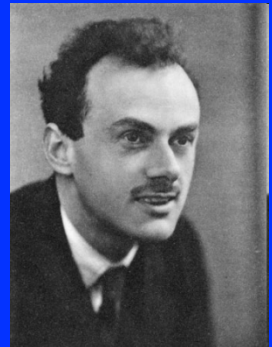
Interaction + Statistics + ?



L. V. de Broglie 1922



S. N. Bose, A. Einstein 1924-25

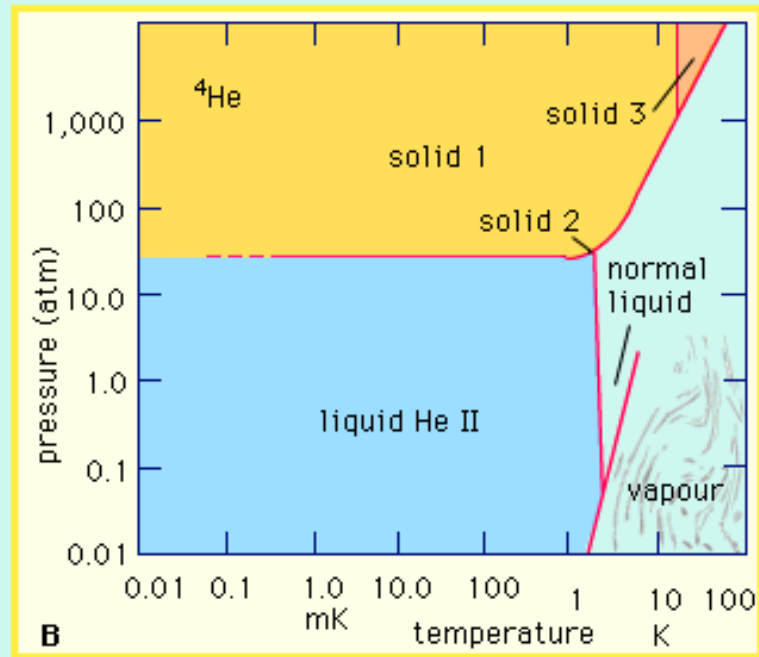
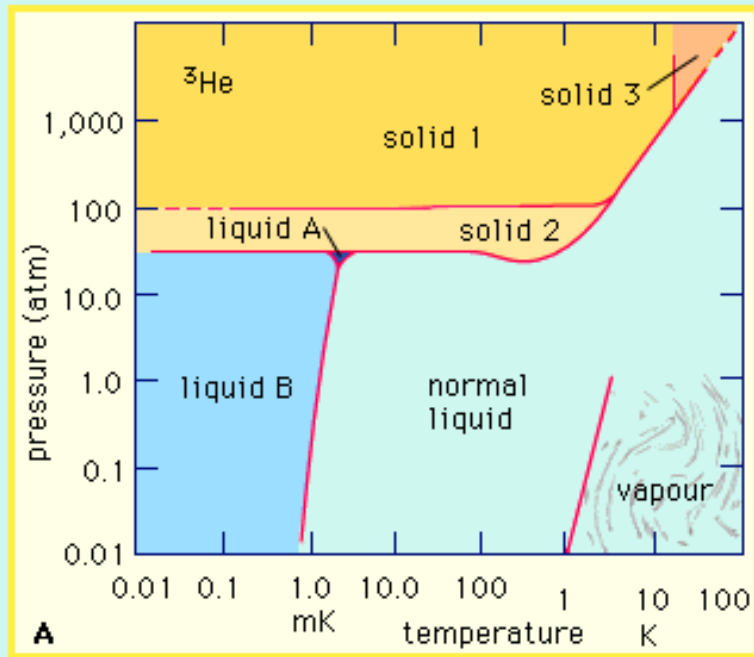
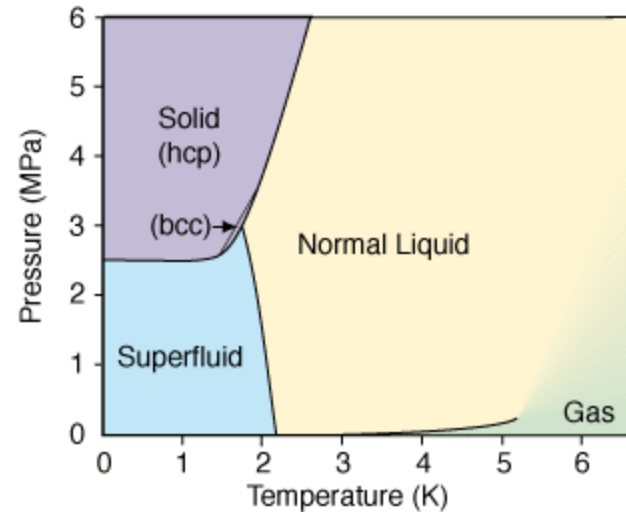
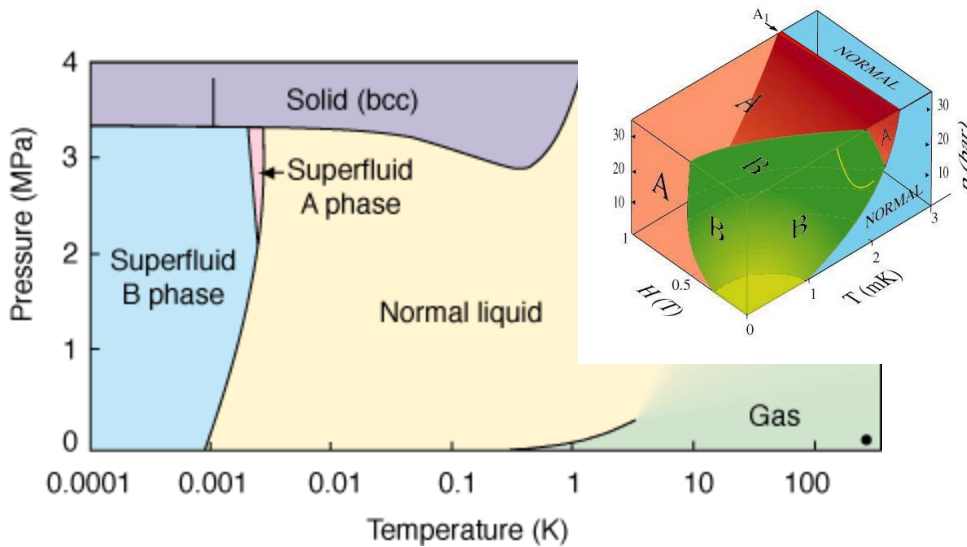


E. Fermi, P. Dirac 1926

Helium as a Quantum Fluid

The behavior of liquid helium-4's two fluid phases, helium I and helium II, is important to researchers studying [quantum mechanics](#) (in particular the phenomenon of [superfluidity](#)) and to those looking at the effects that temperatures near [absolute zero](#) have on matter (such as [superconductivity](#)).

Phase Diagram of ^3He and ^4He



Superfluid Helium II

Phase transition and viscousless flow

http://www.youtube.com/watch?v=TBi908sct_U

Superfluid fountain

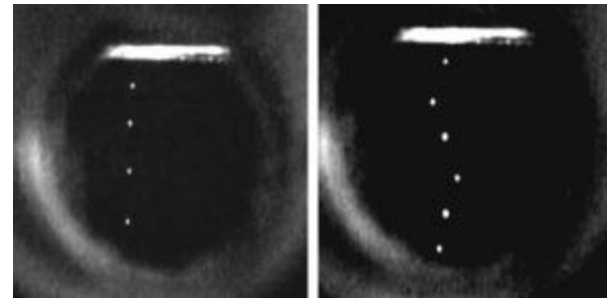
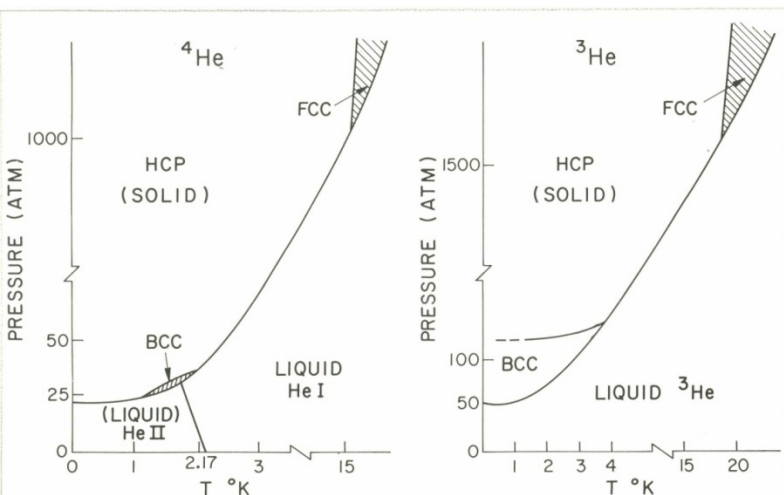
<http://www.youtube.com/watch?v=kCJ24176enM>

Liquid Helium II: The Superfluid (Physics demonstration by Alfred Leitner, 1963)

<http://www.youtube.com/watch?v=uw6h4K6begA>

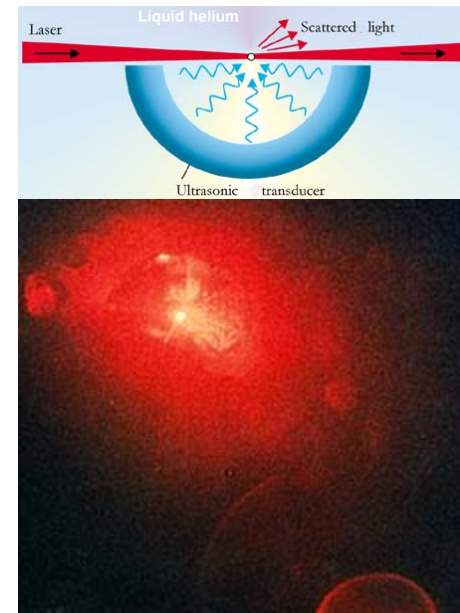
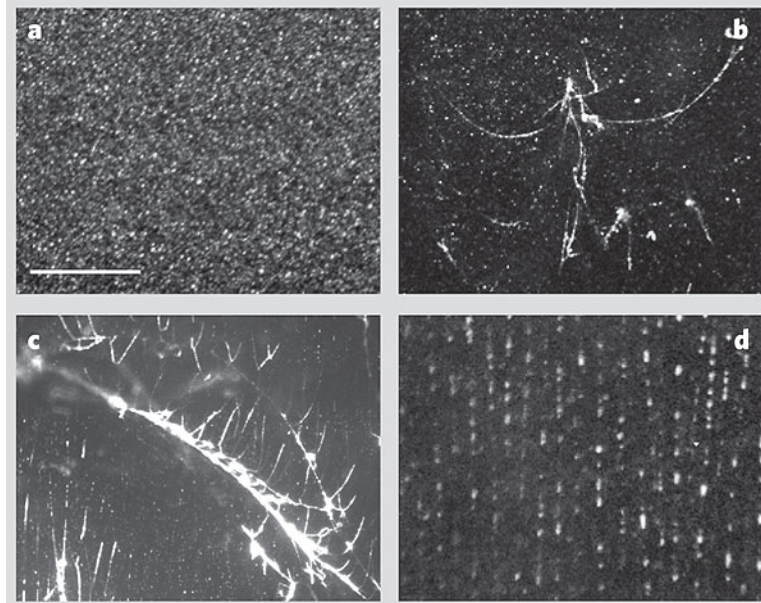
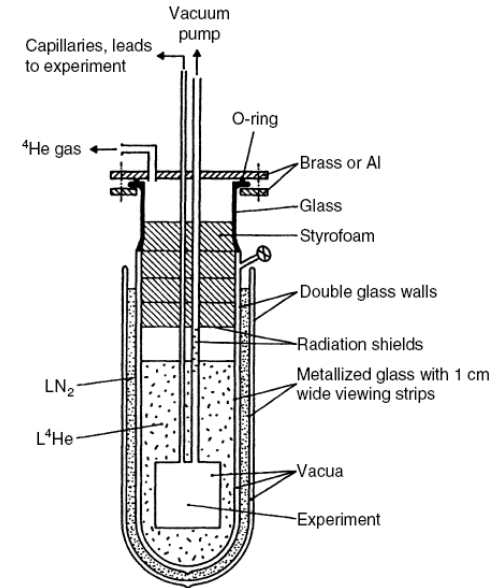
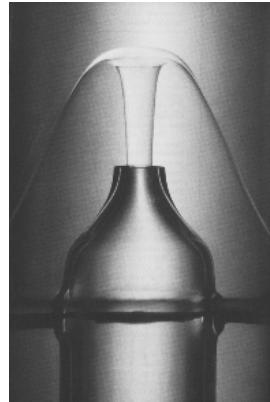
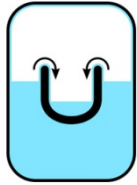
Movement of single electron in helium

<http://www.youtube.com/watch?v=04KaWCXkSC0>



Captured on a home video camera, some electrons follow a straight path through superfluid helium (far left). Those entrained in a superfluid vortex follow a snakelike path. (Credit: Humphrey Maris and Wei Guo)

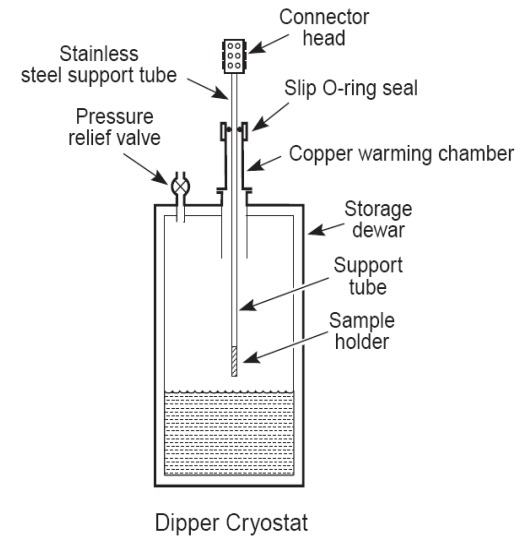
Select Amazing Phenomena of Helium as "Superfluid"



Periodic Table of Superconductors

1 H																	2 He
3 Li	4 Be 0.023											5 B	6 C 15	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al 1.2	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti 0.40	23 V 5.4	24 Cr 3.0	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn 0.85	31 Ga 1.1	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr 0.61	41 Nb 9.3	42 Mo 0.92	43 Tc 7.8	44 Ru 0.49	45 Rh 0.0003	46 Pd 3.3	47 Ag	48 Cd 0.52	49 In 3.4	50 Sn 3.7	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La 4.9	72 Hf 0.13	73 Ta 4.5	74 W 0.015	75 Re 1.7	76 Os 0.66	77 Ir 0.11	78 Pt 0.0019	79 Au	80 Hg 4.2	81 Tl 2.4	82 Pb 7.2	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Dm	111 Rg	112 Uub						
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu				
90 Th 1.4	91 Pa 1.4	92 U 0.20	93 Np	94 Pu	95 Am 0.60	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr				

- superconductor
- superconductor under pressure
- special form is a superconductor
- not a superconductor



Superconductor

- Meisner effects (levitation)

<http://www.youtube.com/watch?v=4VGACLNfZ8s>

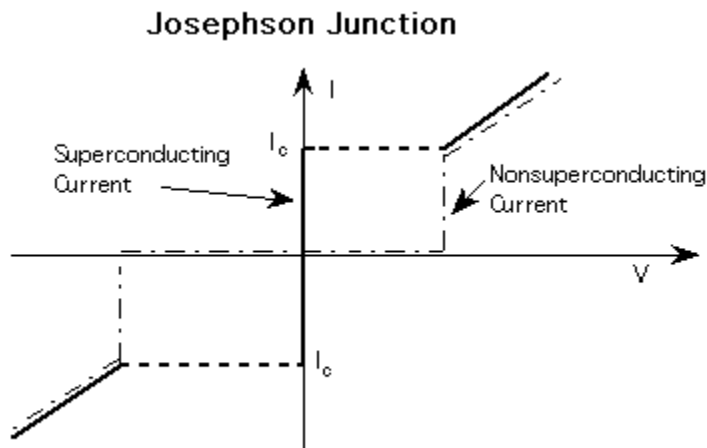
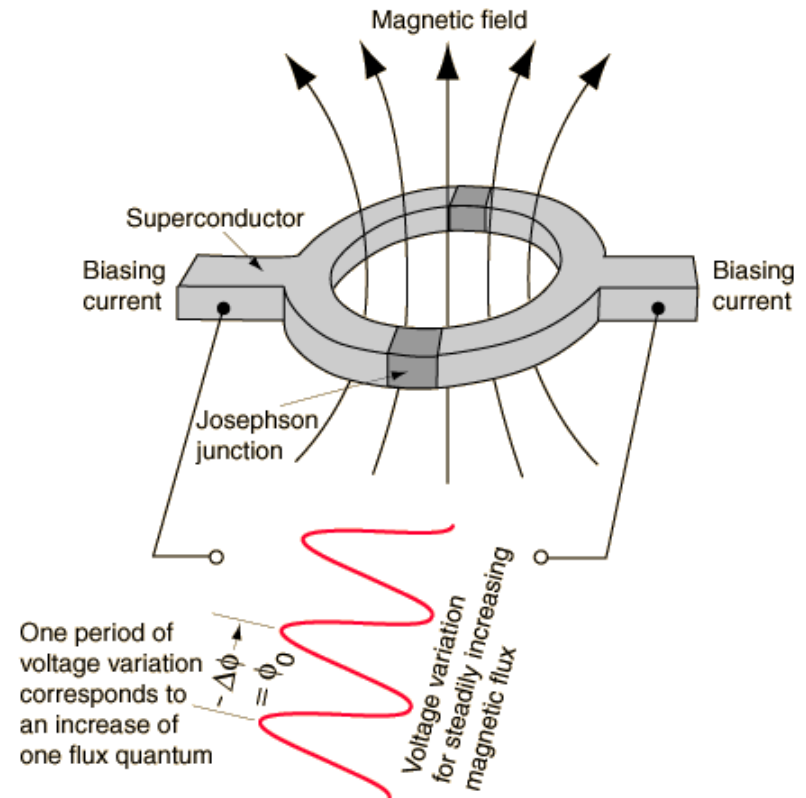


Fig. 14



Superconductor

- Meisner effects (levitation)

<http://www.youtube.com/watch?v=4VGACLNfZ8s>

Physical realization of quantum computation

Condensed Matter

Liquid-state NMR
NMR spin lattices

Impurities in semiconductors & fullerenes
Nitrogen vacancies in diamond
Spins in quantum dots

Electrons on liquid He
2DEG in the quantum hall regime

Josephson junctions (superconductor-based)
– charge, flux, and phase qubits

AMO

Linear ion traps

Neutral-atom optical lattices

Cavity QED + atoms

Linear optics/single photons

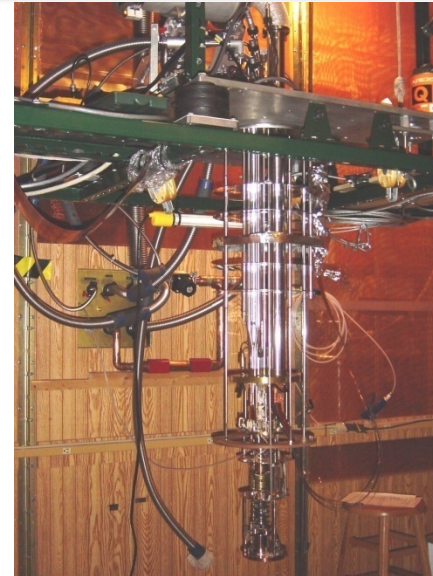
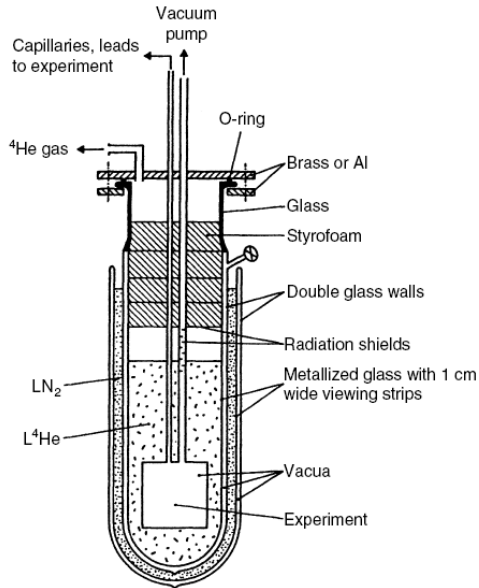
Preparation – Manipulation/Control – Detection

How to accomplish these before the coherence (entanglement) is lost!

Storage of cryoliquids: cryogenic dewars (cryostats)



Cryostats



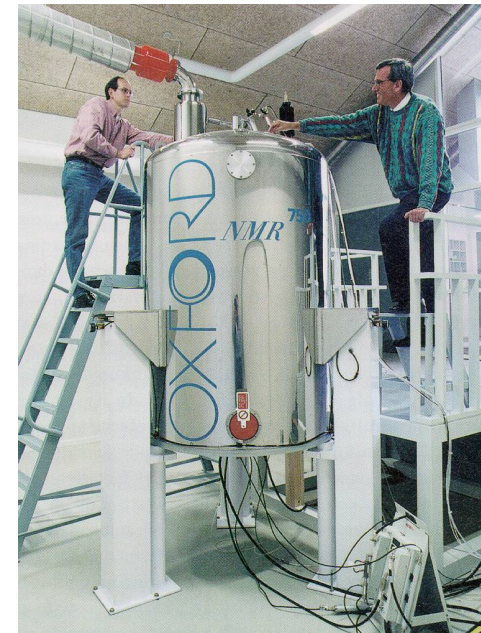
Flow cryostat



Magnetic optical cryostat

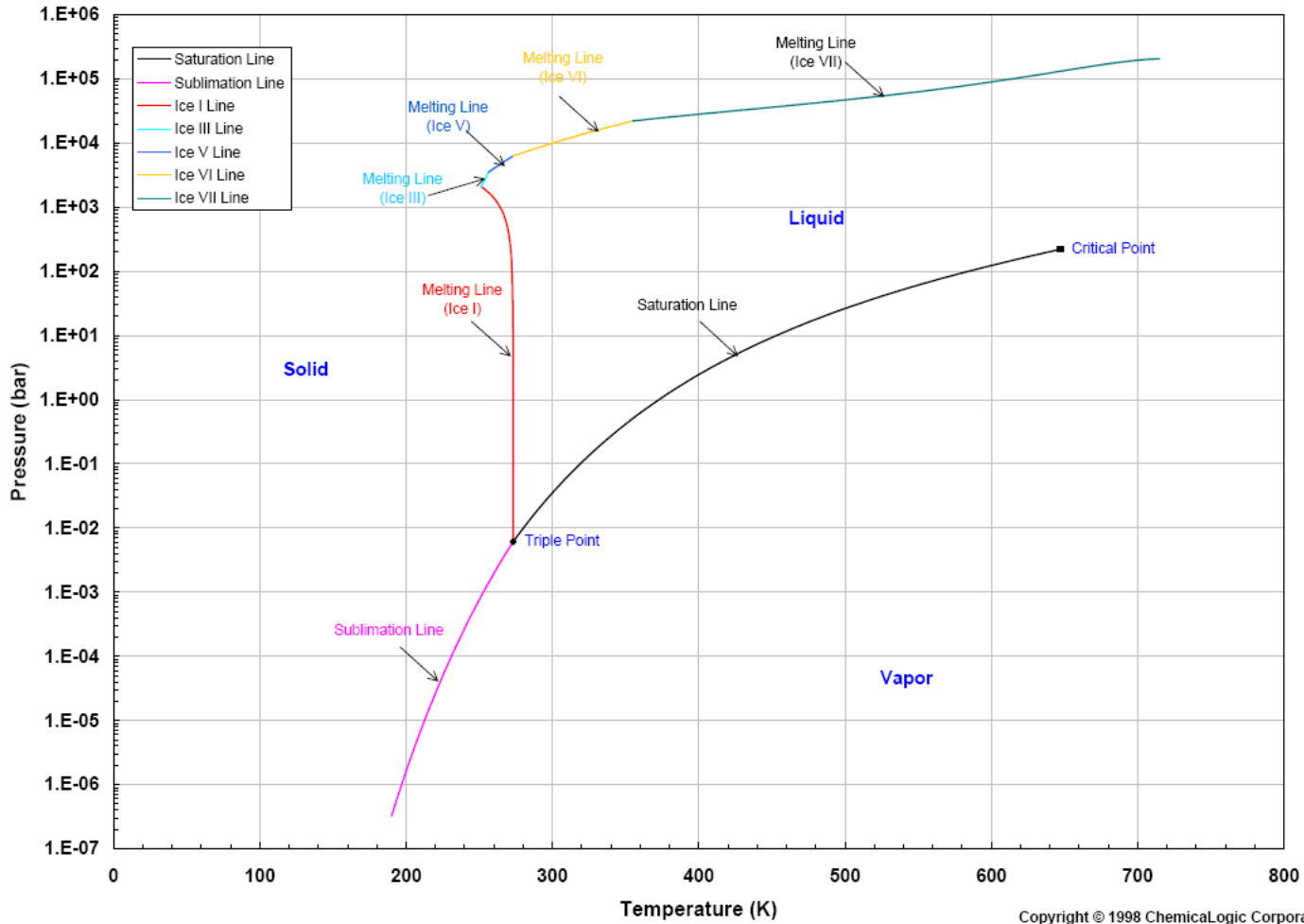


Closed cycle



Water Phase Diagram

Phase Diagram: Water - Ice - Steam



CO₂ Phase Diagram

