The Impact of Theory on Applied Physics*

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Stephen B. Libby
Theory & Modeling Group Leader
V Division
Physics and Advanced Technologies
Lawrence Livermore National Laboratory
University of California

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The Purpose of Theory is to Gain Fundamental Understanding of Nature - In Applied Physics it Drives Invention and the Finer Control of Nature

- There are an enormous number examples of how theoretical physics has directly impacted applied science. In the past century, many came from the heroic days of the discovery of quantum mechanics and its immediate impact on *everything*: condensed matter/materials science, chemistry, electronics, lasers, applications of nuclear physics,…

- A current example of an invention illustrating the powerful influence of a discovery familiar to you: Beta detected nuclear magnetic resonance

- Two Personal Experiences in Applied Physics & Numerical 'Experimentation.'

- A current case (personal taste here!) of a broad area in need of overarching insights.
    - The design and control of plasma machines
        - entropy flow and the optimization of x-ray sources (e.g. X-Ray Lasers)
        - inertial fusion devices - thermal efficiency analysis
        - optimal extraction of energy from collisionless plasmas - non-Abelian phase space rearrangement (for later discussion)

- The emergence of key themes
    - The compression of information
    - If you can't calculate it (in principle), you don't understand it! Numerical 'experiments' and the discovery of basic principles - "what lies beneath"
    - How to gain insights into systems not susceptible to standard experimental science (climate, geophysics, large scale engineering - space shuttle, Reactors, ITER, NIF, …)?

The Invention of Beta-Detected Nuclear Magnetic Resonance Immediately Followed T. D. Lee and C. N. Yang’s Discovery of Parity Violation and C. S. Wu et. al. ’s Direct Experimental Demonstration

- T. N. Novey & V. Telegdi suggested to D. Connor the use of parity violating beta emission asymmetry from polarized, radioactive nucleus to measure its g factor.

- Initial experiment relied on ~ 80% polarization of ^{8}Li arising from slow polarized neutrons captured on ^{7}Li.

- muon spin resonance version & high flux radioactive beams using the “ISOL” method result in powerful condensed matter applications decades later.

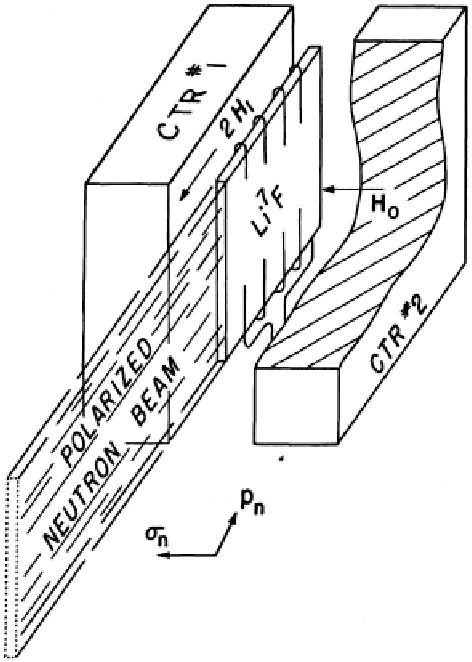


FIG. 1. Schematic experimental arrangement. Beta counters CTR No. 1 and CTR No. 2 detect the electrons emitted with a momentum component parallel or antiparallel to the nuclear polarization. The coil shown around the LiF target provides the rf field $2H_1$ which, at resonance, depolarizes the Li^8 nuclei.

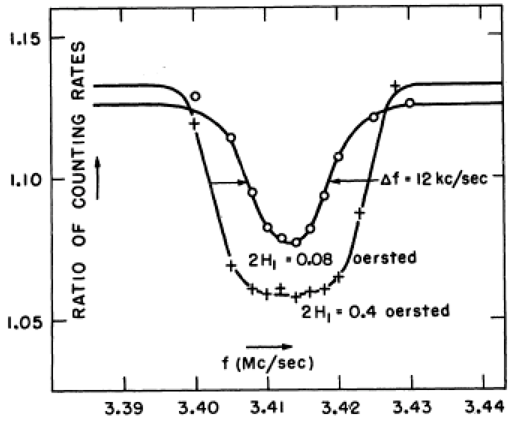


FIG. 2. Nuclear resonance of Li^8 as shown by change of beta-emission asymmetry when the frequency of the rf field is varied. Static field H_0=5418

D. Connor, “*Measurement of the Nuclear g Factor of ^{8}Li*,” Phys. Rev. Lett. 3, 429, 1959.

^{8}Li $\square_{1/2}$ ~ 1.2 sec, $J^{\square}$ = 2^+ ground state, $Q_{\square}$ ~ 13 MeV

Beta Detected NMR, Relying on ‘ISOL,’ Parity Violation and Laser-Hyperfine Induced Nuclear Polarization can be 10^{10} x more sensitive than Conventional NMR

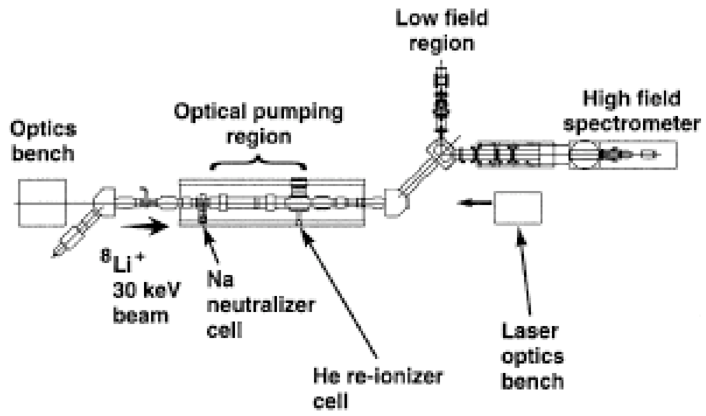


Fig. 1. Top view of the layout of the β-NMR facility at TRIUMF.

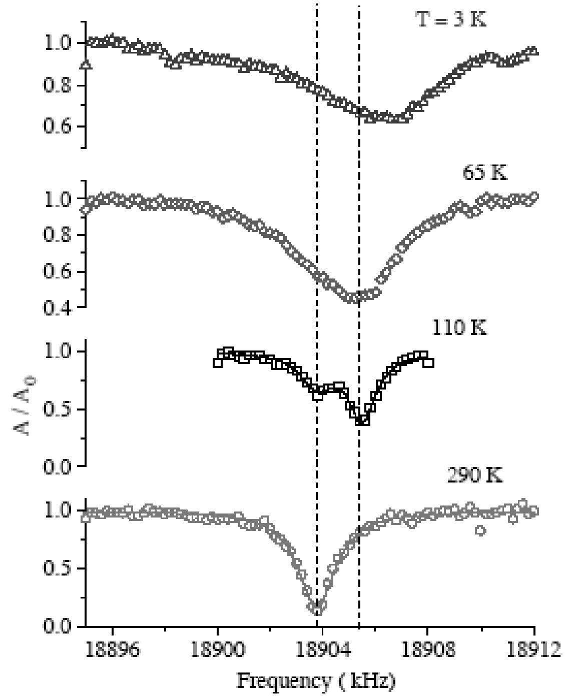


Fig. 5. Temperature dependence of the ^{8}Li β-NMR resonance in a 50 nm silver film on top of 100 nm $YBa_2Cu_3O_{6.95}$ on a $SrTiO_3$ substrate in an applied field of 3 T. Above T_c the spectrum is identical to 90 nm Ag film on sapphire [8], whereas at low temperatures additional broadening of the lines is observed.

- **NMR resonance measurements usually require ≥ 10^{18} target atoms/cc in condensed media.**
- **‘normal’ polarization ~ $1 - e^{-gB\mu/kT}$ ~ 7x 10^{-6} for B=10^4 gauss and T ~ .025 eV**
- **ISOL produces pure ^{8}Li at 10^8/sec via proton spallation**
- **Parity violation asymmetry gains ~ 10^5**
- **Hyperfine coupled laser induced polarization gains ~ 10^5**

Kiefl et. al. Physica B 326, 2003, 189. (note signal is from 50 nm Ag film)

Experiences in Applied Physics (1): Soft X-ray Laser Interferometery of Transient Plasmas

- To ‘see,’ or image anything requires illumination with a source with higher spectral brightness (effectively ‘hotter’) than the object.

- The effective spectral brightness of the 155 Å (80 eV) Yttrium soft XRL is equivalent to a 1 GeV Planckian source.

- Interferometric measurements of 3 x 10^{13} W/cm^2 laser produced ~ keV plasma done with high fringe visibility.

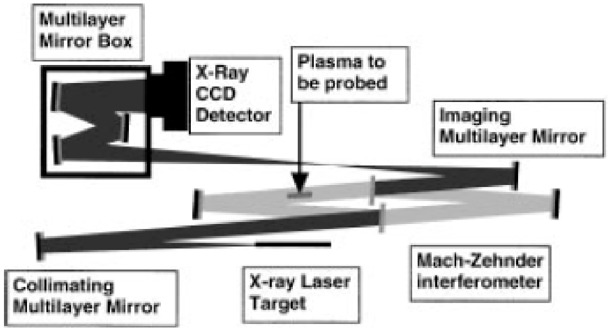


FIG. 2. Experimental setup showing the optical components for plasma probing using a soft x-ray Mach-Zehnder interferometer.

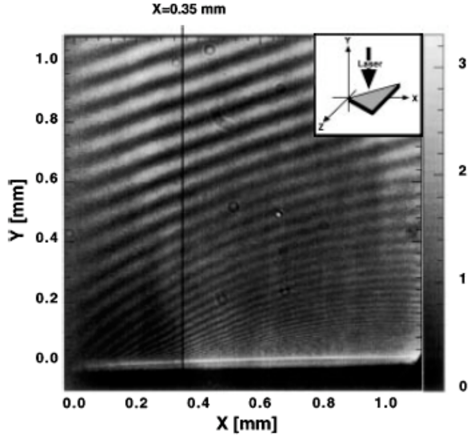


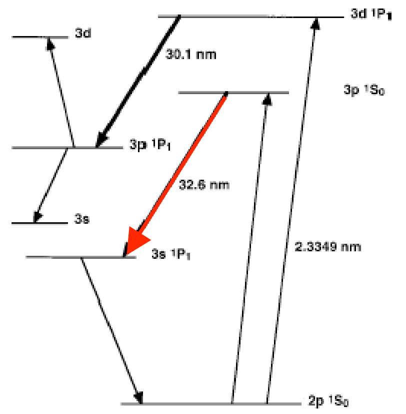
FIG. 4. Interferogram of CH target irradiated at 2.7 × 10^{13} W/cm^2. The inset shows the target geometry.

L. B. Da Silva, T. W. Barbee, Jr., R. Cauble, P. Celliers, D. Ciarlo, S. Libby, R. A. London, D. L. Matthews, S. Mrowka, J. C. Moreno, D. Ress, J. E. Trebes, A. Wan, F. Weber, "**Electron Density Measurements of High Density Plasmas Using Soft X-Ray Laser Interferometry**," Phys. Rev. Lett. 74, (1995), 3991

X-Ray Lasers as a High Energy Density ‘Heat Engine’ - Application to Imaging Hot Transient Plasmas

Energy Level Diagram and Spectrum for Ne-like and Ni-like ion Soft X-ray Lasers

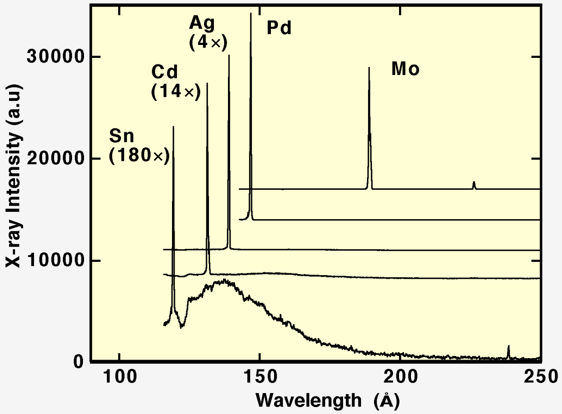
Ne-like Ti Ion X-ray Laser Energy Level Diagram



J. Nilsen *et al.*, *J. Opt. Soc. Am. B.* 17(6), 1084 (2000)

- Strong monopole collisional excitation drives gain on 32.6 nm 3p - 3s line

Ni-like Ion X-ray Laser Spectra



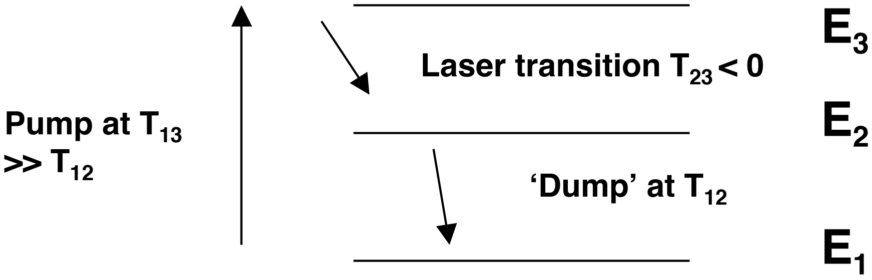
J. Dunn *et al.*, *Phys. Rev. Lett.* 84, 4834 (2000)

- Ni-like ion x-ray lasers are many orders brighter than other spectral lines

- ‘laser driven’ XRL works by line focused laser producing cylindrical plasma @ ~ 1keV, 10^{20} ions/cc
- quasi-steady state non-equlibrium Carnot engine
- 3 level maser action
- ‘ideal efficiency’ ~ 8% far larger than actual 3 x 10^{-6}
- eliminate wasted kinetic pathways?

X-ray lasers have very high peak brightness 10^{24} - 10^{25} Ph. mm^{-2} $mrad^{-2}$ s^{-1} (0.1% BW) $^{-1}$]
Effective Brightness temperature ~ 1 GeV black body!

High Energy Density Plasma Machines (1): Non-Equilibrium Radiation Transport & Thermodynamics - Entropy Flow, Computational Acceleration & X-Ray Source Optimization



Pump at T_{13} >> T_{12}

Laser transition $T_{23} < 0$

'Dump' at T_{12}

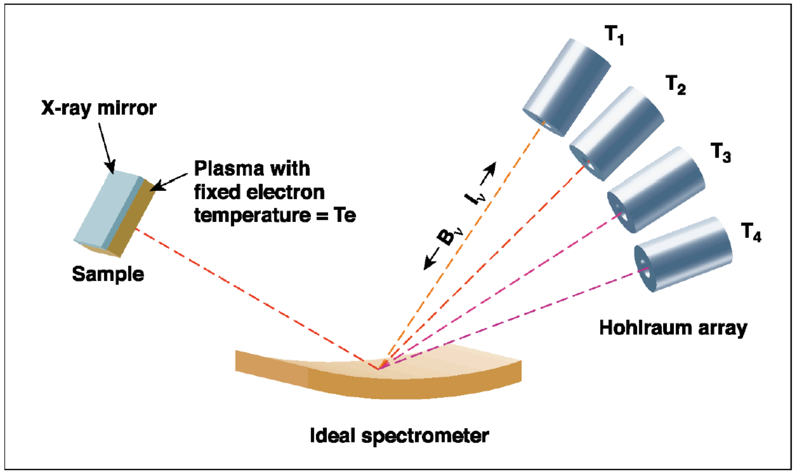
E_3

E_2

E_1

$$n_3/n_1 = \exp(-E_{31}/kT_{13})$$
$$n_2/n_1 = \exp(-E_{21}/kT_{12})$$
$$n_3/n_2 = \exp(-E_{31}/kT_{13} + E_{21}/kT_{12})$$
$$T_{23\ \text{effective}} \sim T_{13}/\left(1 - T_{13}/T_{12}\right) < 0$$

H. E. D. Scovil and E. O. Schulz-Dubois, **Three Level Masers as Heat Engines**, Phys. Rev. Lett. 2, p. 262-263, (1959).



- Each hohlraum has a controlled temperature
- When all temperatures are equal, plasma is in LTE

$$\boxed{(\kappa_\nu^e - \kappa_\nu^a)\, B_\nu = \sum_{\nu'} R_{\nu,\nu'}\, \delta T_{\nu'} + O\,(\delta T^2)}$$

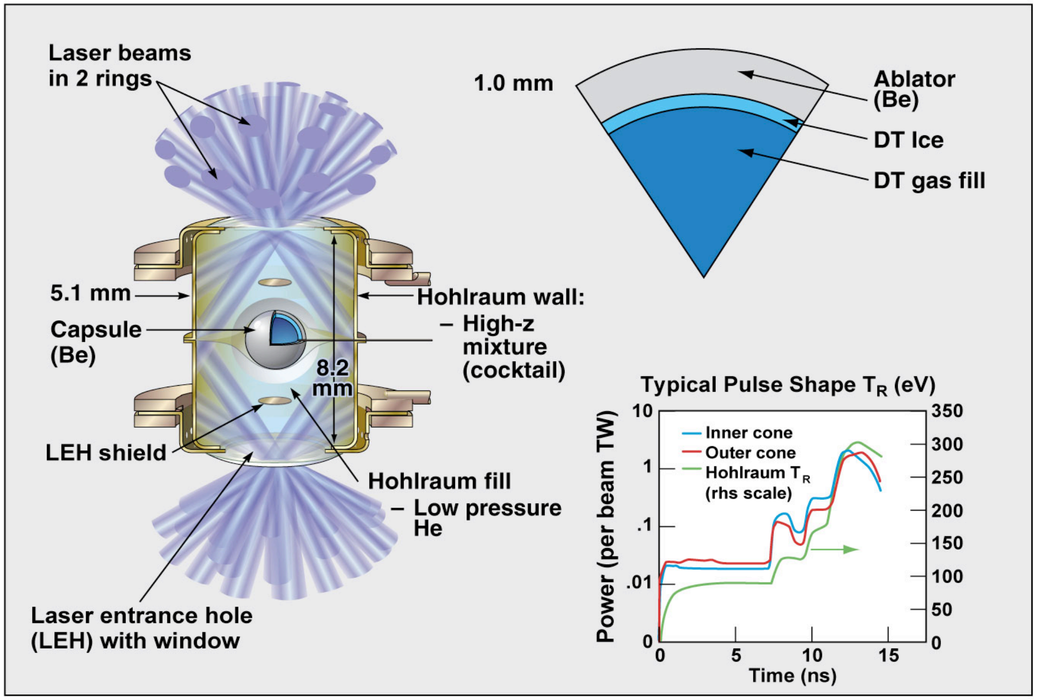
$$R_{\nu,\nu'} = \frac{\delta E_\nu}{\delta T_{\nu'}} = \frac{h\nu h\nu'}{kT^2} A_{j\to i} A_{l\to k} (n_\nu^0 + 1)(n_{\nu'}^0 + 1) Q_{kl}^{ij}.$$

Follow the entropy: Non-equilibrium corrections to Kirchoff's law factorize into 'linear response matrix' $R_{□□'}$ accelerating radiative transfer calculations 10^3 fold; use $R_{□□'}$ to optimize laser schemes.

R. M. More, S. B. Libby, G. Faussurier, and T. Kato, "**Atomic Processes in Near Equilibrium Plasmas**," Journal of Quantitative Spectroscopy & Radiative Transfer, 71 (2-6): 505-518 Oct-Dec 2001.

Inertially Confined Fusion is a Primary Example of a High Energy Density 'Plasma Engine.' Are there rules controlling its efficiency? How do the 'degrees of freedom' play?

NIF Indirect Drive target point design



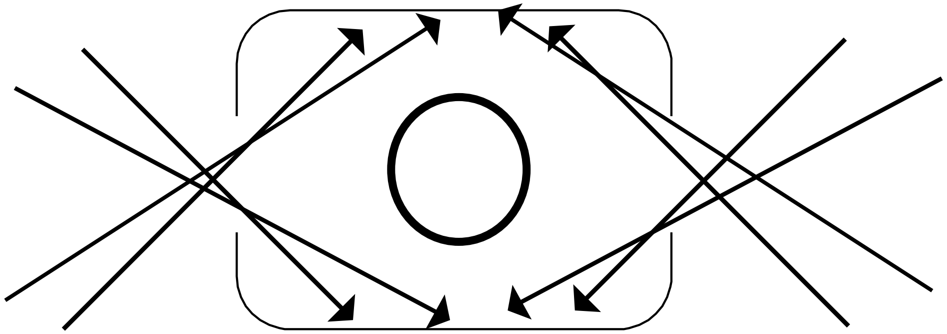
NIF-0505-10823r2
4/28JL/cld

- For ignition, need hot-spot with T_{ion} ~ 10 keV, ρR_{HS} ~ 0.3 g/cm^2 ρ_{HS} ~ 80 gm/cc.

- For confinement need ρR_{tot} > 1 g/cm^2 — otherwise hot-spot disassembles before igniting. (burn fraction) = $\rho R/[\rho R+6]$ assumes burning sphere, don't get there if ρR_{tot} < 1 g/cm^2)

- Ignition begins at ~isobaric stagnation. $R_{DT\text{-}Be}$~30 microns

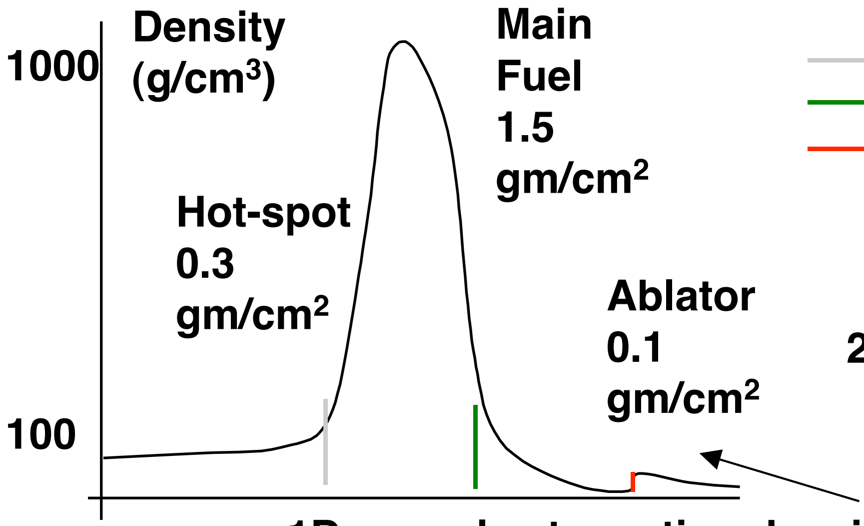
Indirect Drive Applies Accurately TImed Laser Heating Pulses to Hohlraum to Make Controlled Quasi-Planckian Soft X-Ray Drive - What Laws Apply to this ‘Engine?’



- Goal is keep main DT fuel near adiabat, heating only 2% of DT to center ‘hot spot’ 10 keV □ need only ~ 1.25x10^5 J coupled of 2 10^6 J drive. *Is this the most efficient way*?

$P_{FD}(B) = 21.8\square\square^{5/3}$ $E_{FD}(\mathrm{J}) = 3.3\cdot 10^6\square\,\square_{DT}^{2/3} M_{DT}(kg)$

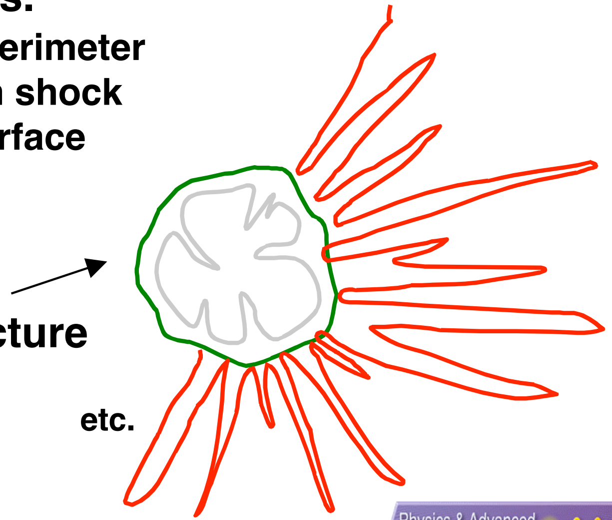
- Control of hohlraum coupling, shock timing, hydrodynamic instabilities could benefit from comprehensive ‘thermal analysis.’



1D capsule stagnation density picture

▬ Hot-spot perimeter
▬ Stagnation shock
▬ DT/Be interface

2D or 3D picture



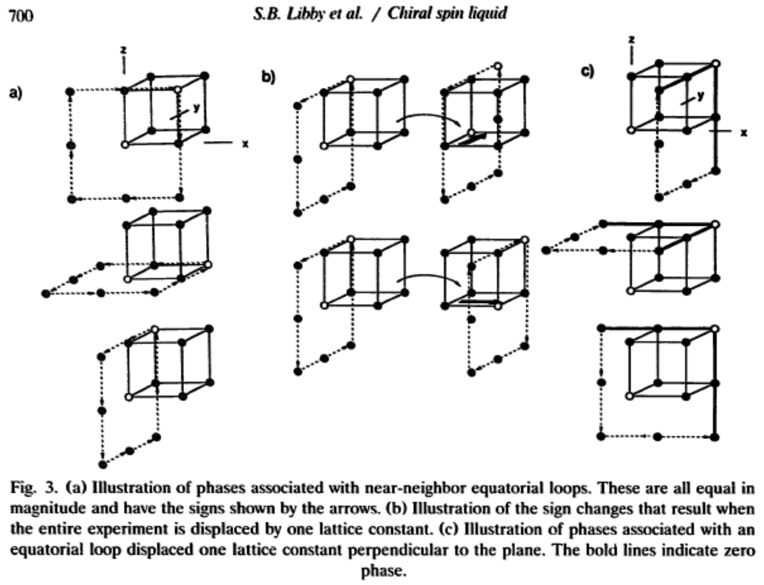
An Experience in Numerical Experimentation (2): Chiral Spin Liquids & High T_c Superconductivity

- **2D Chiral Spin Liquid States motivated by Hubbard Model, Mott insulators, & High Tc effective Chern-Simons interaction and fractional statistics.**

- **What happens in 3D chiral spin liquid state?**

- **Wrote code to map Berry phases of interacting fundamental excitations ("spinons & holons") - played "Faraday" on Cray YMP ~ 1991**

- **Discovered 'spontaneous' Non-Abelian Interaction with strange lattice topological term - significance unresolved!**



700 *S.B. Libby et al. / Chiral spin liquid*

Fig. 3. (a) Illustration of phases associated with near-neighbor equatorial loops. These are all equal in magnitude and have the signs shown by the arrows. (b) Illustration of the sign changes that result when the entire experiment is displaced by one lattice constant. (c) Illustration of phases associated with an equatorial loop displaced one lattice constant perpendicular to the plane. The bold lines indicate zero phase.

$$\mathscr{L}_C = p \sum_{\mu\nu\rho} \sum_{a}{}' \epsilon^{\mu\nu\rho a} A^0_\mu \partial_\nu A^a_\rho ,$$

S. B. Libby, Z. Zou, and R. B. Laughlin, "**Non-Abelian Monopoles in the 3-Dimensional Chiral Spin Liquid**," Nuclear Physics B<u>348</u> FS, (1991) 69

A. Tikofsky, S. B. Libby, and R. B. Laughlin, "**Gauge Theory of the 3 - Dimensional Chiral Spin Liquid**," Nuclear Physics B<u>413</u>, (1994), 579

Interplay of Theory and Applied Science: Key Themes

- **With its goal of understanding nature, theoretical physics results in the powerful 'compression of information' - lists of mere facts become organized as principles and these ideas act as fundamental underpinnings of applications.**

- **Great discoveries often quickly lead to inventions in surprising places.**

- **Applications offer wonderful prospects for theorists. The 'ripeness' of many applications is unappreciated and unknown, but the opportunities are all around us. Be entrepreneurial!**

- **Large scale computation is now being applied both for discovery in basic science *and* where traditional reductionist science doesn't work easily (e.g. climate). Can these latter, important areas be informed by the viewpoint of a theorist?**

"Why Americans are more Concerned with the Applications than with the Theory of Science…"

"It may be assumed that the more democratic, enlightened, and free a people is, the greater will be the number of those selfish admirers of scientific genius,and the more profit will be made out of discoveries immediately applicable to industry, bringing renown and even power to their inventors…

"It is easy to see how, in a society organized on these lines, men's minds are unconsciously led to neglect theory and devote an unparalleled amount of energy to the applications of science…"

"Nowadays the need is to keep men interested in theory…."

" ….Confining ourselves to practice, we may loose sight of basic principles….we might be left without the capacity to invent new methods and only be able to make a clumsy and an unintelligent use of wise procedures no longer understood…"

- Alexis de Tocqueville 1848

- Democracy In America, Vol. II, Chap. 10