Science with Spallation Neutrons

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Fermilab
Oct 2004

OAK RIDGE NATIONAL LABORATORY

Spallation

[f. SPALL *v.*[1] + -ATION.]

1. *Nuclear Physics*. The detachment of a number of nucleons or small nuclei from a larger nucleus, esp. as a result of the impact of an energetic nucleon or other particle. Freq. *attrib.*, as ***spallation product***.

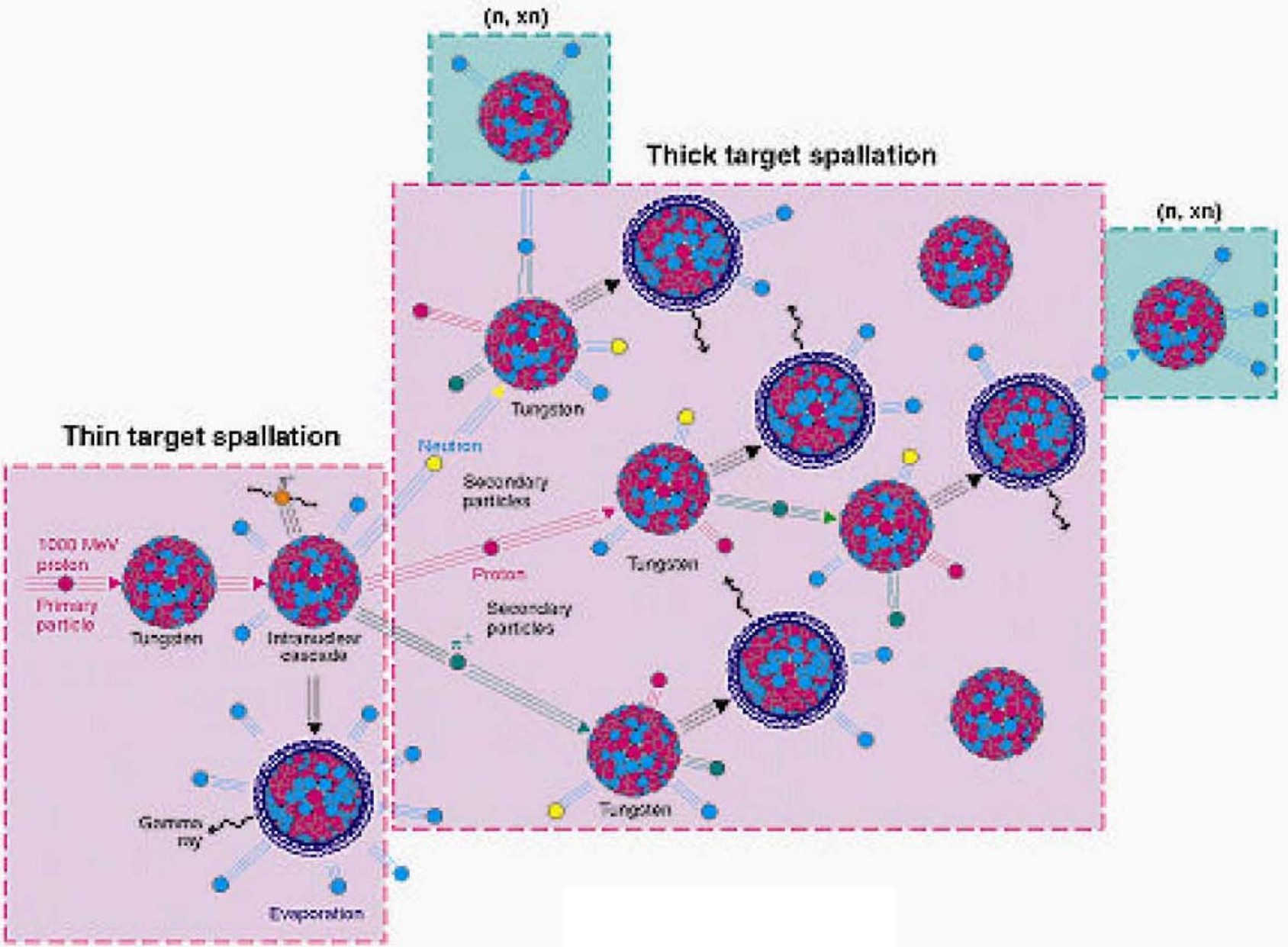
Spall

A chip or splinter, esp. of stone or ore.

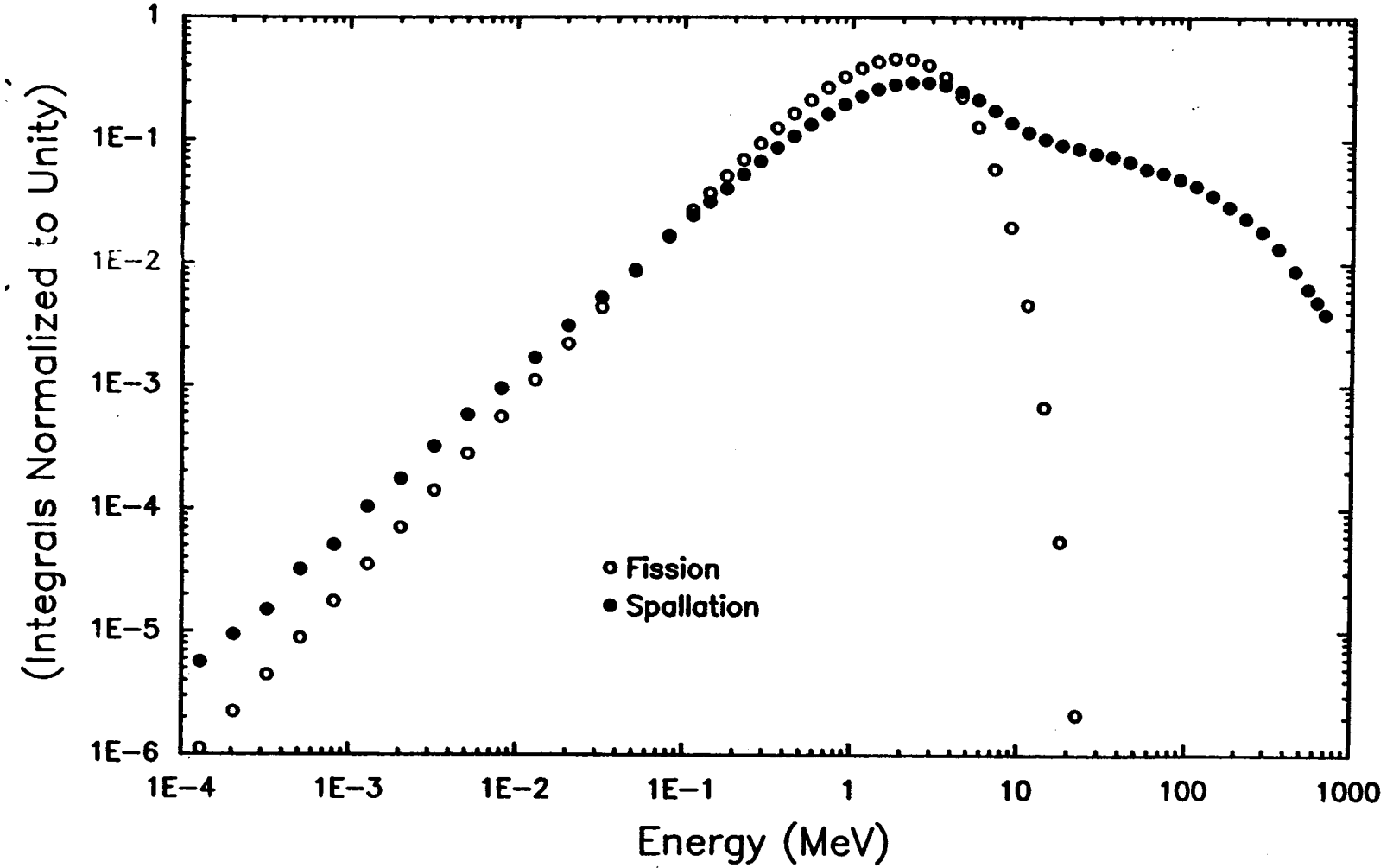
…**1611** ***"the peeces which flie from stone in the hewing thereof."…***

Oxford English Dictionary, 2nd Edition

At ~8 GeV, each incident proton liberates ~250 neutrons

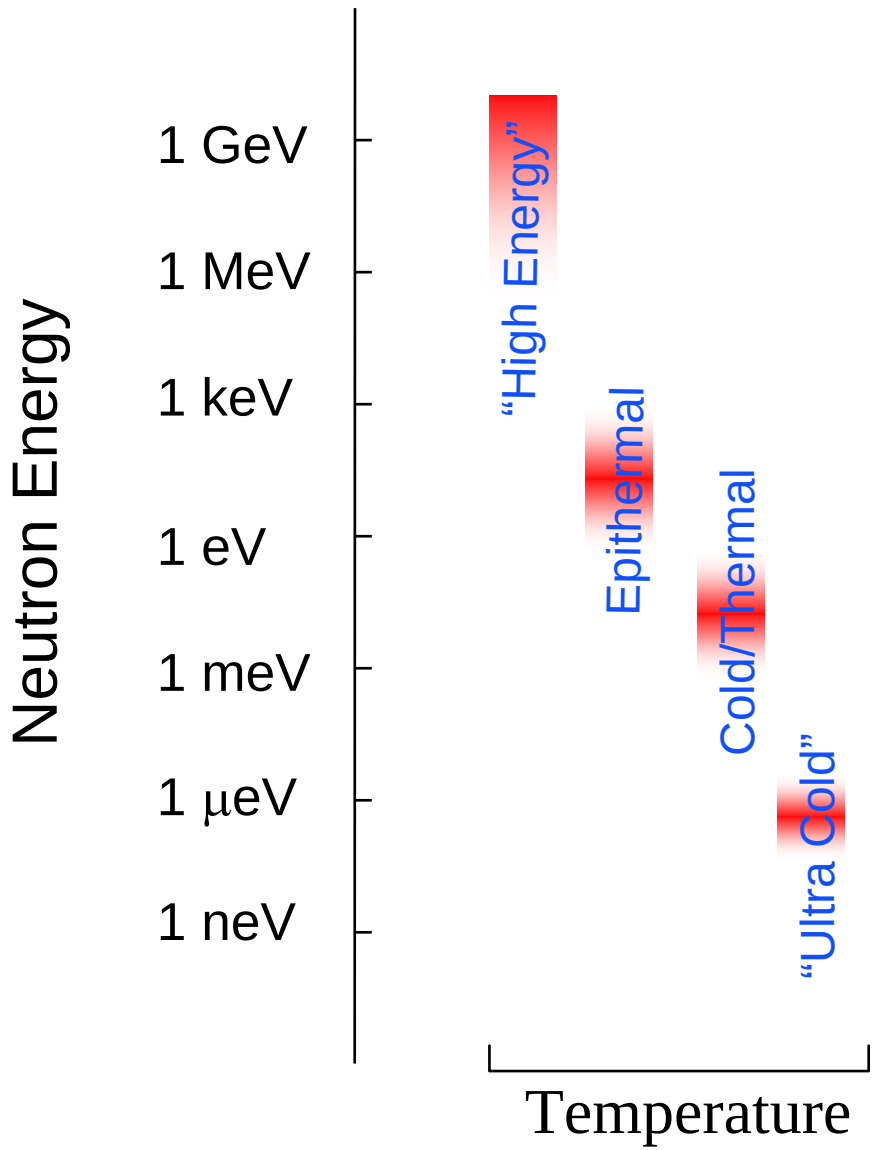


The Spallation Neutron Spectrum is Broad



(Courtesy,Gary Russell)

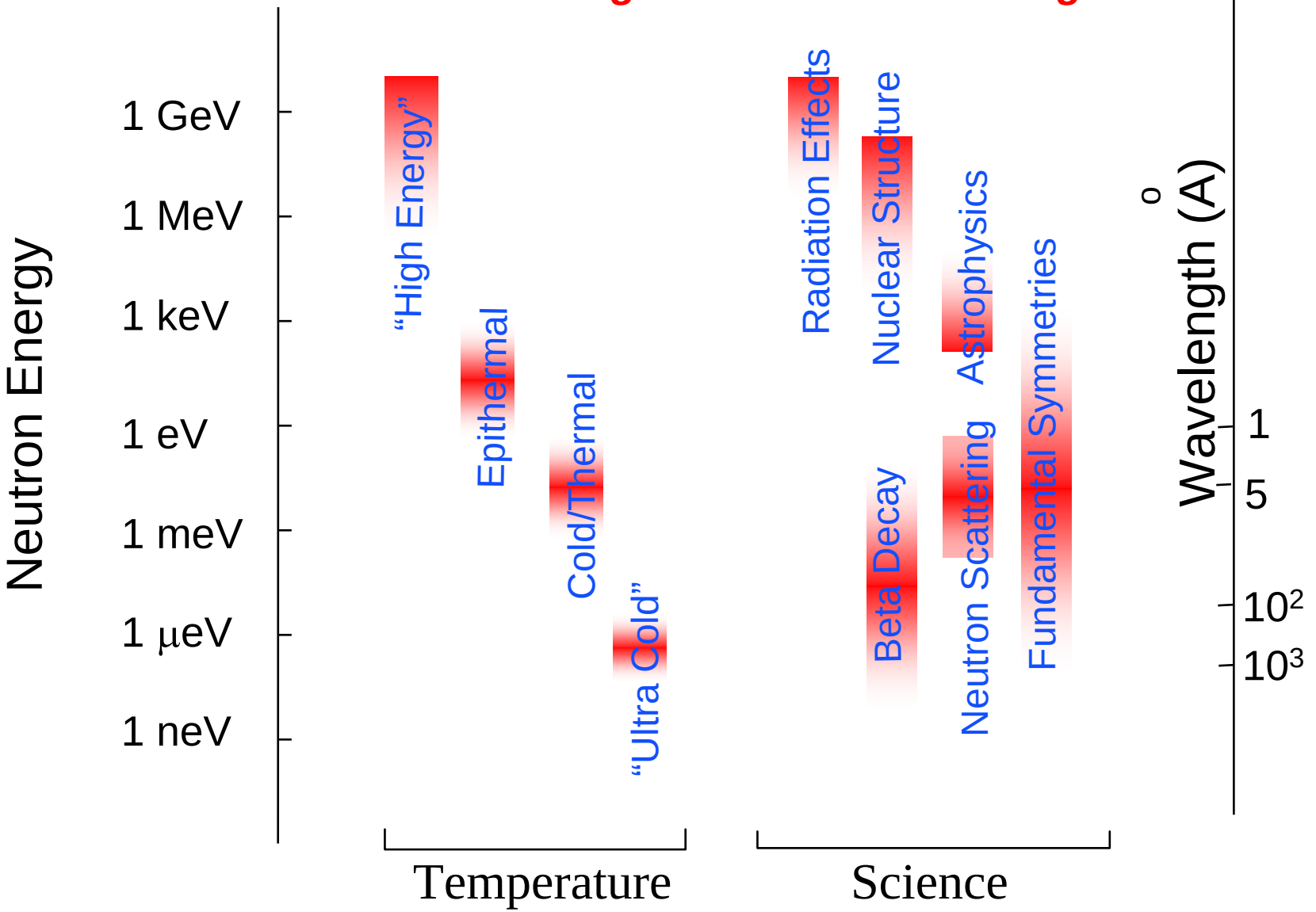
Spallation Neutrons and Spallation Science



A spallation neutron source can produce "useful" fluxes of neutrons over ~15 orders magnitude in energy.

Spallation Neutrons and Spallation Science

There is interesting Science at ALL Energies



The Spallation Neutron Source

- The SNS will begin operation in 2006 in Oak Ridge, Tennessee
- Baseline design is 1.4 MW (1 GeV, 1.4 mA), 60 Hz operation
- Initial facility will have 1 target station with 24 instruments

Mev Neutrons

Example: Radiation Effects in Semiconductors

BOEING 777
777

FLY-BY-WIRE 777 KEEPS TRADITIONAL COCKPIT

DAVID HUGHES/BOEING FIELD, SEATTLE

The 777 cockpit is a cross between the 747-400's and 767's, but the similarities are only skin deep. The new flight control system depends on wires rather than cables

Boeing has combined a fly-by-wire system with traditional cockpit controls in the 777 to create a large, twin-engine transport that represents an evolution rather than a revolution in its product line.

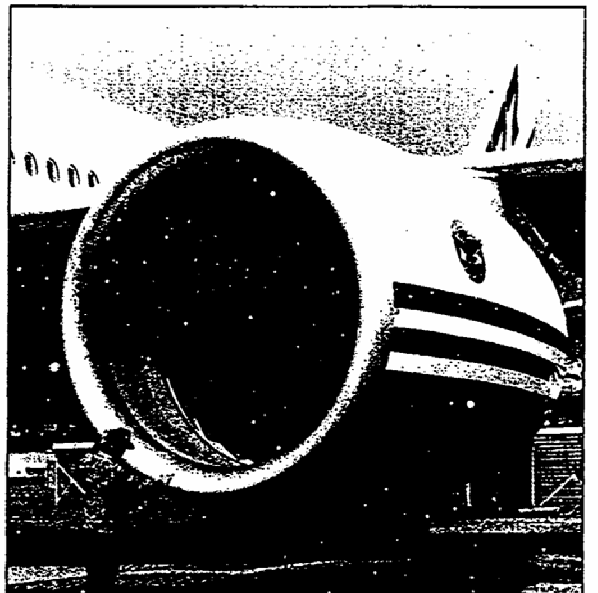
Pilots of cable-controlled, glass-cockpit aircraft will feel right at home in the 777 cockpit. Its front panel is very similar to the one in a Boeing 747-400. The overhead panel and pedestal copy the 767 layout. There is a yoke that moves when the autopilot is engaged, and the throttles move when the autothrottle system adjusts power. This tactile feedback is an additional cue to the pilot as to what the auto-flight systems are doing. (Airbus has taken a different approach on fly-by-wire cockpits by employing side-stick controllers and throttles that remain fixed when the autothrottle adjusts power.)

Boeing also has added speed stability to the fly-by-wire logic so that forces build up on the control column when the aircraft changes speed. The pilot then neutralizes the forces with trim.

The internal structure of the 777 avionics system represents a dramatic departure from previous Boeing designs. Fly-by-wire computers warn pilots when they are flying too fast or slow, or when they are overbanking. Boeing does not limit

The aircraft also handles well on one engine with no unusual control problems, even though up to 77,200 lb. of thrust is provided on one side of the aircraft. The 777 is quite agile for a heavy transport, providing rapid roll rates of up to 20 deg./sec. for evasive maneuvering.

This *AVIATION WEEK & SPACE TECHNOLOGY* pilot had the opportunity to fly a 777 at Boeing Field last month. The flight test aircraft, sequence number WA001,



John E. Cashman, chief pilot on the 777 program, occupied the right seat while I took the left seat. After we entered the cockpit, Cashman started the APU and switched power on the 777 electrical system, which made a smooth "no break" transition from ground cart power. The overhead scan of system status is very straightforward.

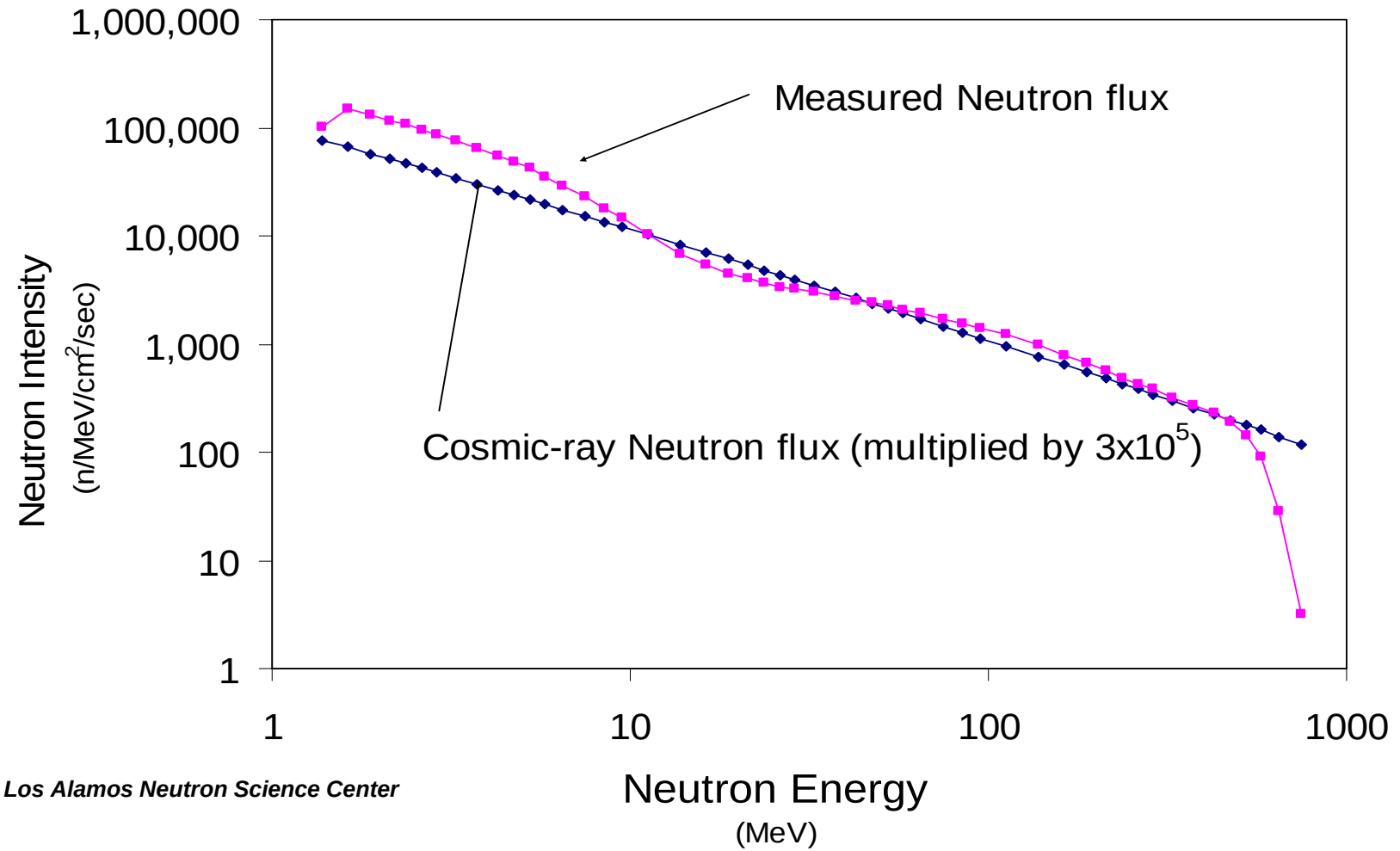
The aircraft's gross weight was 445,000 lb., including 135,500 lb. of fuel. Cashman set up our takeoff speeds in the flight management system (FMS) control display unit. V_1 would be 125 kt., rotate (V_R) would be 129 kt. and takeoff safety speed (V_2) would be 137 kt. The speeds are all marked on the vertical tape on the primary flight display. We would climb out initially at about 152 kt. (V_2 + 15) as commanded by the flight director when VNAV engages at 400 ft. above the ground.

The 777 has two 8 X 8-in. flat-panel, liquid crystal displays (LCDs) in front of each pilot—one for primary flight information and one for navigation. There is also one multifunction display (MFD) in the center of the panel and a second one below it in front of the throttle quadrant on the center pedestal. The large-format displays from Honeywell make even minute details easy to read on the navigation map display. The three small Rockwell Collins LCDs for standby attitude, speed and altitude are remarkably clear and easy to read.

When 777s enter service, they will also have data-link capability that will allow pilots to

Neutrons are the dominant reliability concern to semiconductor devices at aircraft altitudes.

Spallation neutrons are ideal for accelerated testing



Data from Los Alamos Neutron Science Center

Accelerated Testing of Semiconductors Using Spallation Neutrons

- ***Reliability tests using spallation neutrons helped to prove the air worthiness of the Boeing 777!***

- *Boeing, Aerospatial, Texas Instrument, Intel, Lockheed, Hewlett-Packard, Digital Equipment, Fujitsu, Honeywell, Saab, Hitatchi,…are testing their chips using spallation neutrons.*

- *Even the Bay Area Rapid Transit (BART) System has tested semiconductor switches for reliability using spallation neutrons!*

THE HARDER SIDE OF SEARS | SUN'S DARK SECRET

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NOVEMBER 13, 2000

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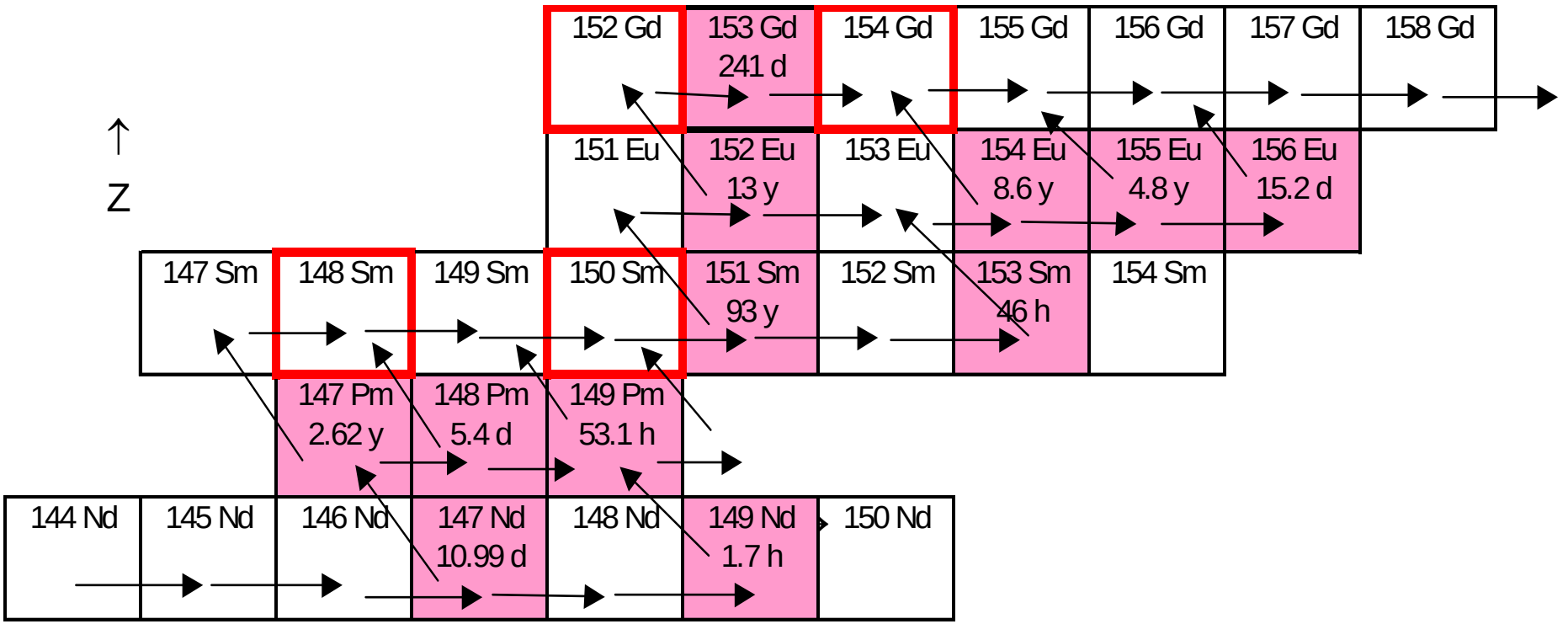
keV Neutrons

Example: Stellar Astrophysics

The Stellar "S-Process"

A quasi-equilibrium slow (S) process in which nuclei are "cooked" in the stellar interior (Temperature ~10^8K, Energy ~20keV). This process involves a complex competition between neutron capture and nuclear beta decay.



The S-Process is Complex!

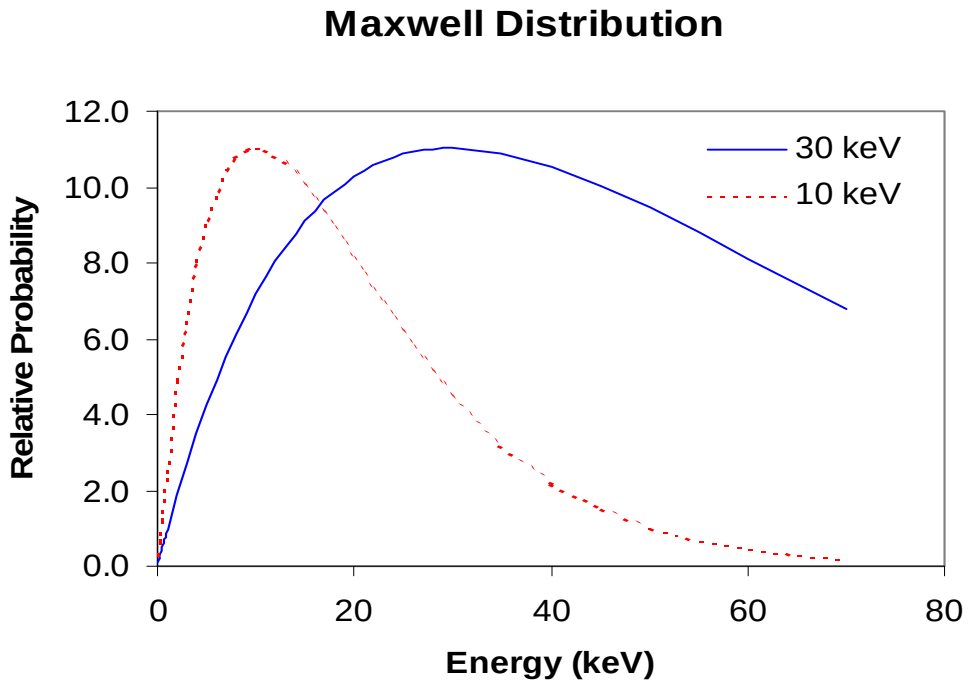
To Determine the relative abundances of elements formed during the S-Process it is necessary to know:

1. *Stellar Temperatures*
2. *Stellar Neutron Densities*
3. *Stellar Mass Densities*
4. *Beta Decay Lifetimes*
5. *Neutron Capture Cross Sections as a Function of Energy*

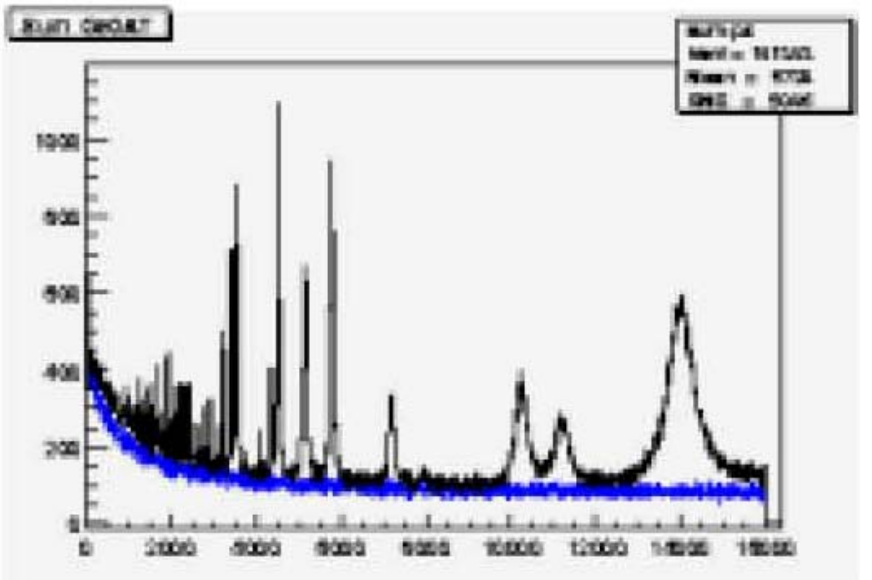
   - Especially for Radioactive Nuclei ! -

OR... if we know the nuclear properties, and astronomically determine isotopic abundances, we can understand what goes on in the interior of stars.

Resonance Structure is Very Important in the S-Process



Time of Flight n Capture Spectrum on ^{131}Sm



An intense <u>pulsed</u> neutron source is an ideal tool for the study of S-Process nucleosynthesis

meV Neutrons

"Neutron Scattering"

Why Neutron Scattering?

- *Low energy (meV) neutrons have wavelengths comparable to length scales associated with atomic order in condensed materials.*

  "neutrons probe the structure of materials"

- *Low energy neutrons have kinetic energies comparable to excitations (phonons, molecular vibrations/rotations,…) in condensed material*

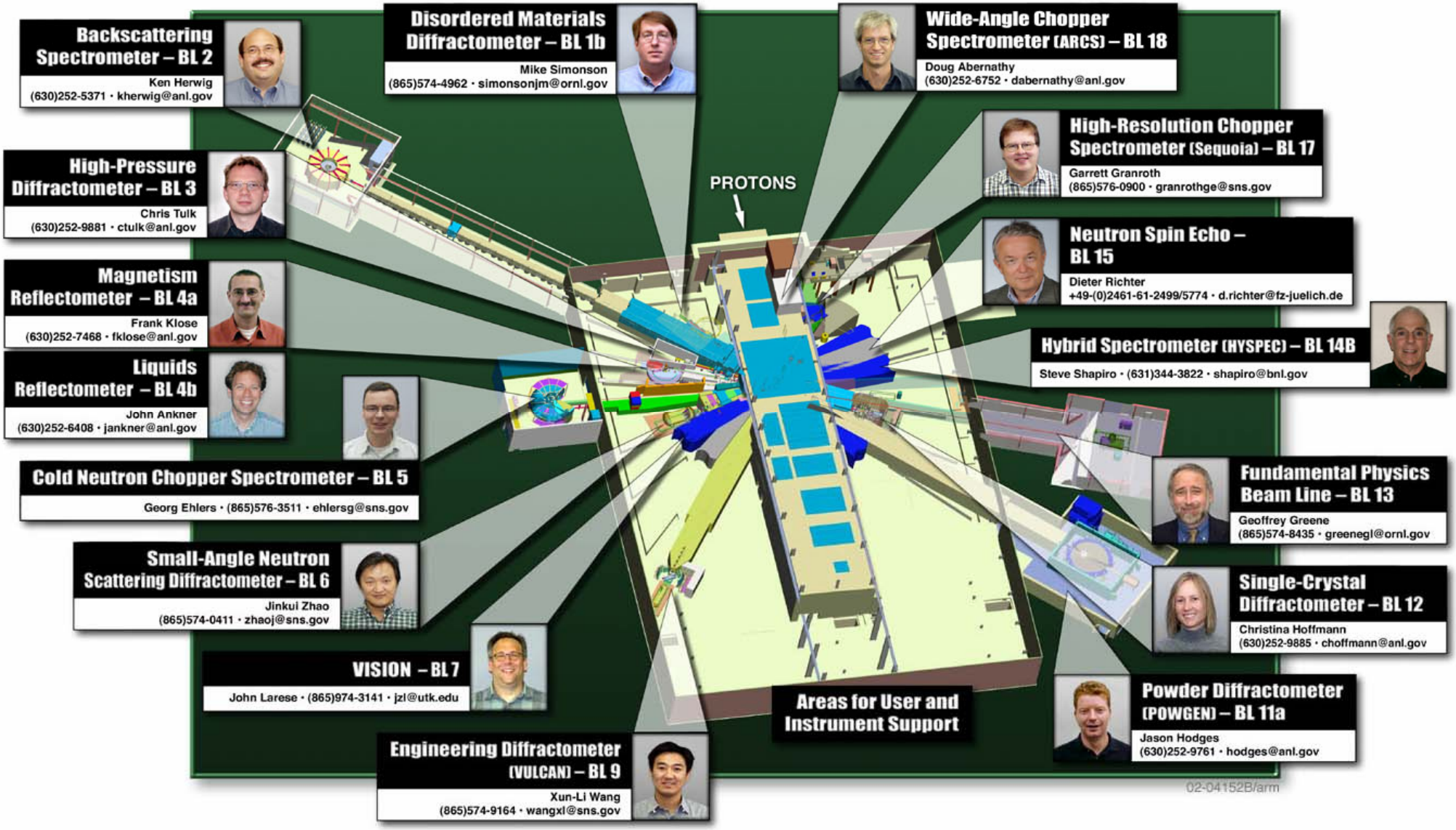
  "neutrons probe the dynamics of materials"

DISCLAIMER

"Neutron Scattering" includes important activities in Solid State Physics, Crystallography, Mechanical Engineering, Chemistry, Polymer Science, Biology, Geology,….

In the time allotted, it is not possible to do justice to this extremely broad field of research

SNS Initial Instrument Suite



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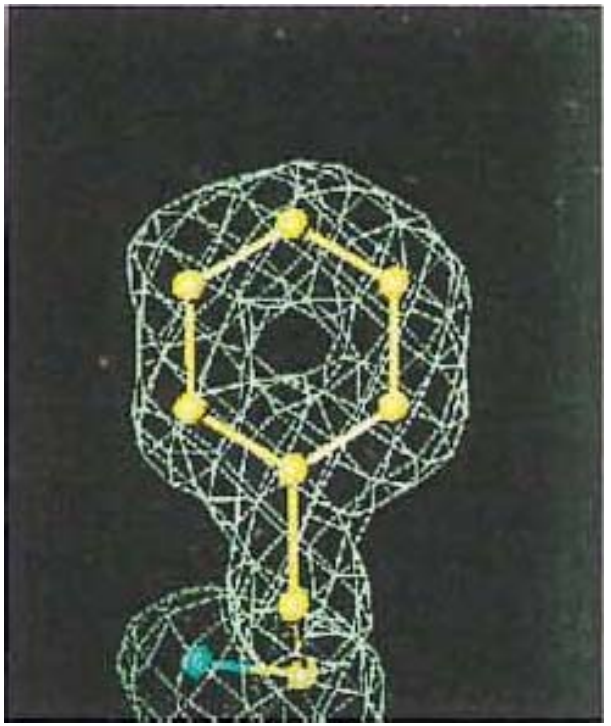
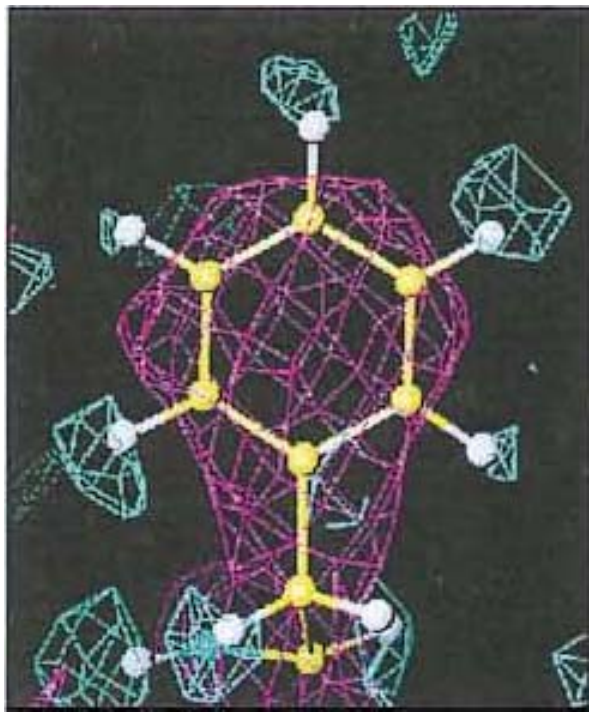
Example: Neutron Diffraction / Protein Crystallography

Neutrons scatter strongly from hydrogen and light elements whereas x-rays scatter strongly only from heavy elements

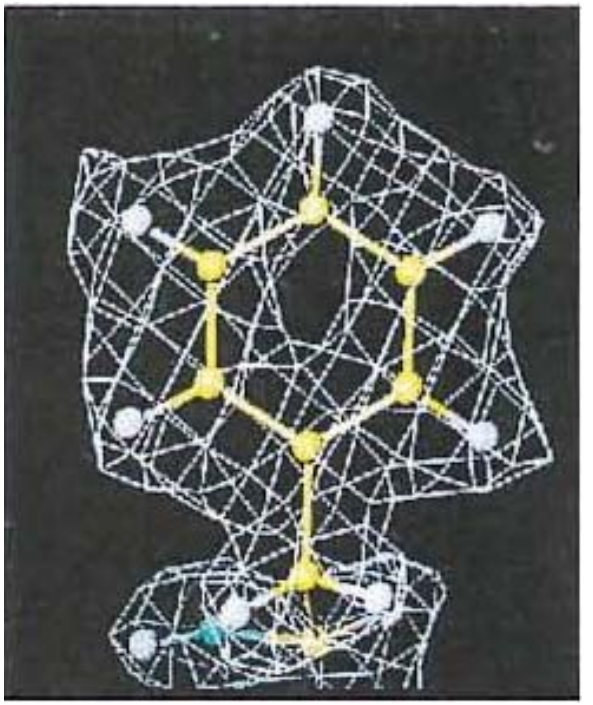
Isotopic Contrast Used to Determine Hydrogen Location



X-ray Diffraction



Neutron Diffraction

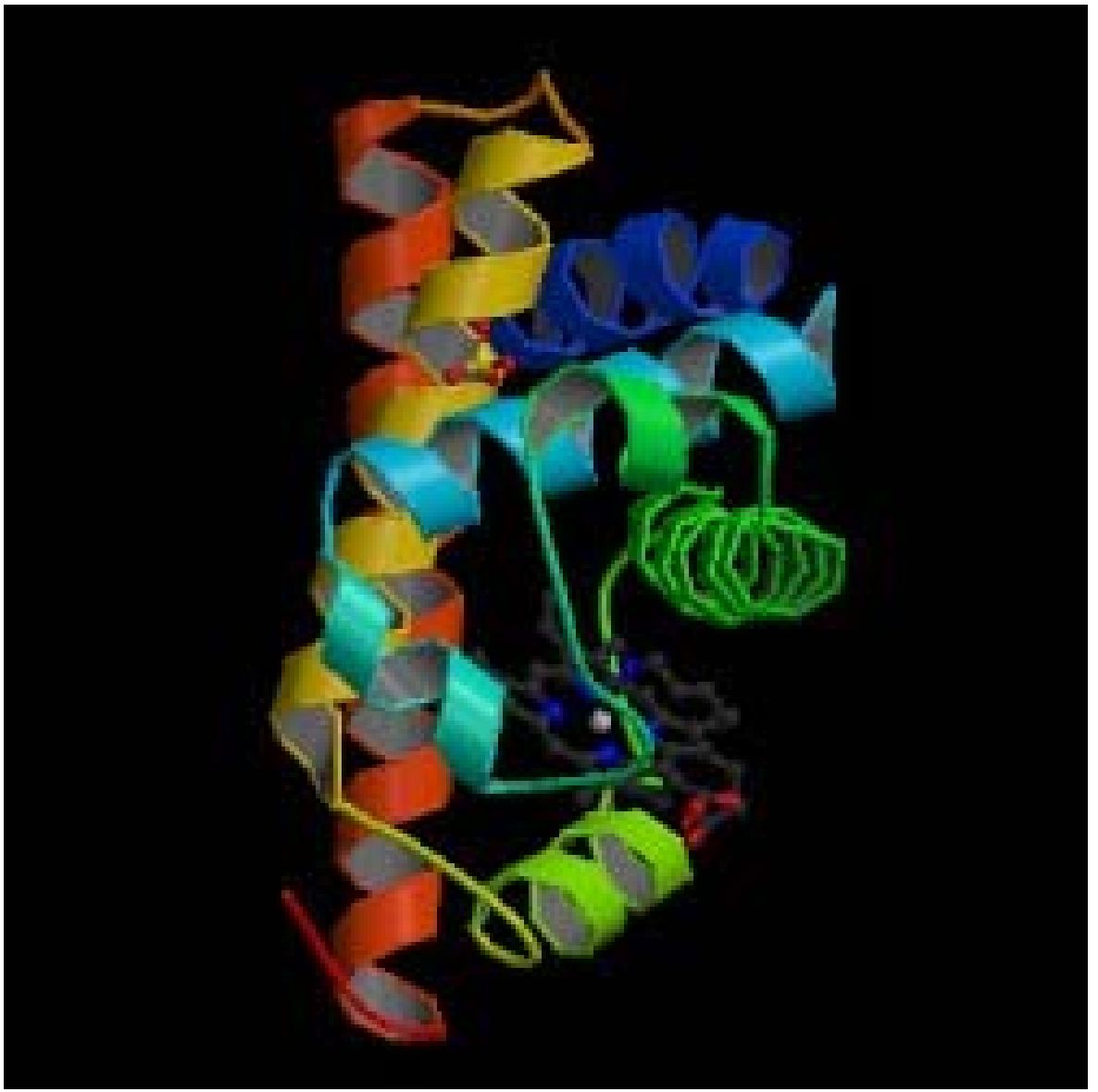


Neutron Diffraction

Deuterated Sample

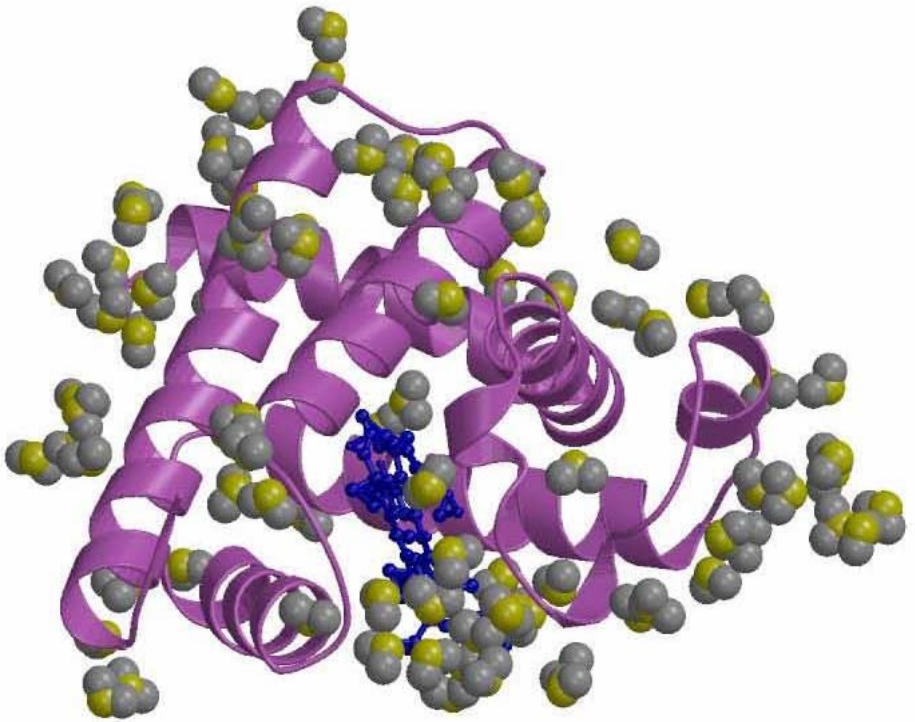
Shu, Ramakrishnan, and Schoenborn
PNAS 97 (8), 2000, 3872–3877

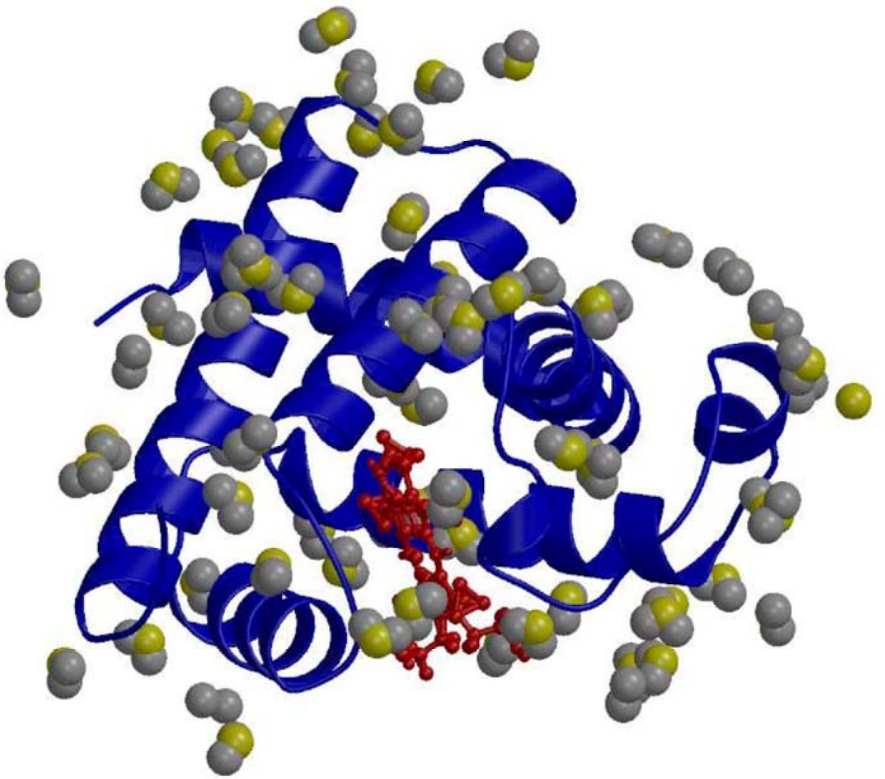
Structure of Myoglobin Determined Using X-ray Diffraction



Source: The Protein Data Bank
http://pdbbeta.rcsb.org/pdb/Welcome.do

Structure of Myoglobin Determined using Neutron Diffraction



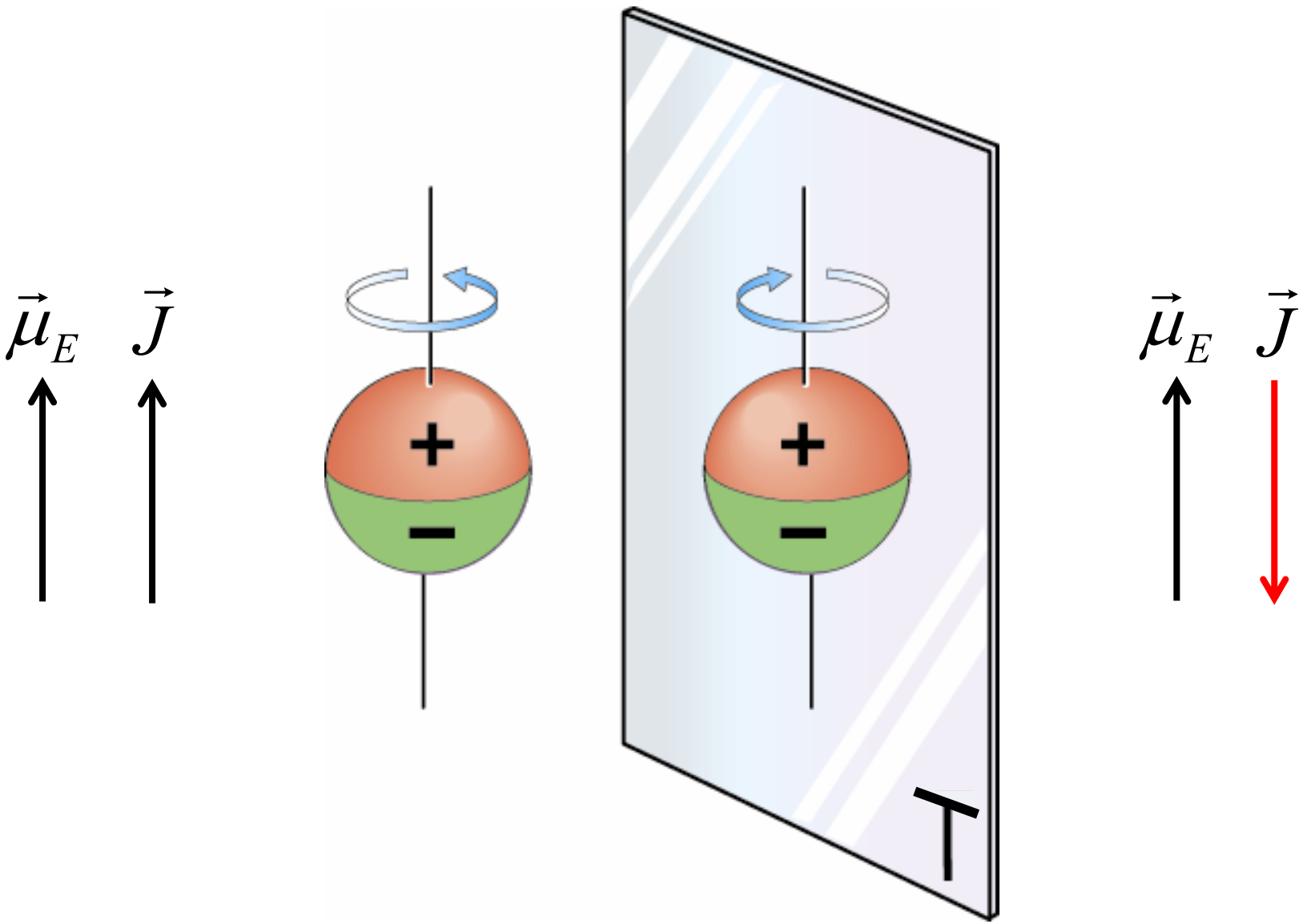


X. Cheng and B. P. Schoenborn ((1990) Acta Crystallogr. B46, 196 et seq.).
F. Shu, V. Ramakrishnan and B. P. Schoenborn ((2000) Proc. Nat'l Acad. Sci. USA 97, 3872-3877)

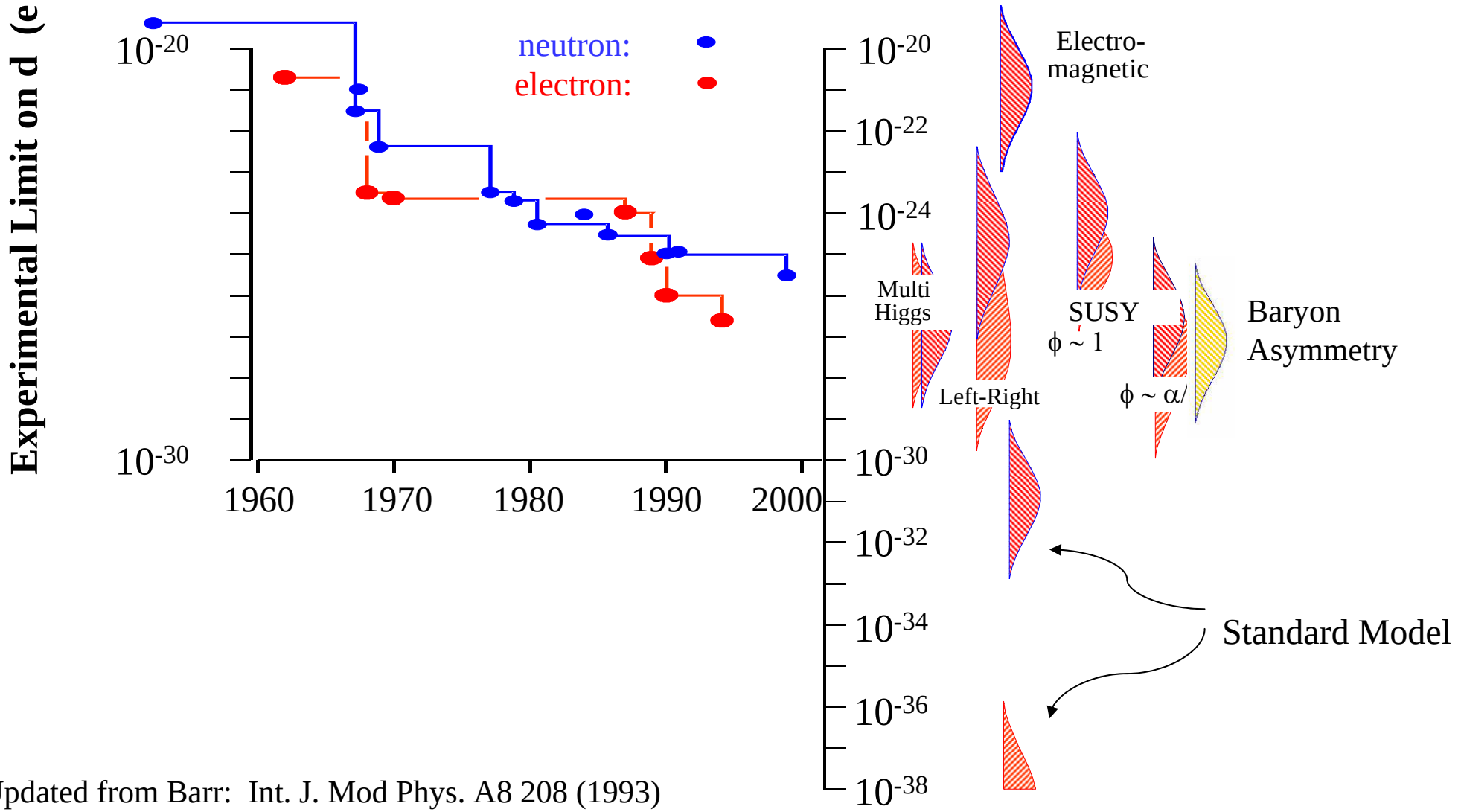
neV Neutrons

Example: The Neutron Electric Dipole Moment

An Electric Dipole Moment Violates T Non-Invariance



EDM limits: the first 50 years



Updated from Barr: Int. J. Mod Phys. A8 208 (1993)

EDM Statistical Sensitivity

$$\sigma_{edm} \propto \frac{1}{ET\sqrt{N_n m}}$$

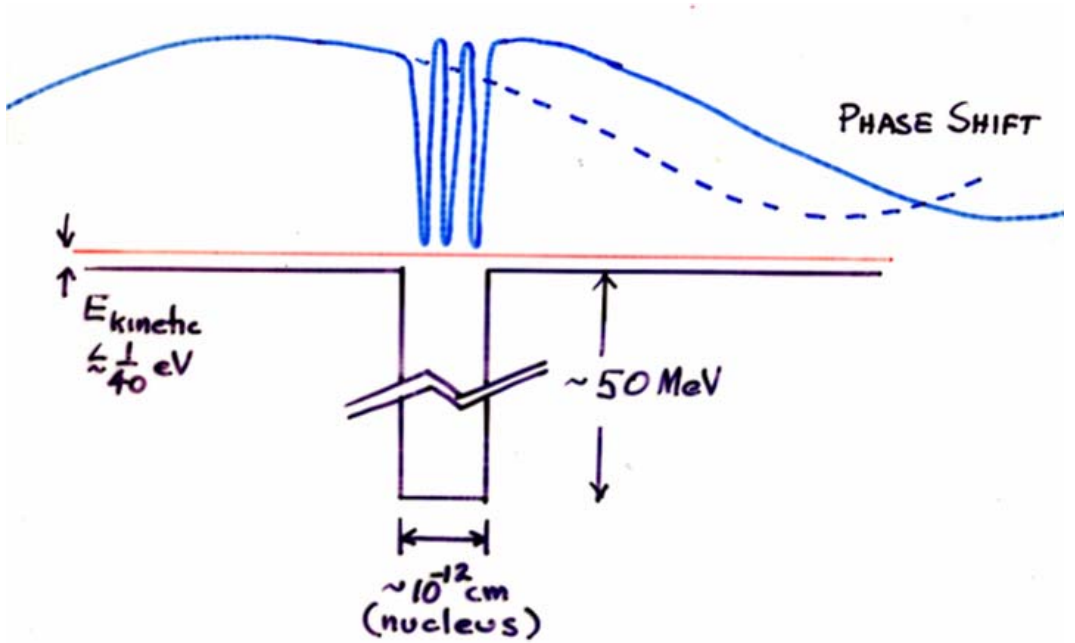
E = Applied Electric Field

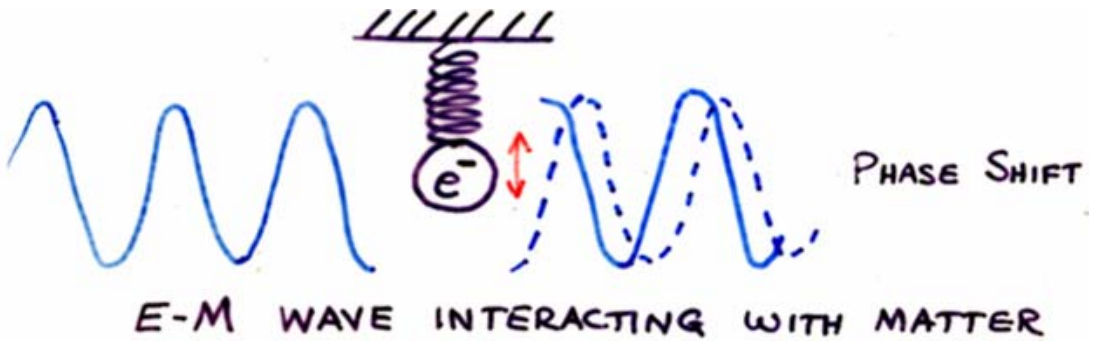
T = Observation Time per run ($\Delta\omega \approx T^{-1}$)

N_n = Number of neutrons observed per run

m = number of individual runs

Coherent ("Optical") Interaction Between Neutrons and Matter

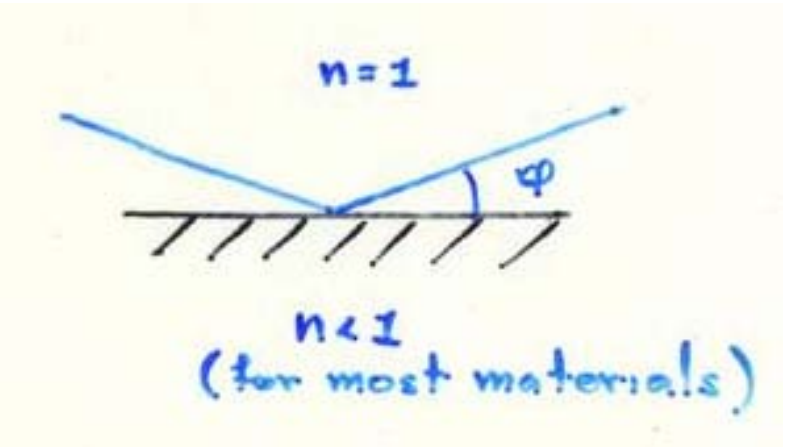




Phase Shift* ⟶ *Index of Refraction

Neutron Index of Refraction

$$n^2 = 1 - \frac{\lambda^2 N b_{coh}}{2\pi} \longrightarrow \cos\varphi_{crit} = n$$



For sufficiently large neutron wavelength, λ, n=0 and $\cos\varphi_{crit}$ =90°

This implies that neutrons will be reflected at all angles
and can be confined in a "bottle"

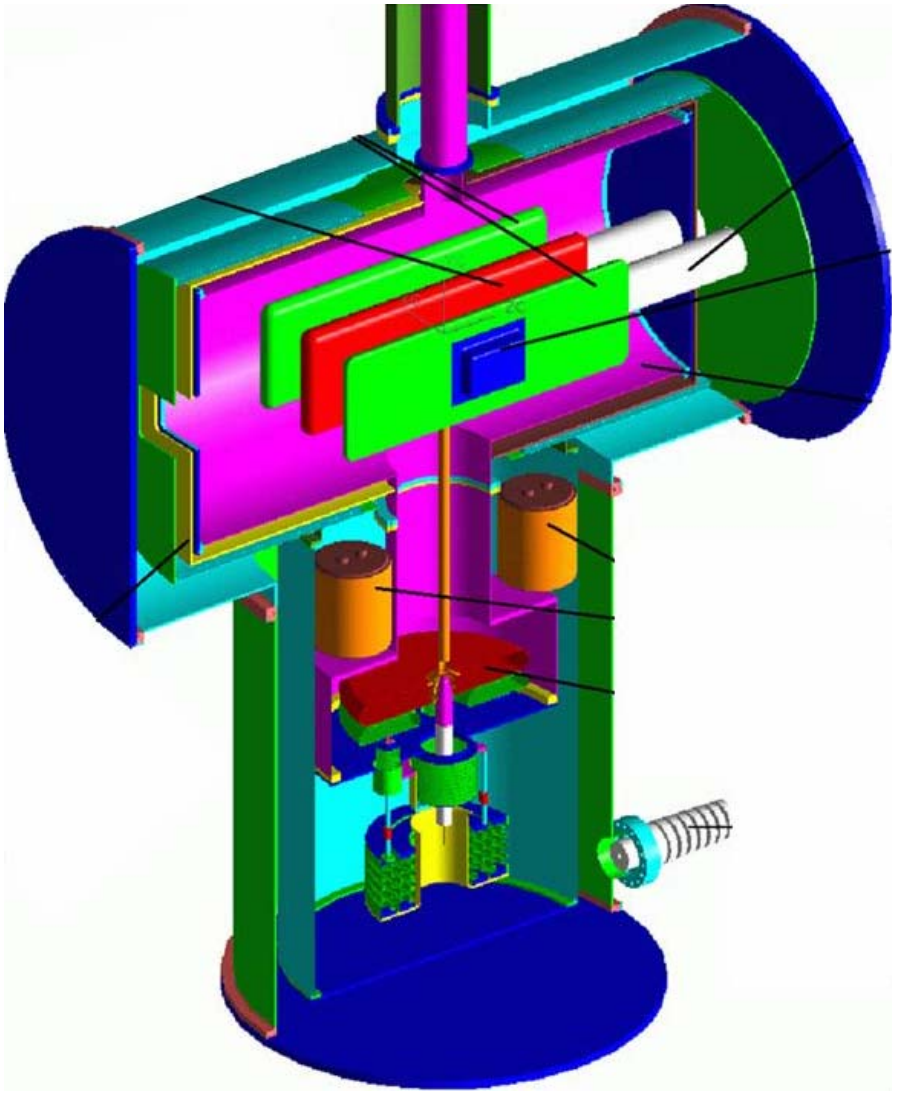


Figure Courtesy of M. Cooper and the EDM Collaboration

New Concept for Measurement of the Neutron EDM in a Superfluid Helium Bottle

(After Lamoreaux & Golub)

Collaboration Spokesmen:
M. Cooper and S. Lamoreaux

- *Polarized ultra-cold neutrons are trapped in a vessel filled with ^{4}He.*
- *The Larmor precession frequency is measured as a function of electric field*
- *The field is monitored by the precession. of polarized 3He in the vessel.*

Spallation Science

Some things I did not talk about

- *Small Angle scattering - polymers, biological structures, composites,...*
- *Reflectometry - magnetic thin films, polymers,…*
- *Inelastic Scattering - chemical, lattice, and magnetic dynamics,*
- *Residual Strain, Material Texture, Engineering studies on composites..*
- *Powder Diffraction and Crystallography*
- *High temperature Superconductor studies*
- *Giant magneto-resistance*
- *Neutron radiography*
- *Nuclear Structure Studies*
- *Neutron Beta Decay and CKM Unitarity*
- *Parity violation and Quark-Quark weak interactions*
- *AND MORE....*

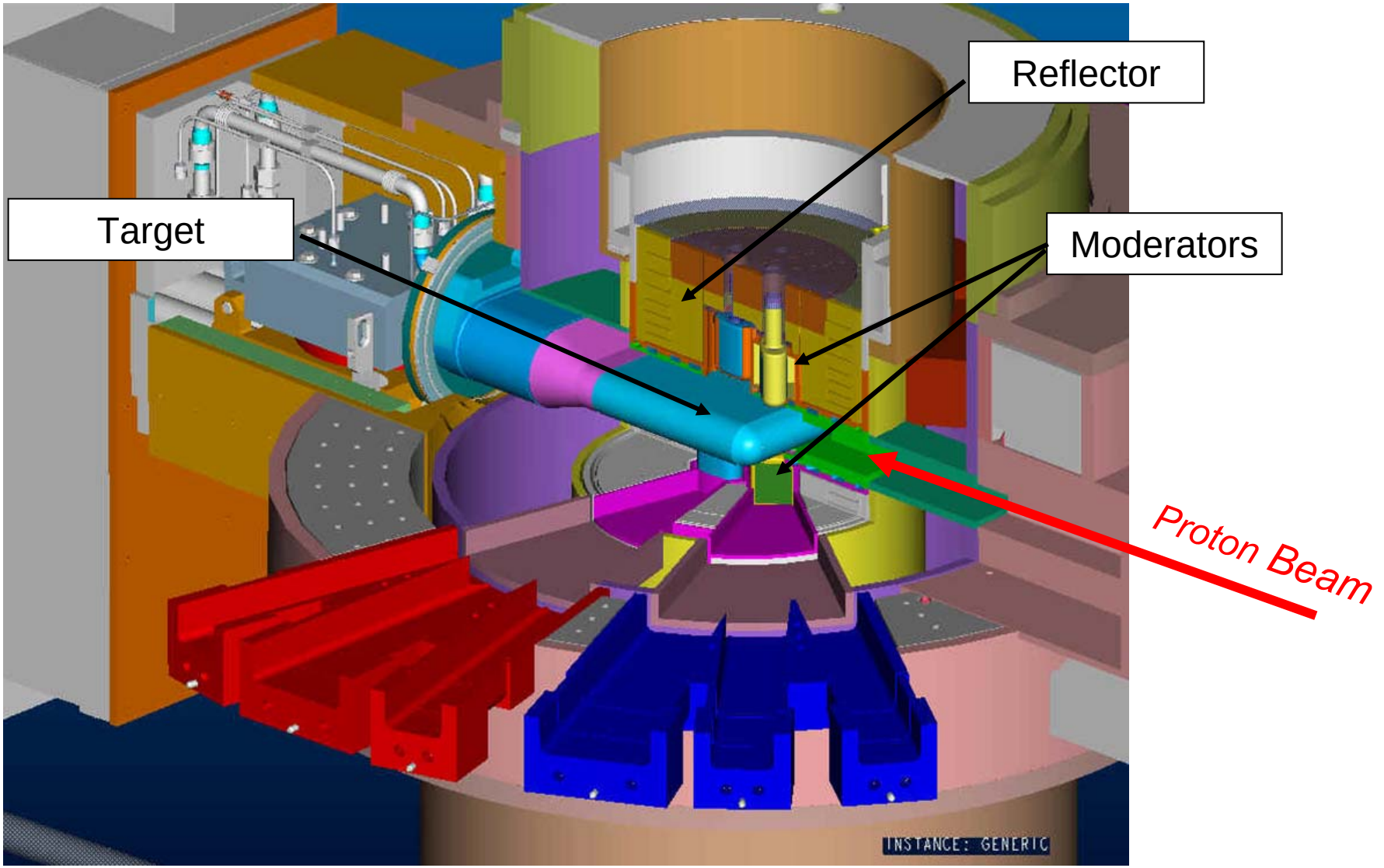
Advisory Note to Engineers (and Accountants)

A stopping target makes lots of neutrons, but it is quite expensive to get them out!

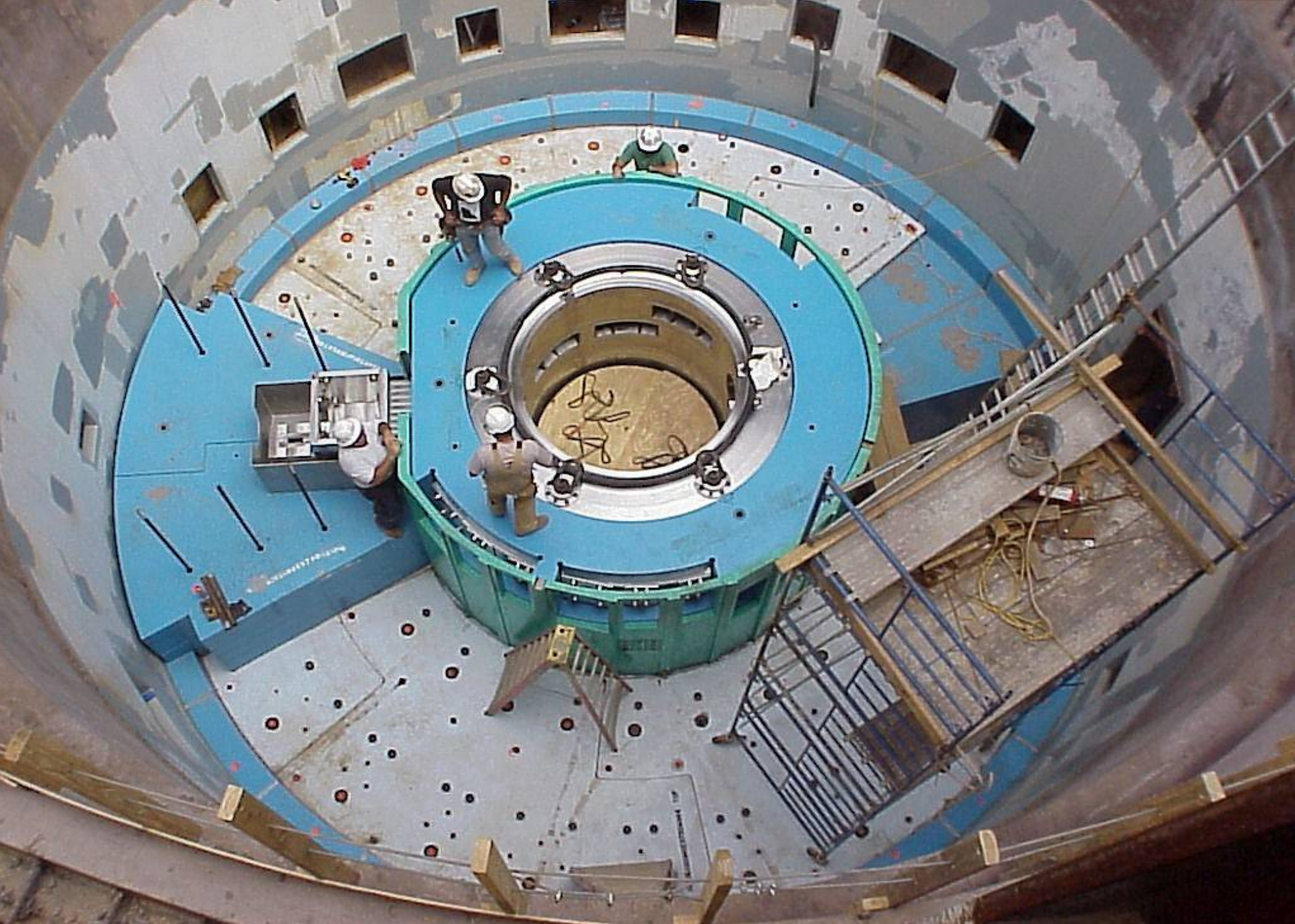
The production and extraction of useful beams of low energy neutrons (≤ 25 meV) require highly specialized neutron "reflectors" and cryogenic moderators that must be an integral part of the stopping target.

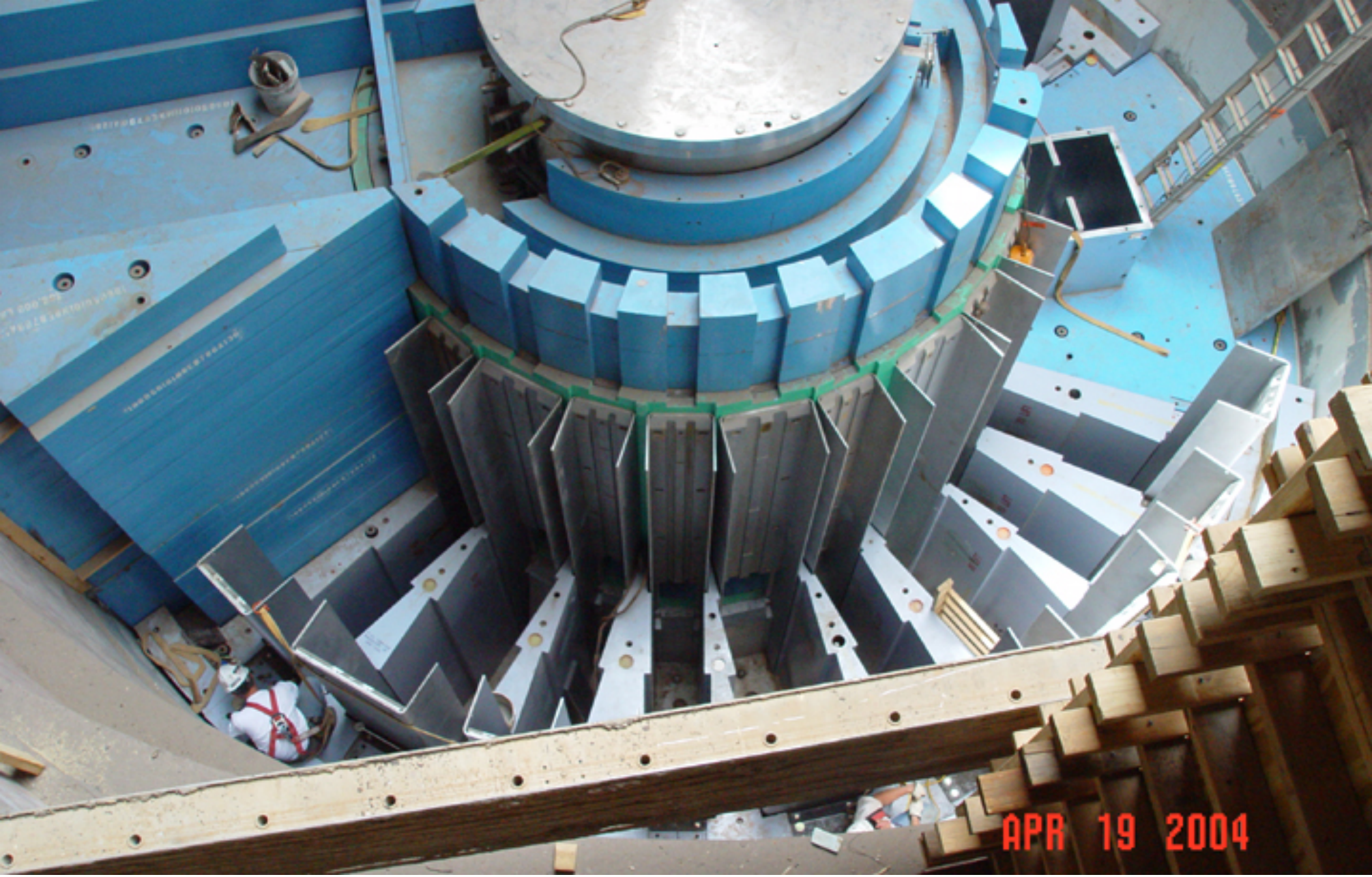
Such facilities will add considerable expense to the construction of the stopping target (several x $10M) as well as adding significant additional operational expense.

Target-Moderator System



MTM
Major
Tool & Machine, Inc.




APR 19 2004

What about the Proton Driver?

Neutrons at the Proton Diver

Incontrovertible Fact:

An 8 GeV, 2MW, 10 Hz proton beam could be used to make a truly outstanding spallation neutron source!

Some Practical Questions:

- *What is the additional cost of the "cold neutron" source?*
- *What is the cost of the neutron scattering spectrometers (~$15M each) and how would they be supported? (DOE BES?)*
- *What would "p Driver" do that the SNS upgrade cannot?*

SNS 20-Year Plan

The SNS is designed to allow operations with two target stations

- *Phase 1 – Power Upgrade*
  - *3-4 MW*
  - *Completion FY09*
- *Phase 2 - Long Wavelength Target Station (LWTS)*
  - *22 Instruments*
  - *440 – 880 kW*
  - *20 Hz*
  - *Completion FY13*

There are (at least) three opportunities that will <u>not</u> be addressed at SNS II

1. *"Stand Alone" Ultra Cold Neutron Source*

2. *High Energy Neutrons for Chip Testing*

3. *Dedicated cold neutron source for n-$\bar{n}$ oscillations*

Opportunity #1: "Stand Alone" Ultra Cold Neutron Source

- *Add a kicker that can direct "a few" linac macropulses to a dense target every few minutes.*

- *UCN are produced in a block of Solid Deuterium placed near the heavy target and suitable reflectors and moderators.*

LANSCE and PSI are already constructing and testing such systems.

Solid Deuterium "Superthermal" UCN Source at LANSCE

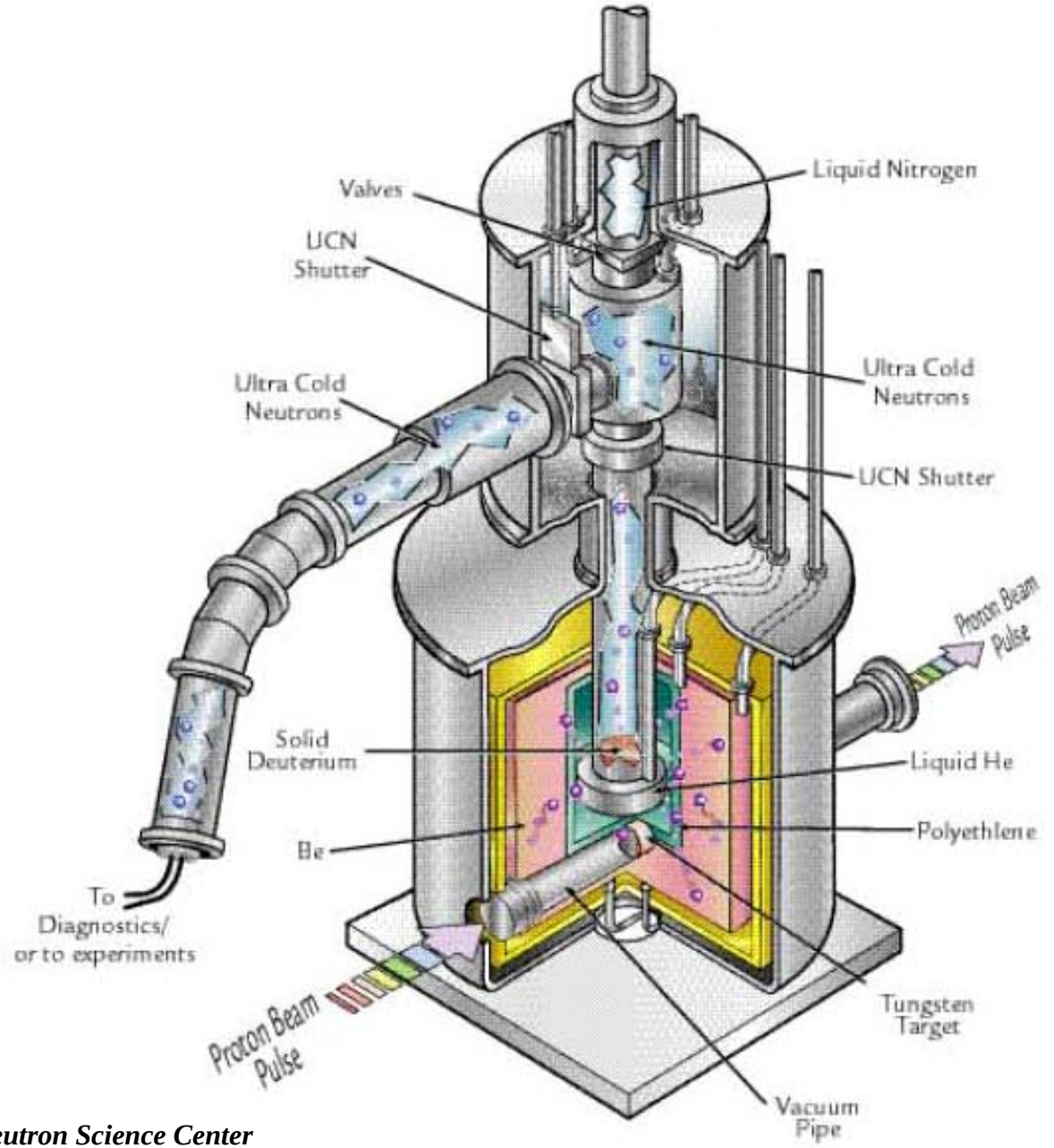


Figure from Los Alamos Neutron Science Center

Solid Deuterium "Superthermal" UCN Source at LANSCE

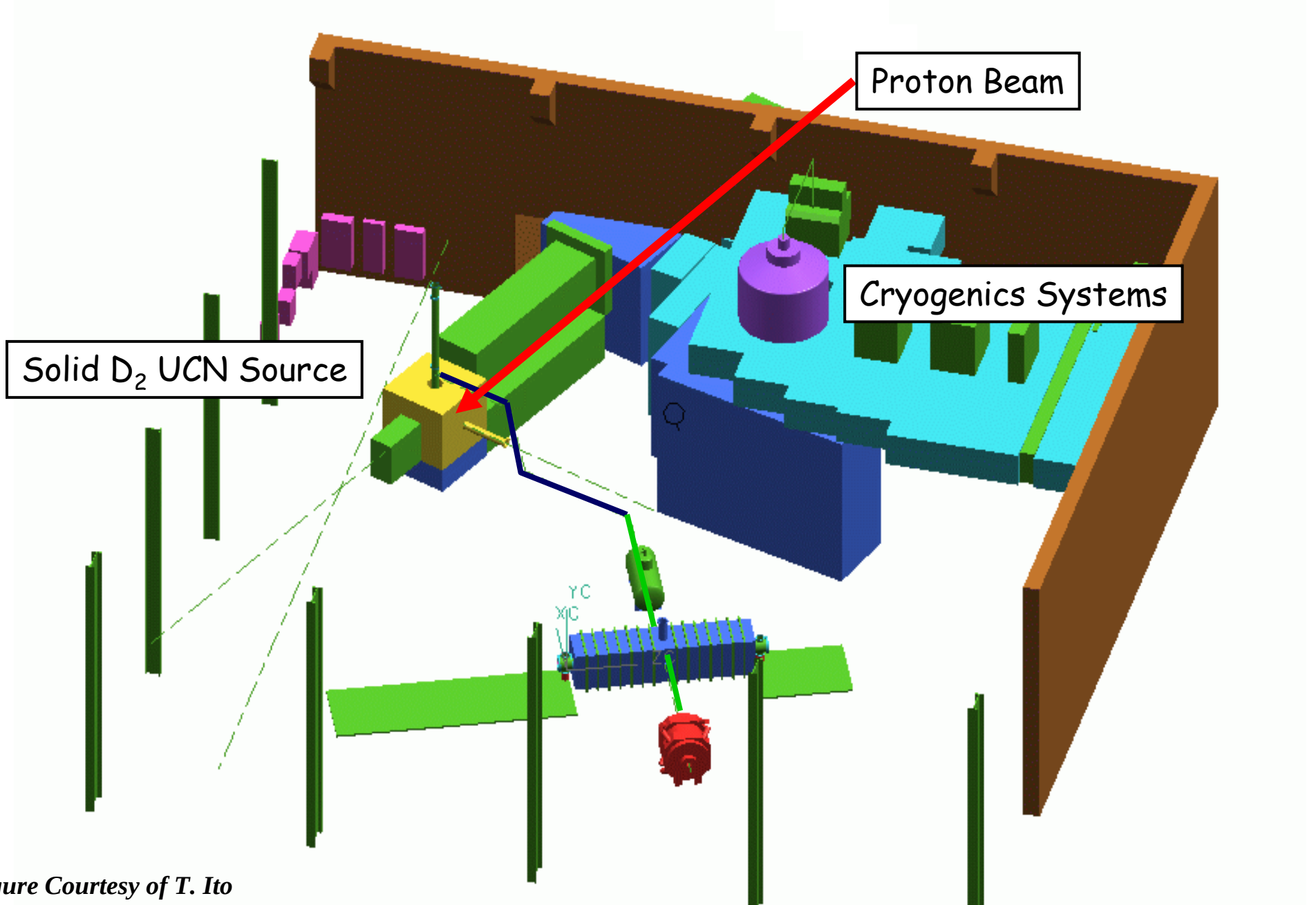


Figure Courtesy of T. Ito

Opportunity #2: High Energy Neutrons for Chip Testing

- *Add a beam line with a view to the stopping target, a heavy shutter, and a shielded room.*

- *Manufactures will pay REAL MONEY to test their chips!*

LANSCE/WNR is currently the only facility in the world that can do accelerated chip irradiations.

An 8 GeV, 2MW Proton Driver will have x100 the flux

JEDEC* STANDARD

Measurement and Reporting of Alpha Particles and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices

JESD89

AUGUST 2001

JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

*Joint Electron Device Engineering Council

Opportunity #3 (?): Neutron-Antineutron Oscillations

- *The stopping target at the Proton Driver would produce enough neutrons to significantly improve the limits on $\Delta B=2$ n-$\bar{n}$ oscillations.*

There is currently no prospect for this being at the SNS,

OR ANYWHERE ELSE!

LIMIT ON $n\overline{n}$ OSCILLATIONS

Mean Time for $n\overline{n}$ Transition in Vacuum

A test of $\Delta B=2$ baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\overline{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \rightarrow \overline{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table.

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$>1.3 \times 10^8$	90	CHUNG	02B	SOU2	*n* bound in iron
$>8.6 \times 10^7$	90	BALDO-...	94	CNTR	Reactor (free) neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1 \times 10^7$	90	BALDO-...	90	CNTR	See BALDO-CEOLIN 94
$>1.2 \times 10^8$	90	BERGER	90	FREJ	*n* bound in iron
$>4.9 \times 10^5$	90	BRESSI	90	CNTR	Reactor neutrons
$>4.7 \times 10^5$	90	BRESSI	89	CNTR	See BRESSI 90
$>1.2 \times 10^8$	90	TAKITA	86	CNTR	*n* bound in oxygen
$>1 \times 10^6$	90	FIDECARO	85	CNTR	Reactor neutrons
$>8.8 \times 10^7$	90	PARK	85B	CNTR	
$>3 \times 10^7$		BATTISTONI	84	NUSX	
$> 2.7 \times 10^7 - 1.1 \times 10^8$		JONES	84	CNTR	
$>2 \times 10^7$		CHERRY	83	CNTR	

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18 October 2001

PHYSICS LETTERS B

Physics Letters B 518 (2001) 269–275

www.elsevier.com/locate/npe

Observable neutron–antineutron oscillations in seesaw models of neutrino mass

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Received 12 August 2001; accepted 27 August 2001
Editor: M. Cvetič

Abstract

We show that in a large class of supersymmetric models with spontaneously broken $B-L$ symmetry, neutron–antineutron oscillations occur at an observable level even though the scale of $B-L$ breaking is very high, $v_{B-L} \sim 2 \times 10^{16}$ GeV, as suggested by gauge coupling unification and neutrino masses. We illustrate this phenomenon in the context of a recently proposed class of seesaw models that solves the strong CP problem and the SUSY phase problem using parity symmetry. We obtain an *upper* limit on N–$\overline{N}$ oscillation time in these models, $\tau_{N-\overline{N}} \leqslant 10^9$–$10^{10}$ s. This suggests that a modest improvement in the current limit on $\tau_{N-\overline{N}}$ of 0.86×10^8 s will either lead to the discovery of N–$\overline{N}$ oscillations, or will considerably restrict the allowed parameter space of an interesting class of neutrino mass models. © 2001 Published by Elsevier Science B.V.

n-$\bar{n}$ Oscillations in Models with Large Extra Dimensions

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[2]*C. N. Yang Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794*

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We analyze n-$\bar{n}$ oscillations in generic models with large extra dimensions in which standard-model fields propagate and fermion wave functions have strong localization. We find that in these models n-$\bar{n}$ oscillations might occur at levels not too far below the current limit.

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$n \rightarrow \bar{n}$ Search Sensitivity

Soudan II limit ≈ Grenoble limit = 1 unit (1 u) of sensitivity

Method	Present limit	Possible future limit	Possible sensitivity increase factor
Intranuclear (in N-decay expts)	$7.2 \cdot 10^{31}$ yr = 1u Soudan II	$7.5 \cdot 10^{32}$ yr (Super-K) $4.8 \cdot 10^{32}$ yr (SNO)	× 16 u (*)
Geo-chemical (ORNL)	none	$4 \cdot 10^{8} \div 1 \cdot 10^{9}$ s (Tc in Sn ore)	× 20÷100 u (*)
UCN trap (6×10^{7} ucn/sec)	none	~ $1 \cdot 10^{9}$ s	× 100 u (**)
Cold horizontal beam	$8.6 \cdot 10^{7}$ s = 1u @ILL/Grenoble	> $3 \cdot 10^{9}$ s (e.g. HFIR@ORNL)	× 1,000 u (***)
Cold Vertcal beam	none	> $3 \cdot 10^{9}$ s (TRIGA 3.4 MW)	× 1,000 u (***)

Table courtesy of Yuri Kamyskov

Proton driver might do this well

A Humble Personal Opinion

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Nonetheless, It seems likely that the Proton Driver will "live or die," irrespective of the case for neutron science.

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The important thing for us to do is to insure that we do not unintentionally preclude interesting and important science.

End of Presentation