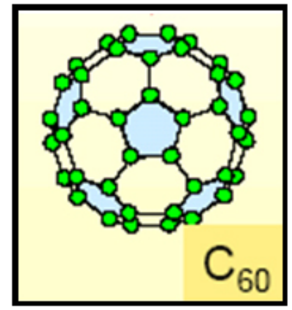
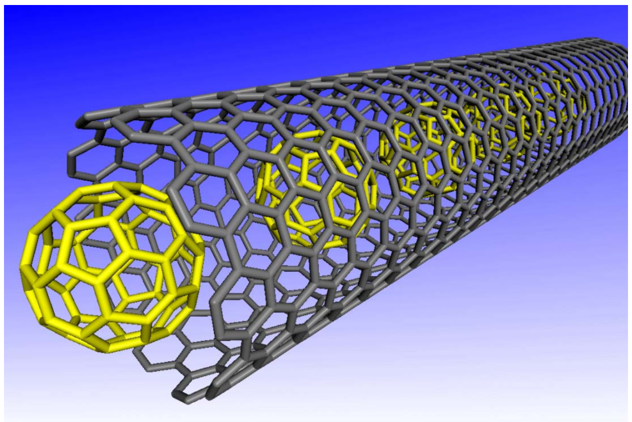
Making buckyballs ring: collective electron motion in a C_{60} molecule.

Shining light from an ultrabright synchrotron light source on a unique nanomaterial



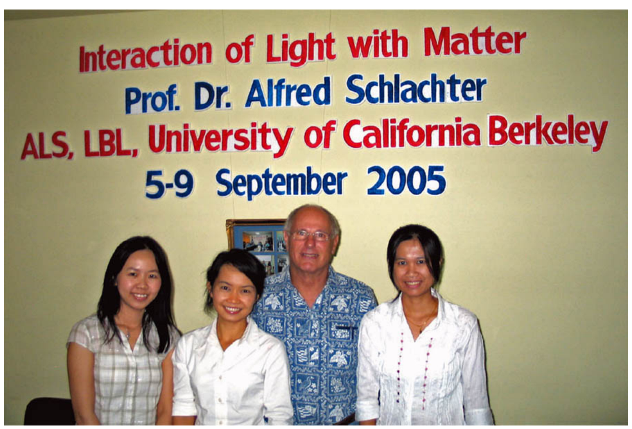


Dr. Fred Schlachter

Lawrence Berkeley National Laboratory

American Physical Society

Chiang Mai University



ดร. เฟรด ชลัคเทอร์

อาจารย์พิเศษ

ภาควิชาฟิสิกส์

มหาวิทยาลัยเชียงใหม่

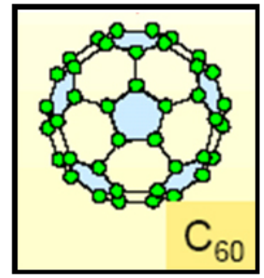
ศูนย์ปฏิบัติการวิจัยแห่งชาติ

ลอเร็นซ์ เบิร์คเลย์

(Lawrence Berkeley National Laboratory)

NANOTEC Bangkok September 28, 2010

Collective electron motion in C_{60}



Absorption of photons from an ultrabright beam of synchrotron radiation illuminates new excitation and ionization processes in the C_{60} molecule

Bridging the gap between atoms and bulk matter.

• Photoionization cross sections are measured for photoionization of C_{60}^{+}.

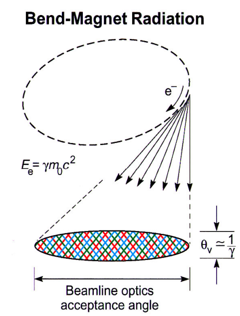
• Two "plasmon" resonances indicating **collective electron motion** are observed, similar to collective resonances found in nuclear and plasma physics.

• *It is remarkable to find this manifestation of bulk matter in a molecule with only 60 atoms*, likely due to the special shape of the C_{60} molecule: a hollow conducting sphere.

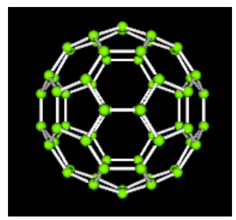
Collective electron motion in C_{60}: outline

Looking for macroscopic (bulk) effects at the nano-level of matter.

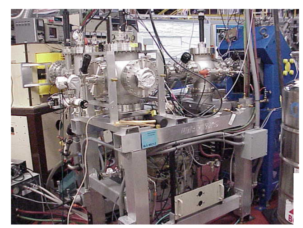
- approach
- producing an ultrabright beam of x rays



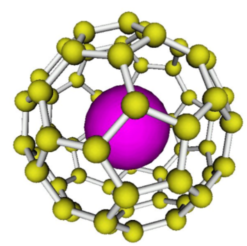
- carbon in its various forms

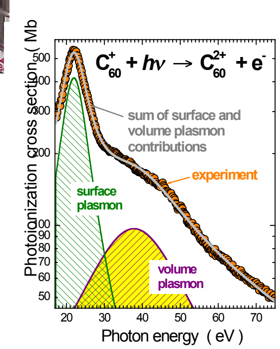


- measurement of photoionization of ions



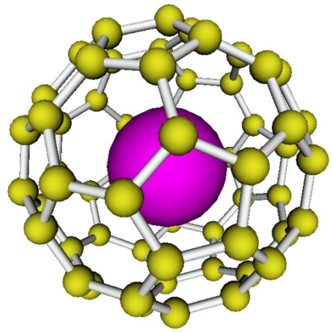
- collective motion of electrons in C_{60}





- endohedral atoms
- photoionization of ions…

Collective electron motion in C_{60}: approach



Look for collective motion of electrons in a large molecule

Collective motion is usually a characteristic of large systems (plasma, metal)

Example: collective motion of water in a bowl being tipped back and forth -> normal mode of motion

Water sloshing in bowl: collective motion of water molecules.

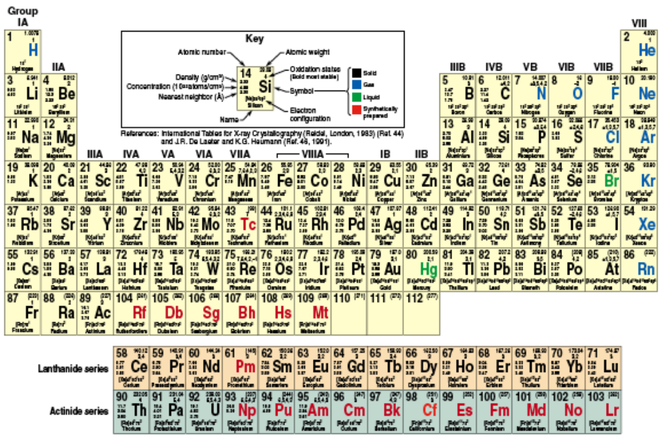
Study by looking for resonances leading to ionization

Perform experiment with ion beam rather than with gas target; 239 or 240 valence electrons behave the same.

X rays and science

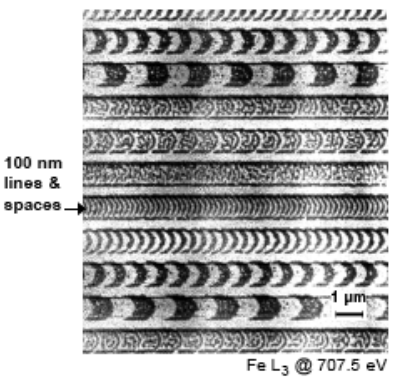
Photons interact selectively with electrons bound in matter.

X rays allow study of the **electronic structure of matter**, seeing inside objects, and determination of spatial structure of small objects. There are uses in many fields of science.

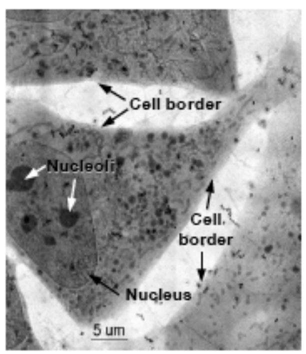


Magnetic Recording Materials

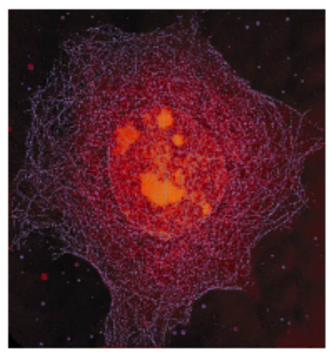
Cryo Microscopy for the Life Sciences



FeTbCo Multilayer
with AL Capping Layer



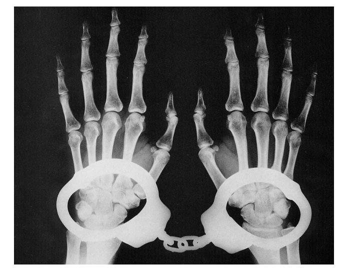
Cryo X-Ray Microscopy
of 3T3 Fibroblast Cells

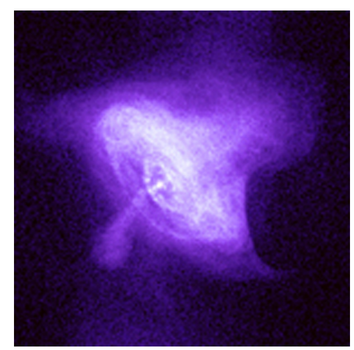


Protein Labeled
Microtubule Network

Courtesy of P. Fischer, Wuerzberg
and G.Denbeaux, CXRO/LBNL

Courtesy of C. Larabell, UCSF
and W. Meyer-Ilse, CXRO/LBNL

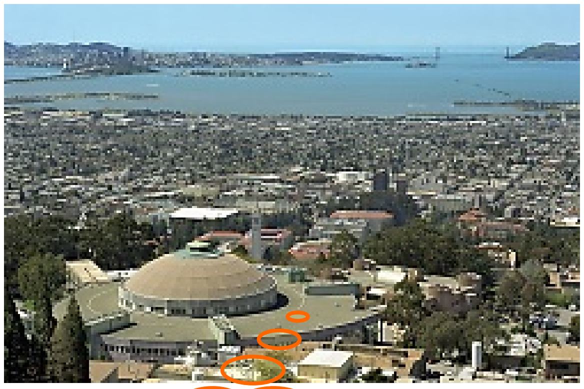




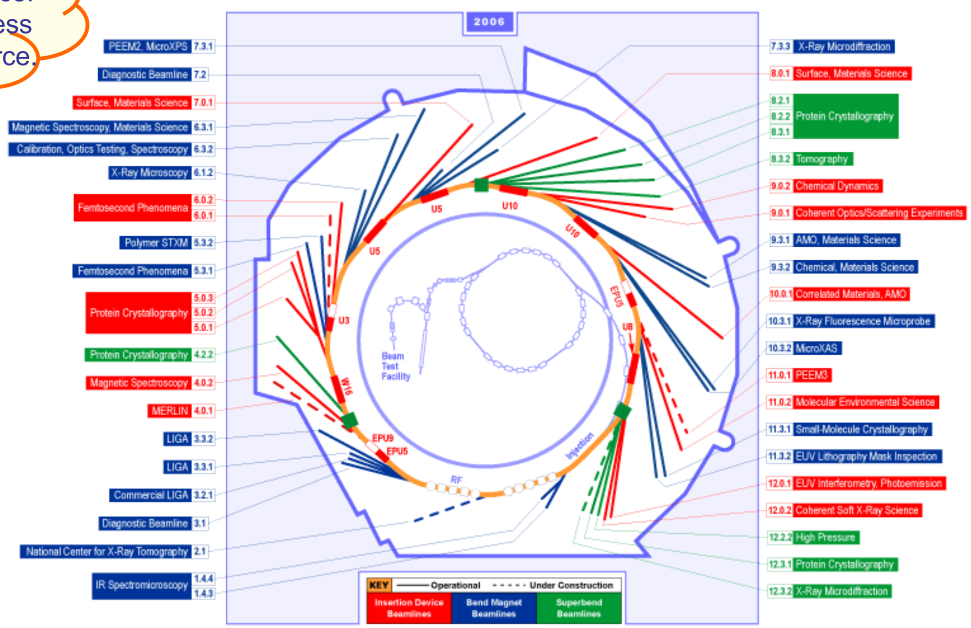
Spectrum of electromagnetic radiation

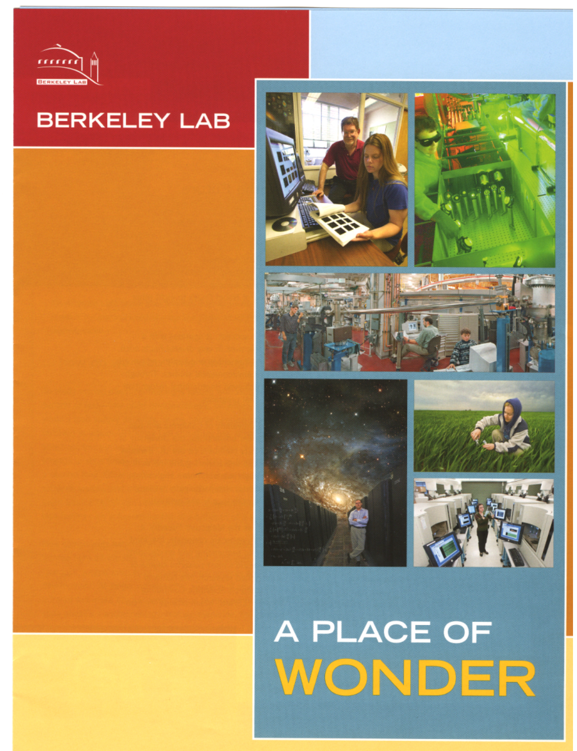
VUV and soft-x-ray regions of the spectrum

Lawrence Berkeley National Laboratory



Advanced Light Source:
an ultra-high-brightness
synchrotron light source.

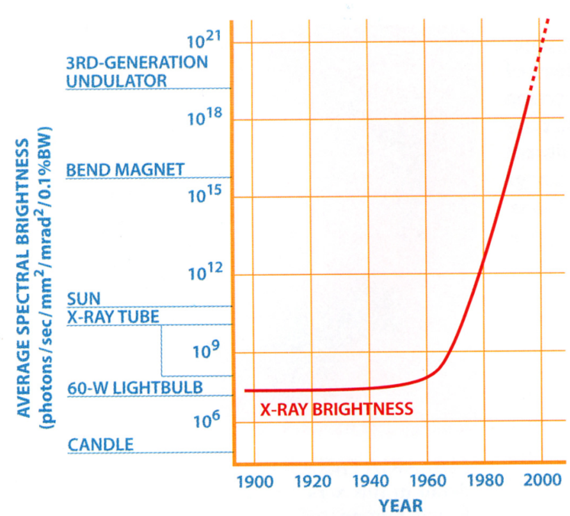




Brightness:

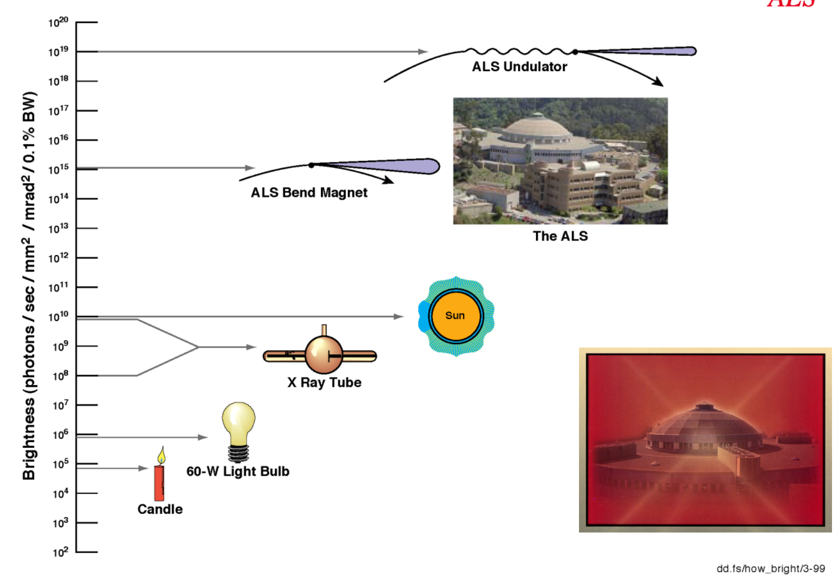
photon flux density in phase space

The brightness of x-ray beams has increased even faster than Moore's Law in the past forty years.



Radiation a billion times brighter than the sun's is produced by an undulator at the ALS.

ALS

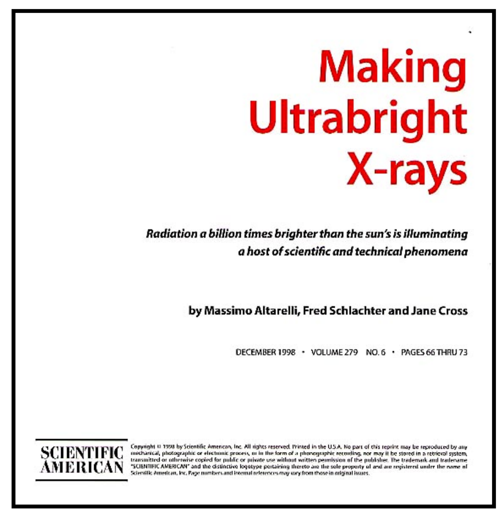


Brightness: photons/second/cm^2/solid angle/bandwidth

Meaning lots of photons in a narrow monochromatic beam with small spatial divergence.

Altarelli, Schlachter, and Cross

Scientific American December 1998



Making Ultrabright X-rays

Radiation a billion times brighter than the sun's is illuminating a host of scientific and technical phenomena

by Massimo Altarelli, Fred Schlachter and Jane Cross

DECEMBER 1998 • VOLUME 279 NO. 6 • PAGES 66 THRU 73

SCIENTIFIC AMERICAN

Brightness:

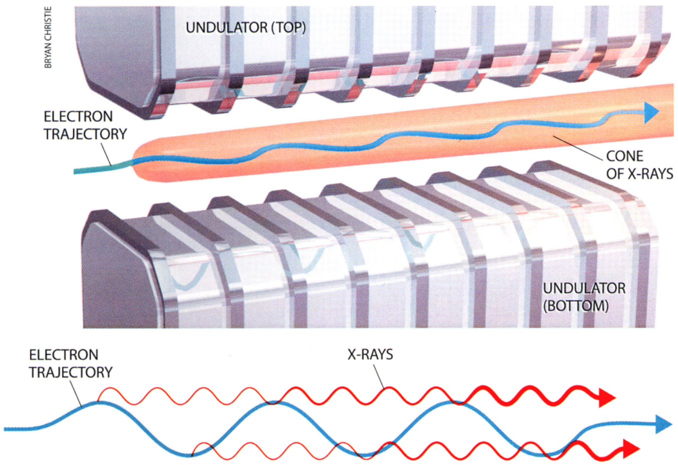
photon flux density in phase space

Brightness: photons/second/cm^2/solid angle/bandwidth

Meaning lots of photons in a narrow monochromatic beam with small spatial divergence.

Producing a high-brightness photon beam requires a very small source size and small angular divergence of the electron beam….plus an undulator.

A high-brightness photon beam with tunable photon energy is produced by an undulator: a spatially alternating magnetic array.

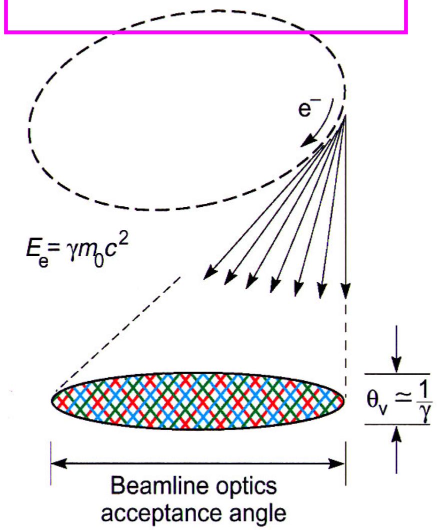


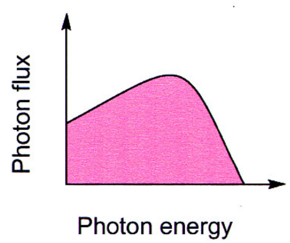
ALS has bend magnets and undulators

Spatial distribution of radiation

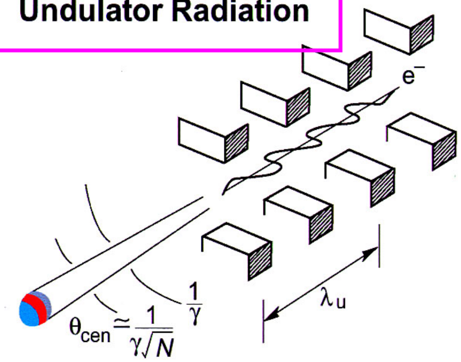
Spectral distribution of radiation

Bend-Magnet Radiation





Undulator Radiation

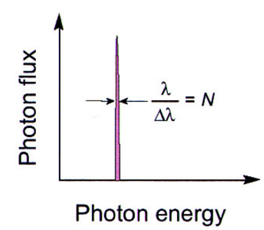


$$\lambda_x = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

In the central radiation cone:

$$\frac{\Delta\omega}{\omega} \simeq \frac{1}{N}$$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

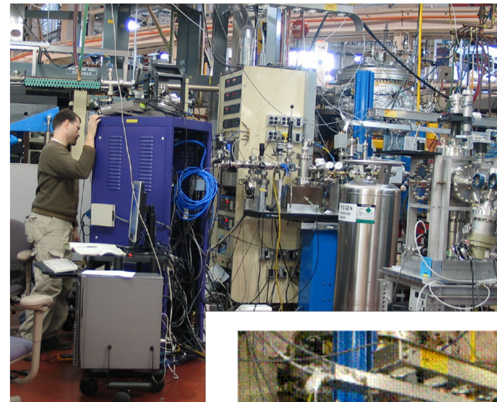


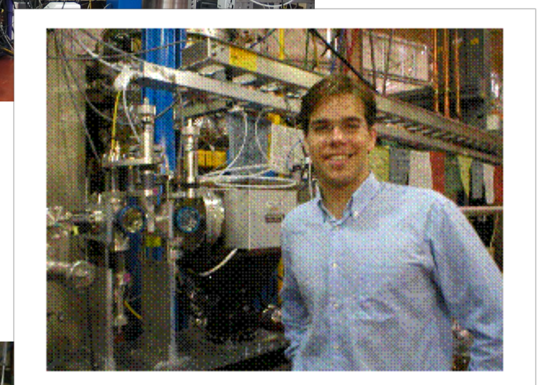
Properties of synchrotron radiation

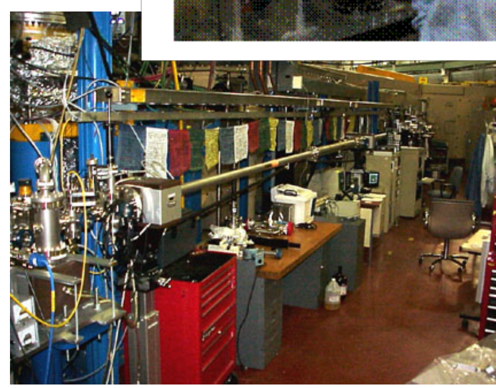
Properties of synchrotron radiation

- Continuous spectrum
- Tunable monochromatic radiation
- High brightness (radiation in a narrow cone)
- Polarization control (linear, circular)
- Time-pulse structure
- Partially coherent

X rays interact selectively with electrons in matter. This allows elemental and chemical sensitivity. The short wavelength allows seeing small features.

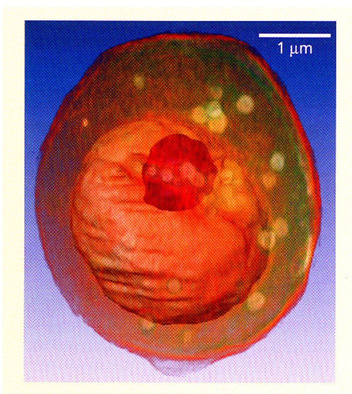






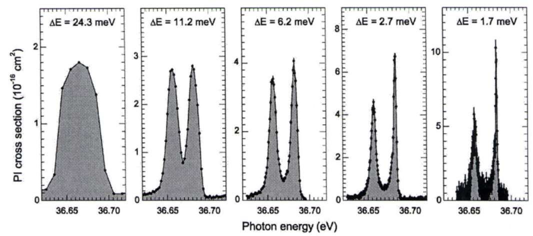
A high-brightness light source provides small photon spot

Microscopy and nanoscience



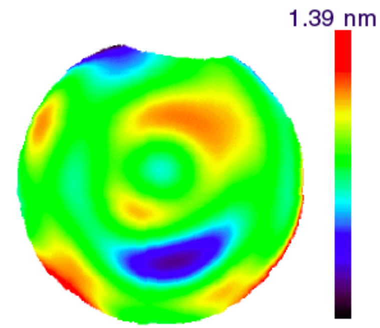
Enabling progress in nanoscience and new microscopies

High-resolution spectroscopy



Enabling researchers to learn in detail about the elemental, chemical, and magnetic structure of matter

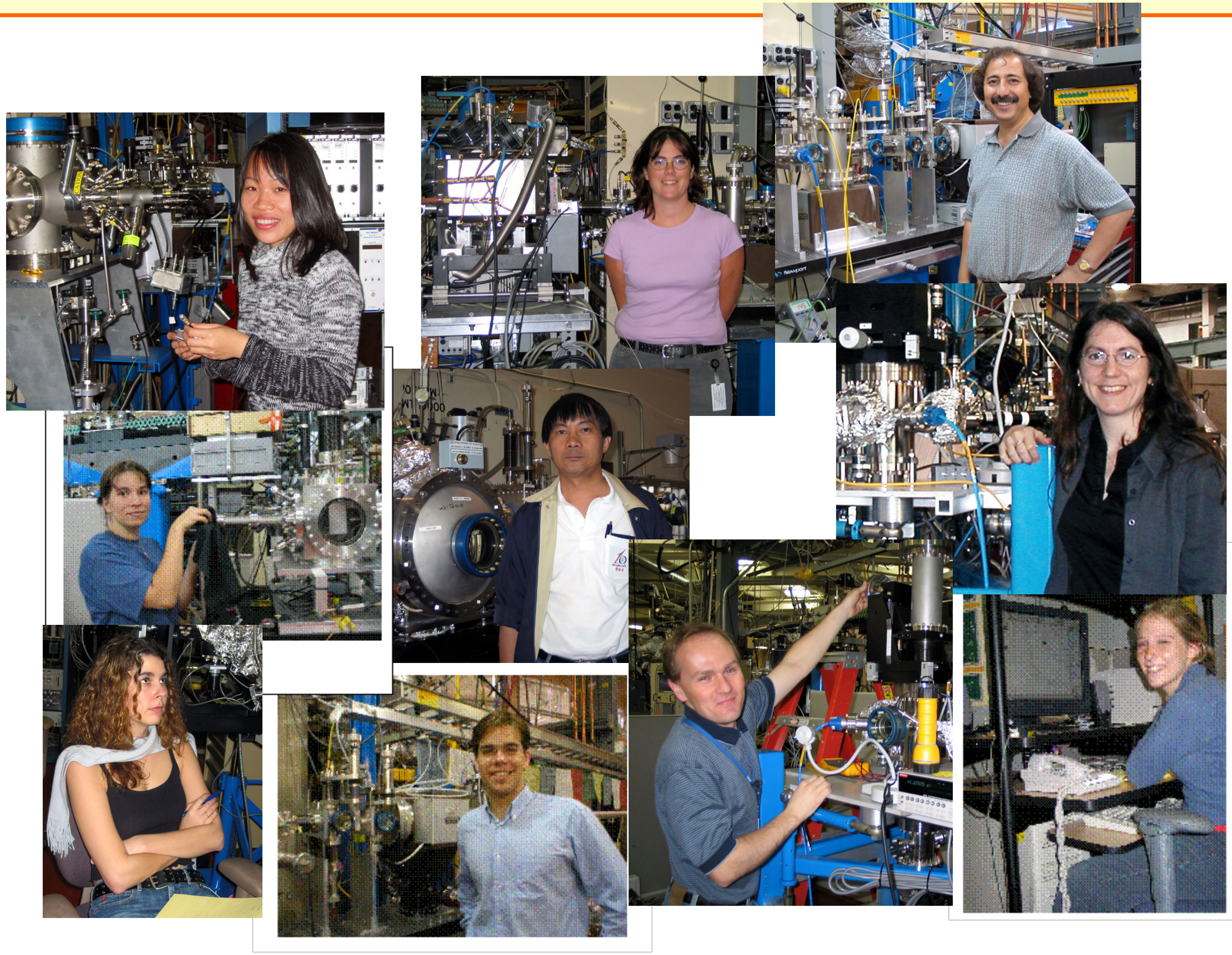
Coherent radiation



Enabling studies using interferometry and speckle techniques.

A high-brightness x-ray beam is required to produce a narrow parallel beam of photons.

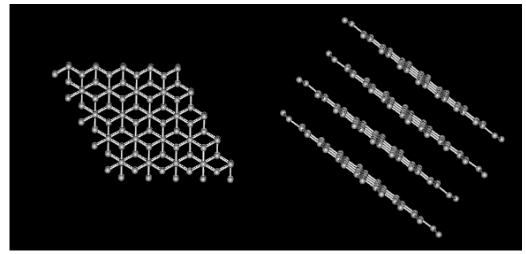
ALS beamline users: students and visitors from around the world



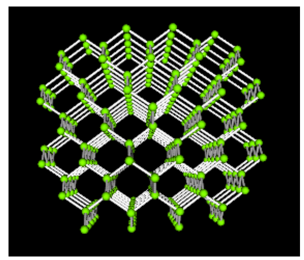
Carbon has three forms: graphite, diamond, and buckyballs

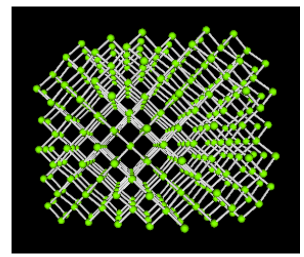
Carbon also has an amorphous form

Graphite. Soft and slippery. Strong covalent bonds between carbon atoms in each layer: 2-dimensional bonding.



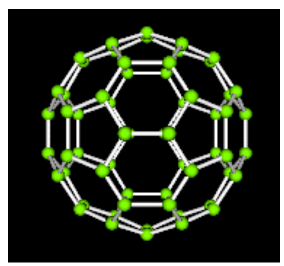
Diamond. Tetrahedral bonds. Very hard**.** Each carbon atom is the same distance to each neighbor in rigid 3-dimensional framework.

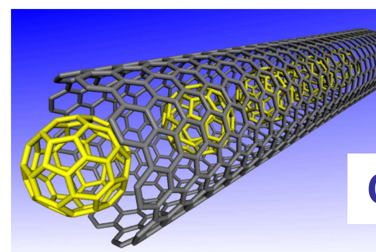




Note: graphite is the stable form of carbon. Diamond undergoes a slow transformation to graphite.

Buckyball (Fullerene). Hollow conducting sphere made of 60 (or more) carbon atoms.

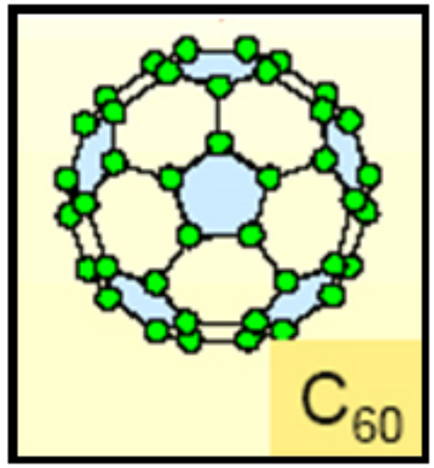




Carbon nanotube….

Different properties are a consequence of different geometrical structure, leading to different bonding between valence electrons. (Vos et al 1997)

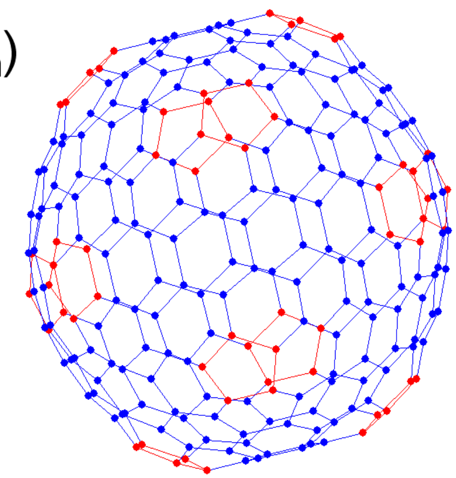
Fullerene = Buckyball



A C_{60} molecule consists of 60 carbon atoms bonded to form a hollow conducting sphere.

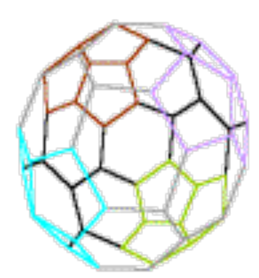
C_{60} is small: diameter 0.7 nm (*less than 5 times the diameter of a hydrogen atom*).

C240 (I_h)

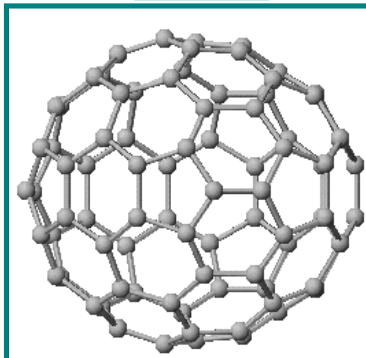


Fullerenes come in many sizes.

C56

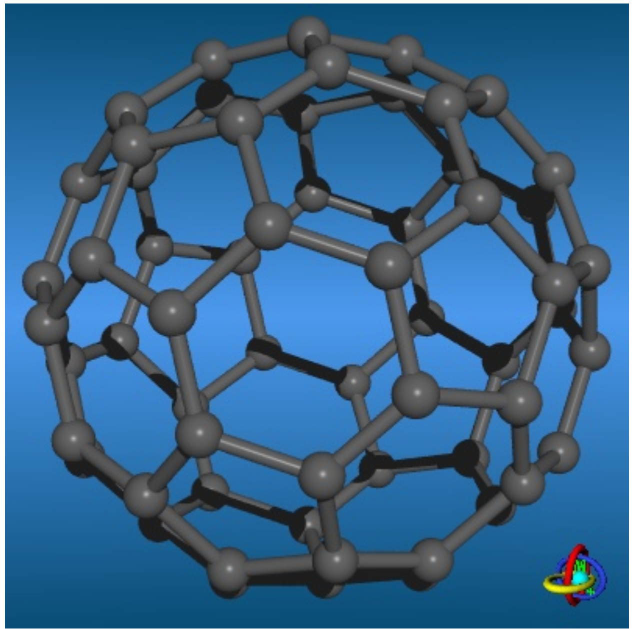


C84



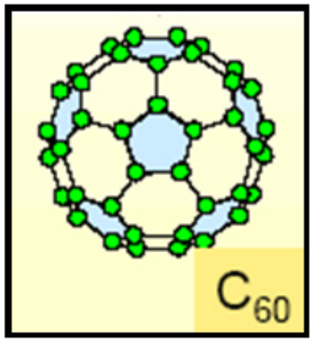
We can study all of these….

Soccer ball: same "bonding" as C_{60}



A soccer ball and C_{60} both are made of alternating pentagons and hexagons.

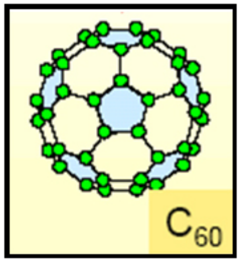
Buckminster Fuller: inventor of geodesic dome



Composed of triangles…

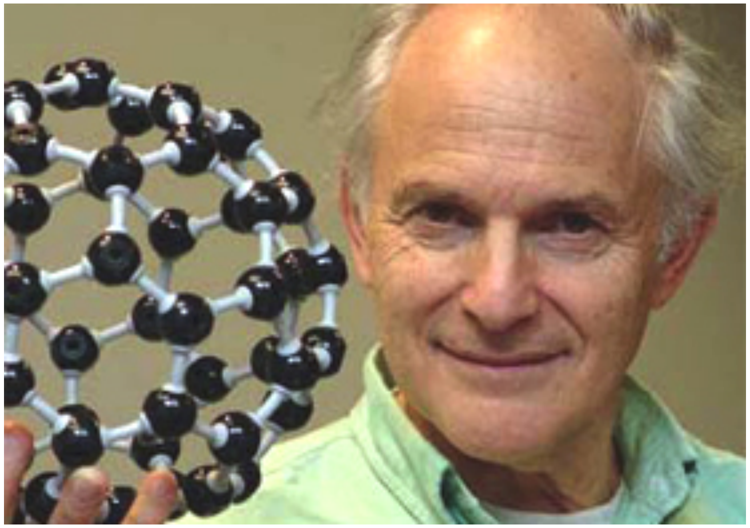
Richard Buckminster “Bucky” Fuller was an American engineer, designer, author, inventor, and futurist. He is most known for the **geodesic dome**.

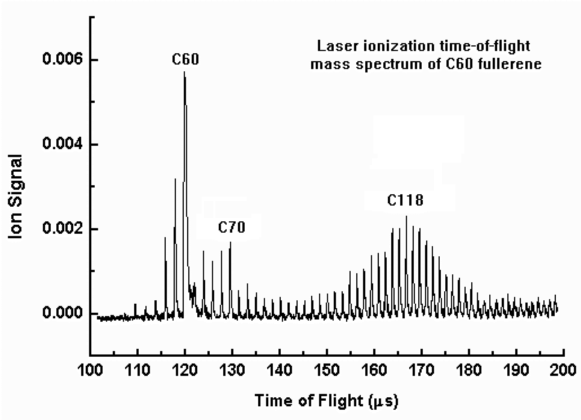
C_{60} was discovered accidentally in 1985.



Mass spectroscopy of laser-produced plasma showed *unexpected* peaks at mass 60, 70, ….

…a serendipitous discovery…

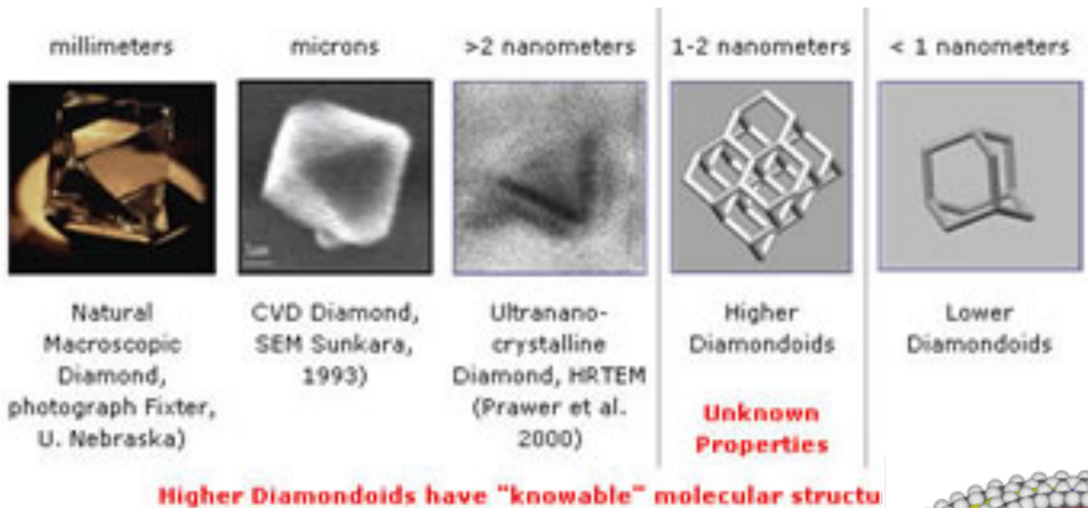


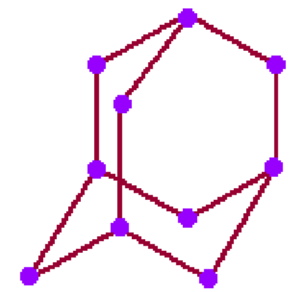


Smalley, Curl, Heath, O'Brien, and Kroto…..1996 Nobel Prize

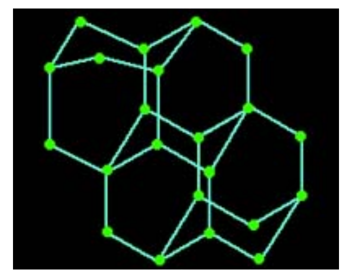
Other structures: diamondoids and adamantane.

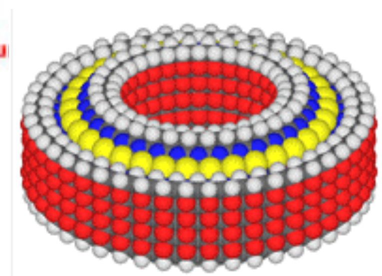
Diamondoids are small molecules with a diamond-like structure.

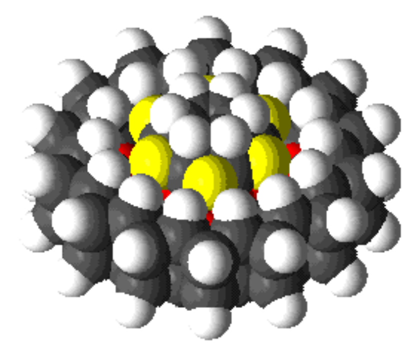




The most common is adamanatane, $C_{10}H_{16}$;

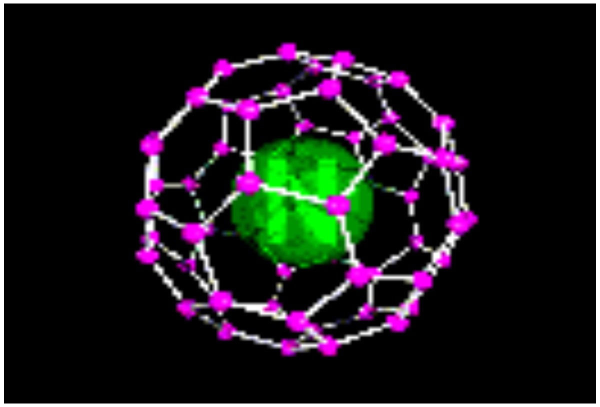






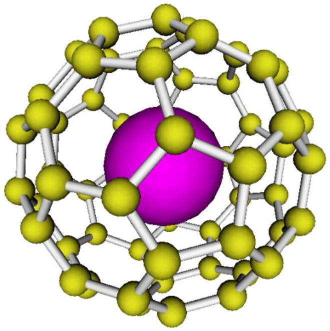
Endohedral Fullerenes*

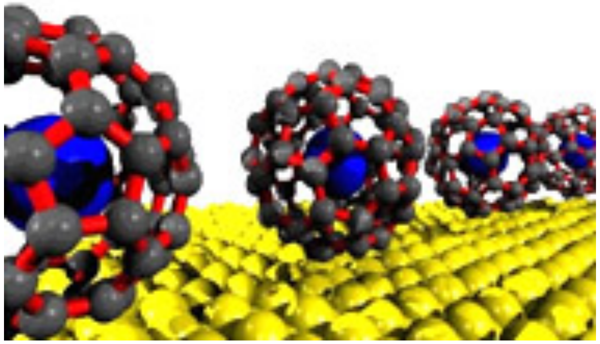
*another name for buckyballs



Fullerenes are hollow molecules providing space to incorporate atoms inside.

There is a great diversity of complexes $X@C_n$
meaning species X is endohedral in the Fullerene C_n cage.





The *endohedral* atom X can be a metal (e.g., La, Ca, etc.), a nonmetal (e.g. Ne, P, etc.) or a molecule (e.g. N_2, CO).

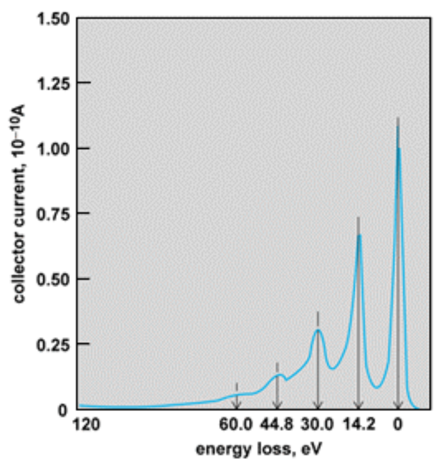
Encapsulating an atom or molecule in a Fullerene structure provides a possibility to alter the atomic or molecular properties of the atom or molecule.

See, for example, Averbukh and Cederbaum, Phys. Rev. Letters 96, 053401 (2006); and references therein.

Collective resonances in physics: a few examples

- **Plasmon**

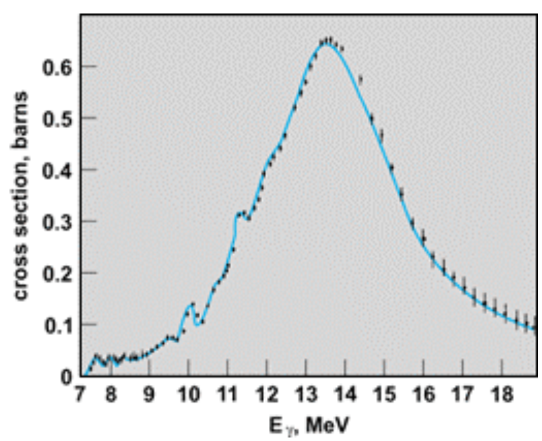
Collective effect of large numbers of electrons in matter when the electrons are disturbed from equilibrium, typically in a metal.



Ferrell et al., Asmer. Sci. **73**, 344 (1985). Electron energy loss in a thin Al foil.

- **Giant nuclear resonance**

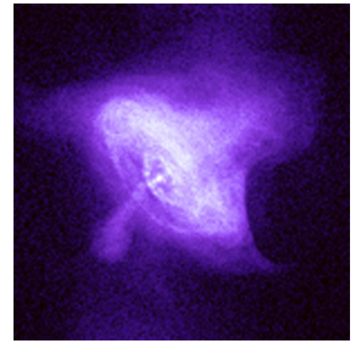
Giant nuclear resonance is elementary mode of oscillation of the entire nucleus. Example is E1 resonance in which all the protons and all the neutrons oscillate with opposite phase, producing a time-varying electric dipole moment.



Veyssiere et al., Nucl. Phys.. **A159**, 5612 (1970). Neutron production of ^{208}Pb and ^{197}Au by gamma-ray bombardment..

Interaction of photons with ionized matter

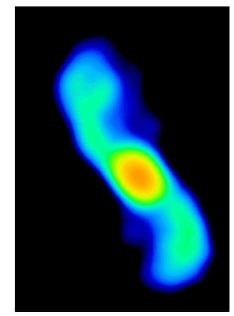
…applications to astrophysics and hot plasmas



Fundamental:

- Most of the visible matter in the universe exists in the ionized state.
- Vacuum ultraviolet photons are a highly selective probe of the electronic structure of atoms, molecules and ions.

Data on photoionization of ions are needed to interpret satellite measurements.

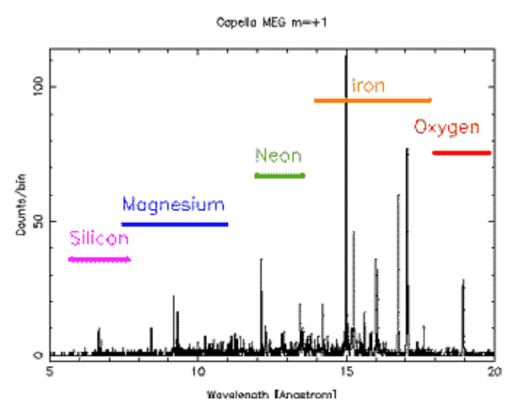


Radio-telescope image of an old star transforming into a planetary nebula.

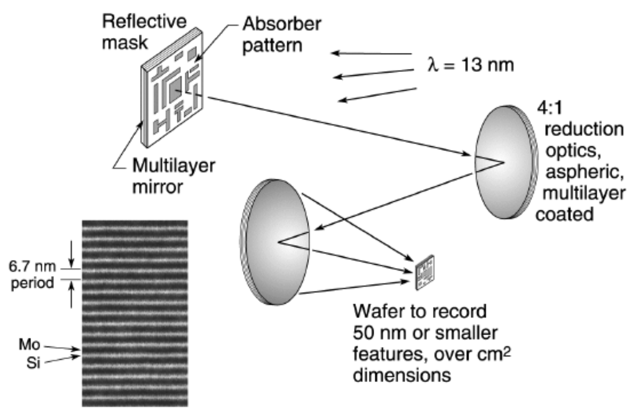
Applications:

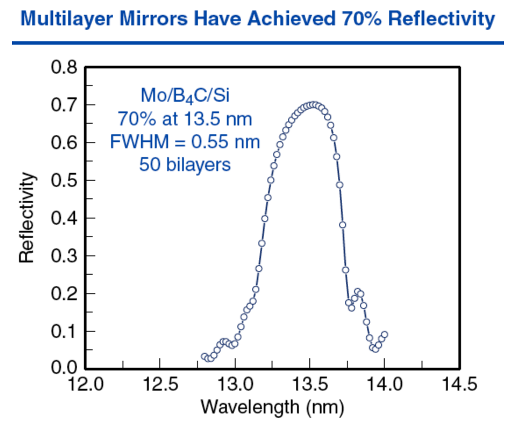
- Photons carry most information that we have about the distant universe.
- Advanced extreme ultraviolet (EUV) lithography light sources are being developed to produce the next generation of semiconductor chips.

Satellite observation of multiply charged ions…

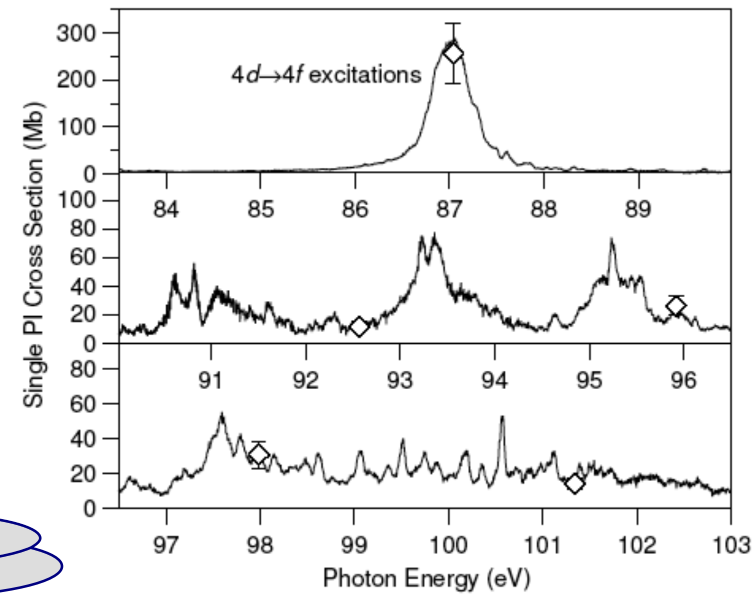


EUV lithography: photoionization of Xe^{3+}





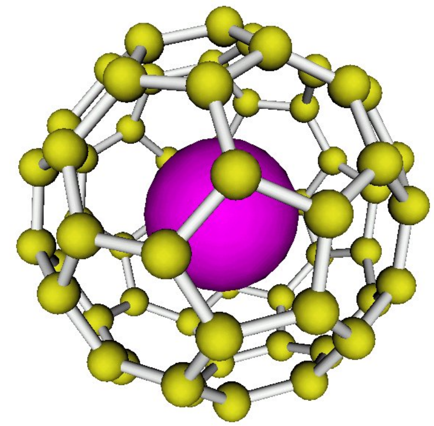
Photoionization measurements at ALS indicate that 4d – nf excitation of Xe^{3+} results in photoabsorption within the EUV lithography light-source window.



Data on interaction of photons with multiply charged ions will aid modeling of plasmas for sources of short-wavelength radiation.

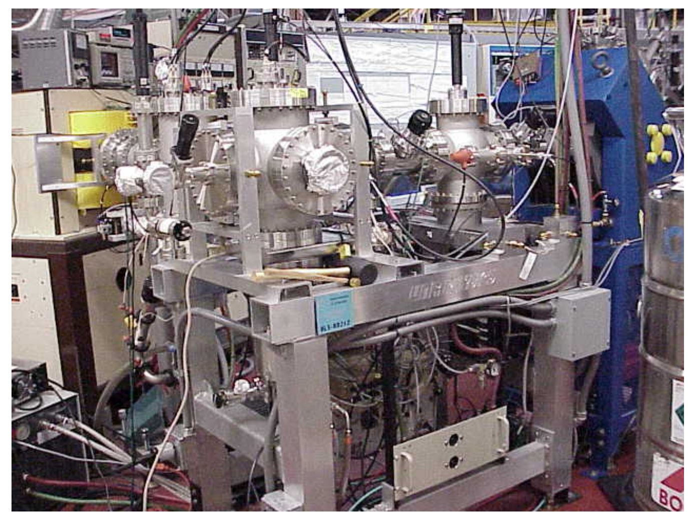
Emmons et al., Phys. Rev. A **71**, 042704 (2005)

Interaction of photons with C_{60} ions



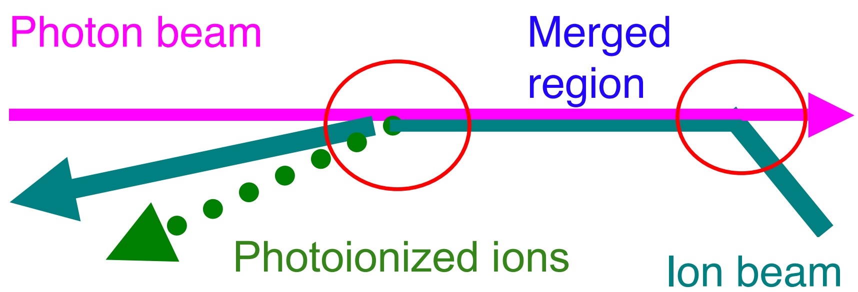
We expect the *same physics* for C_{60} or C_{60} ions, because of the very large number of valence electrons (240 or 239 or 238, depending on ion charge state).

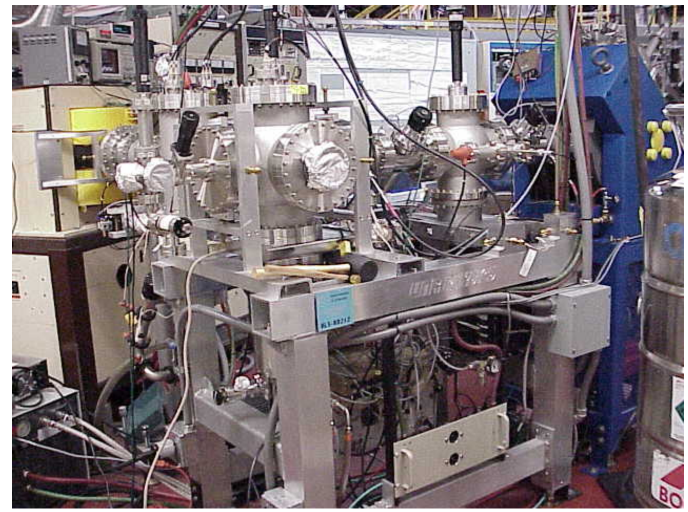
Measurements performed with C_{60} ions rather than C_{60} neutral atoms because an experiment with an ion beam eliminates background and allows clear elucidation of the electronic structure of C_{60}.



A Merged Photon-Beam Ion-Beam Apparatus

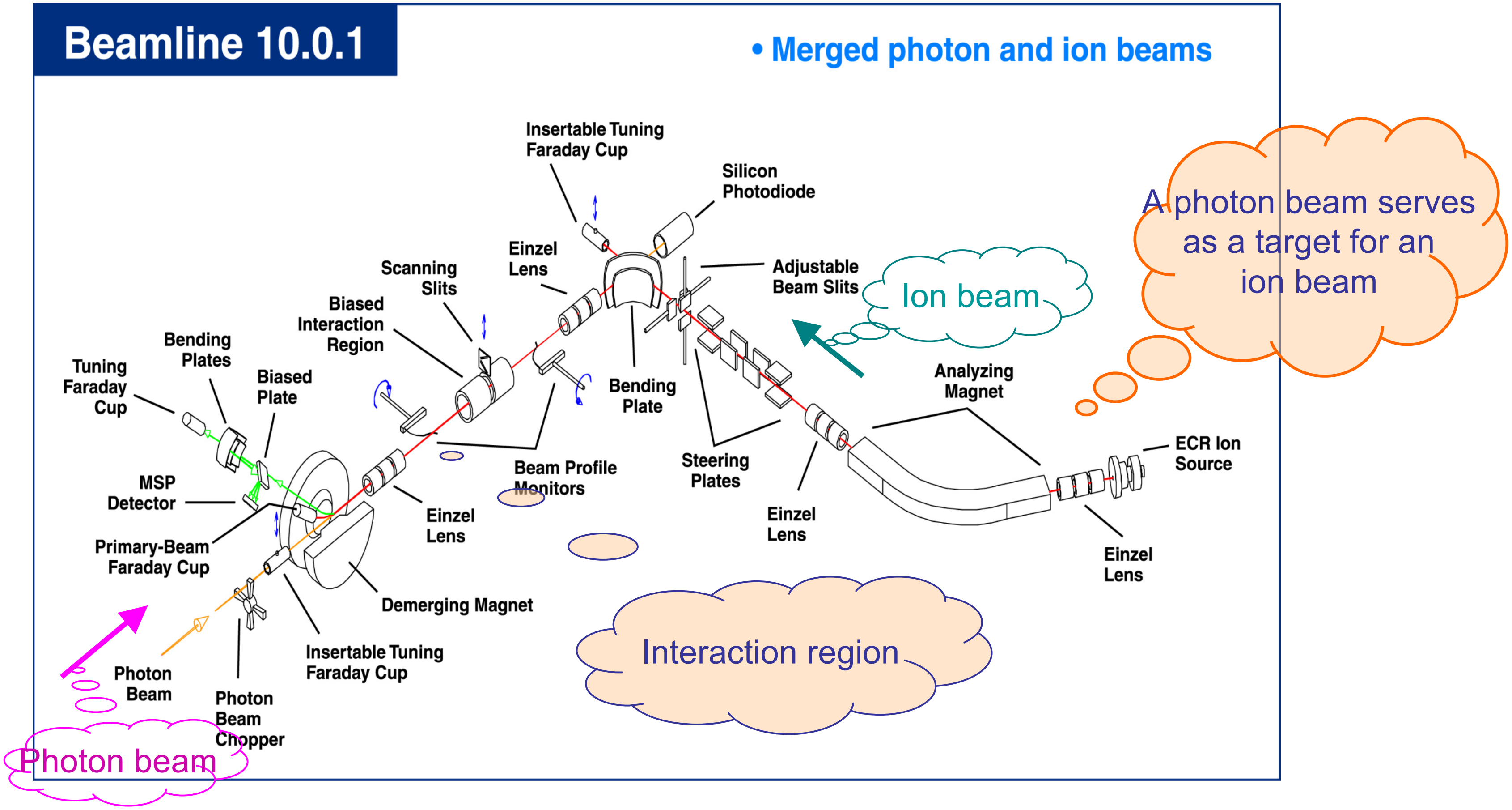
Apparatus to measure interaction of photons with ions



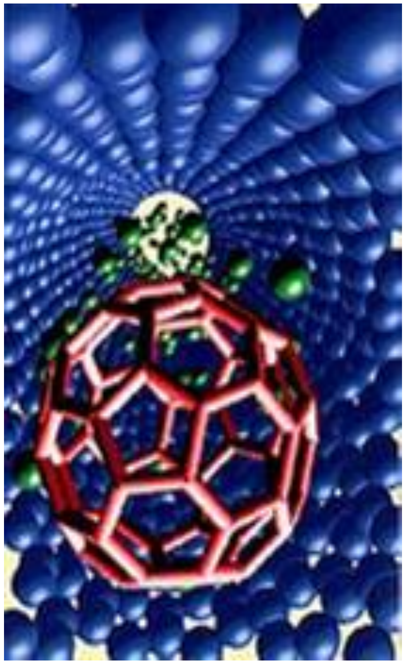


A merged-beams experiment is like guns being fired and the bullets collide.

A Merged Photon-Beam Ion-Beam Apparatus



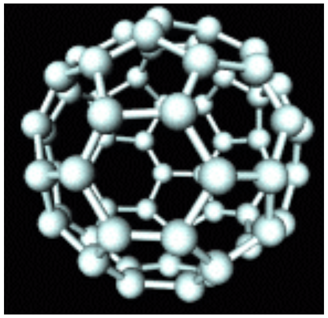
Photoionization of Fullerene Ions: C_{60}^{+}



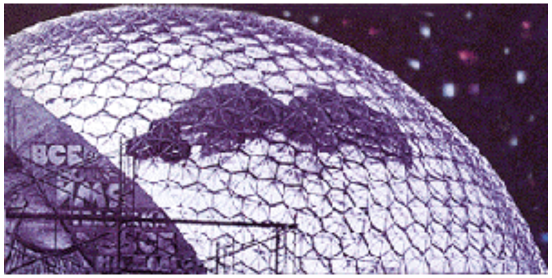
Bridging the gap between molecules and solids: photoionization of buckyball ions.

Buckyball (Fullerene) molecules consist of 60 carbon atoms arranged in a hollow, spherical cage-like structure. The carbon atoms form 20 pentagons and 12 hexagons, like the facets of a football. *Other Fullerenes are possible.*

Experiment is to look for behavior characteristic of a solid in a large molecule where such behavior is unexpected: observe collective motion of the electrons ("plasmon").

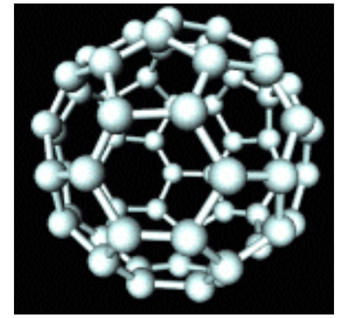


Curl, Kroto and Smalley won the Nobel Prize in 1996 for their 1985 discovery of Fullerenes.

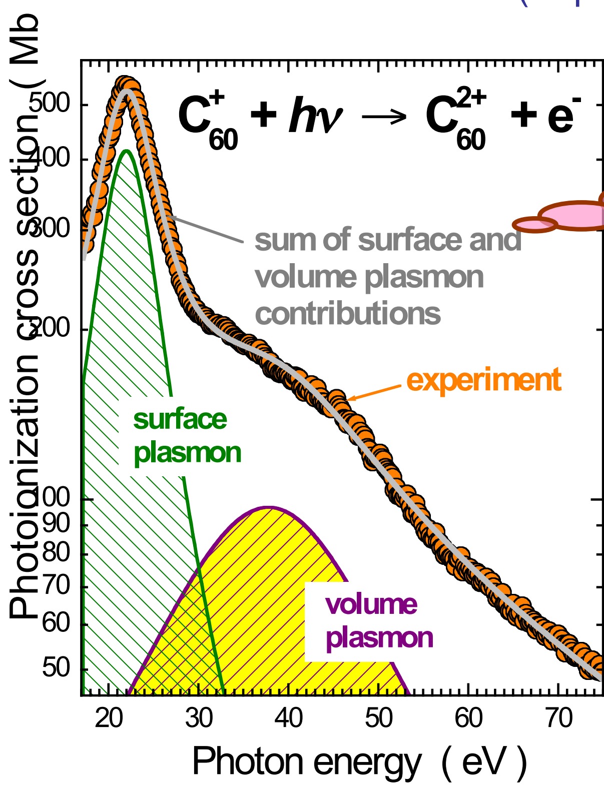


Dome of 1967 World Exhibition in Montreal by the architect R. Buckminster Fuller.

Setting 240 valence electrons in motion: C_{60}^{+}



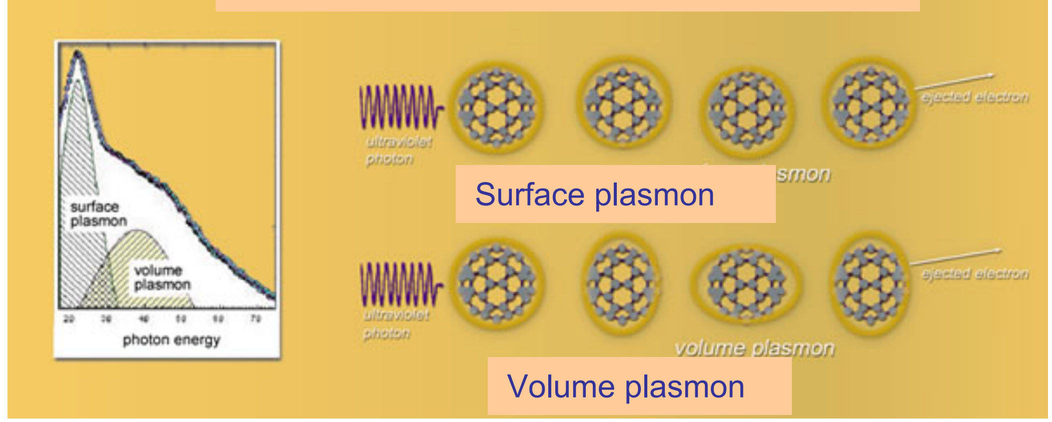
Absorption of a soft-x-ray photon from the Advanced Light Source: the energy of the photon is converted into a collective movement of the electrons (a “plasmon”).



S.W.J. Scully et al., Phys. Rev. Lett. 94, 065503 (2005).

Two resonances are observed: these resonances are attributed by theory to collective motion of the 240 valence electrons.

Two modes of collective motion



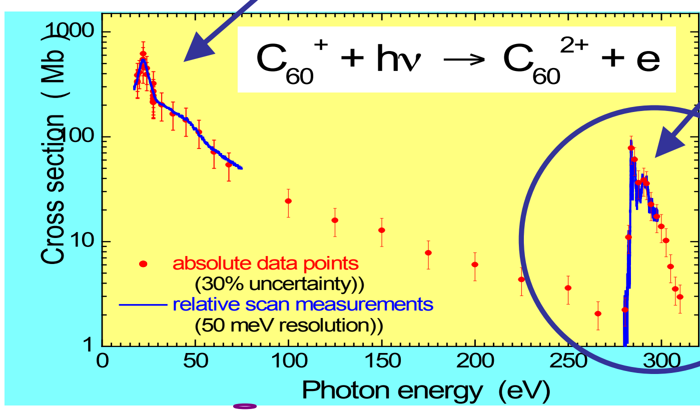
M. Ya Amusia and J-P Connerade Rep. Prog. Phys. 63, 41 (2000).

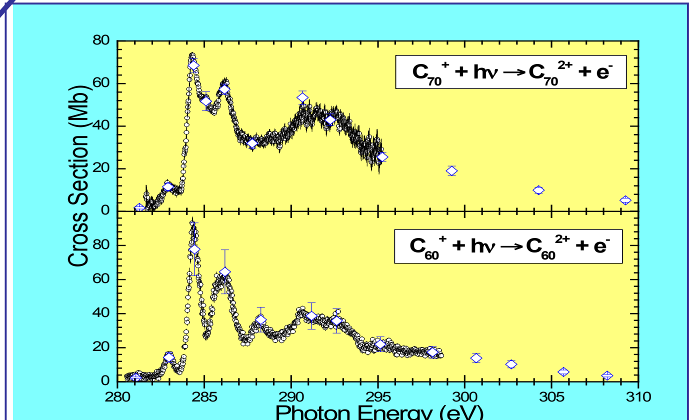
K-shell Excitation of C_{60}^{+} and C_{70}^{+} Ions:

collective and localized effects

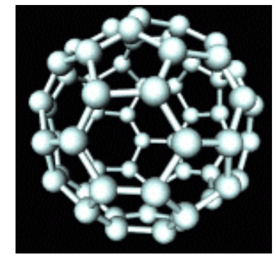
Collective Plasmon Excitations

Localized Molecular Excitations





C_{60}^{+}

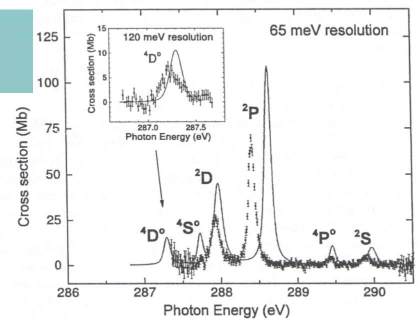


L-shell excitation

K-shell excitation

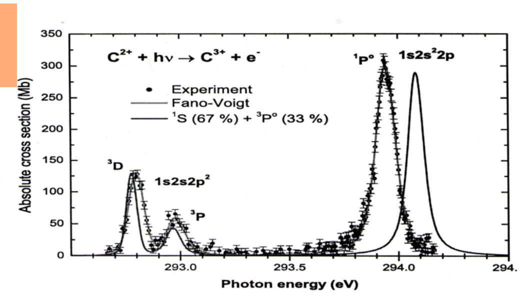
Comparison: K-shell excitation of C^{+} and C^{2+} ions.

C^{+}



Schlachter et al, J. Phys. B **37**, L103 (2004)

C^{2+}

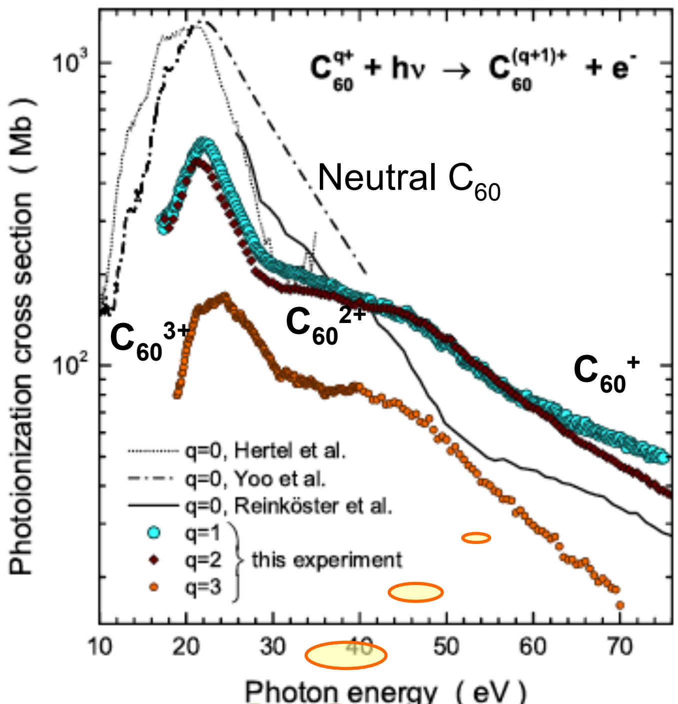


Scully et al, J. Phys. B **38**, 1967 (2005)

More physics of C_{60}^+ and C_{70}^+ Ions

Single photoionization of C_{60}^{q+}:

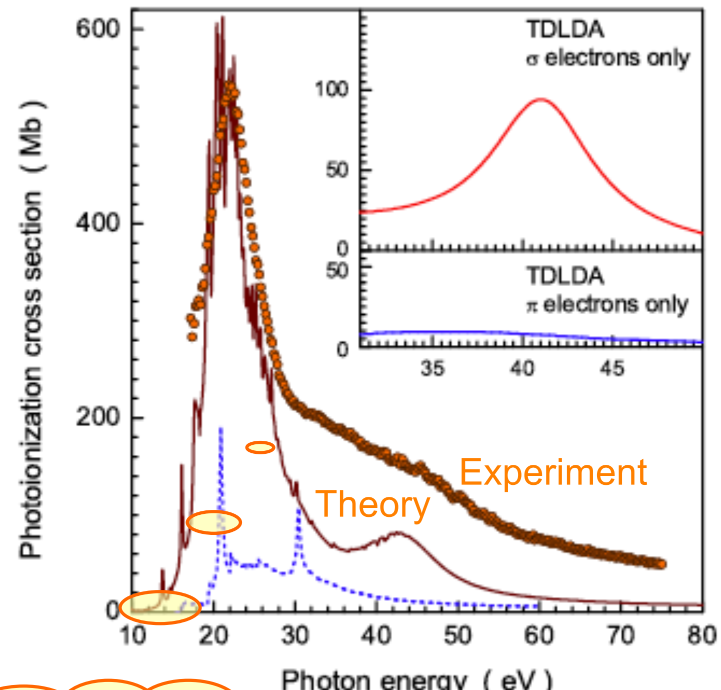
as function of ion charge state and comparison with neutrals



Absolute photoionization cross sections for C_{60} ions

Single photoionization of C_{60}^{q+}:

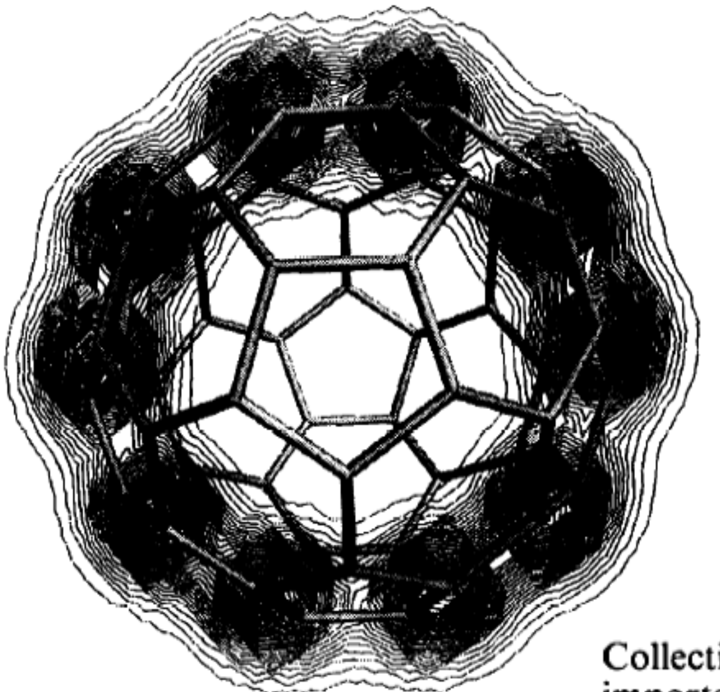
Comparison with theory (Time-Dependent Local-Density Approximation



Theory scaled to experiment at 22 eV. Note that theory shows both resonances

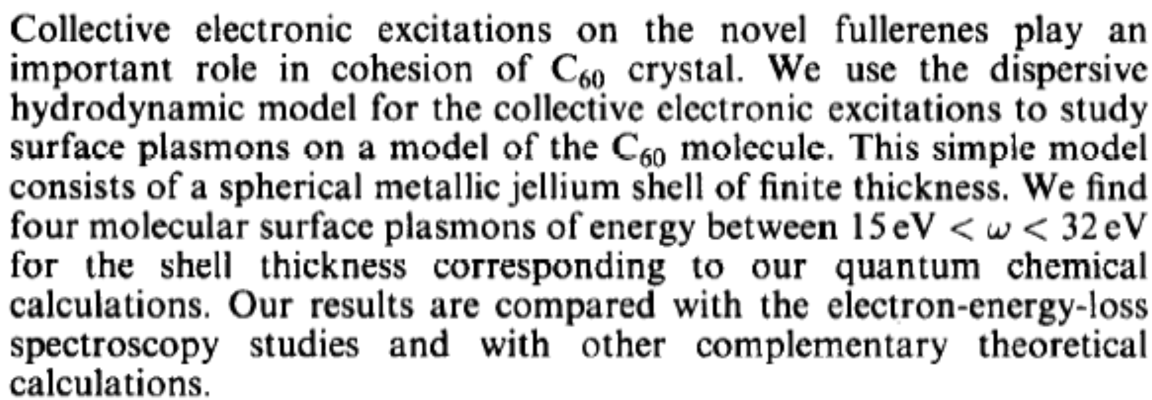
Scully et al., Physical Review Letters **94**, 065503 (2005)

There is considerable theoretical literature…



Two-dimensional cross section along the plane parallel to the pentagonal face of the C_{60} molecule showing the total density of valence electrons.

Michalewicz and Das, Solid State Communications **84**, 1121 (1992)


Collective electronic excitations on the novel fullerenes play an important role in cohesion of C_{60} crystal. We use the dispersive hydrodynamic model for the collective electronic excitations to study surface plasmons on a model of the C_{60} molecule. This simple model consists of a spherical metallic jellium shell of finite thickness. We find four molecular surface plasmons of energy between $15\,\text{eV} < \omega < 32\,\text{eV}$ for the shell thickness corresponding to our quantum chemical calculations. Our results are compared with the electron-energy-loss spectroscopy studies and with other complementary theoretical calculations.

Endohedral atoms: Ce in C_{82}^{+}

Encapsulating an atom or molecule in a Fullerene structure provides a possibility to alter the atomic or molecular properties of the atom or molecule: **creating new forms of matter with new applications.**

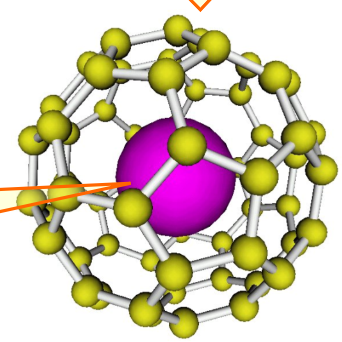
New possibilities for applications in nanostructure science and technology are being vigorously explored….

Potential applications:

• isolating an atom from its environment thus applications as q-bit for quantum computing.

• Chemical isolation of reactive or poisonous atoms may open new possibilities in medical imaging and cancer therapy.

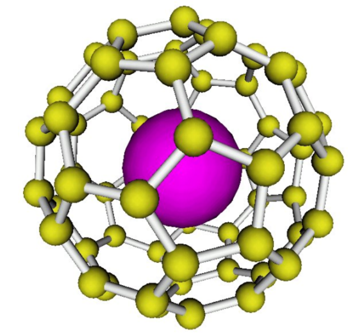
C_{82}^{+} fullerene cage



How are the energy levels of a *cerium atom* changed by being in the unique environment of a fullerene cage?

Mueller et al, Phys Rev Letts **101**, 133001 (2008)

Endohedral atoms: Ce in C_{82}^{+}

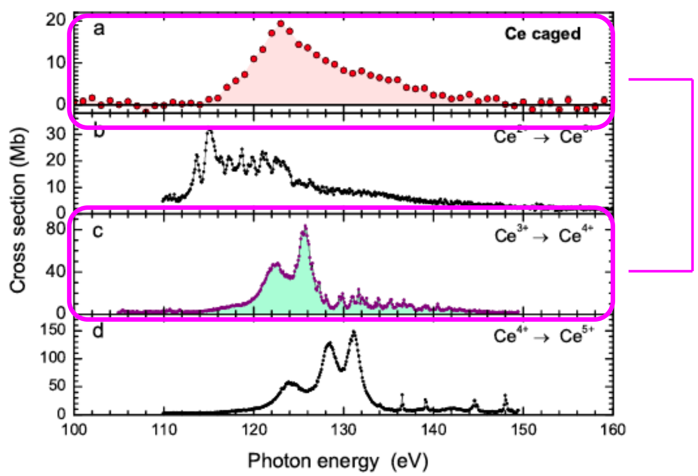


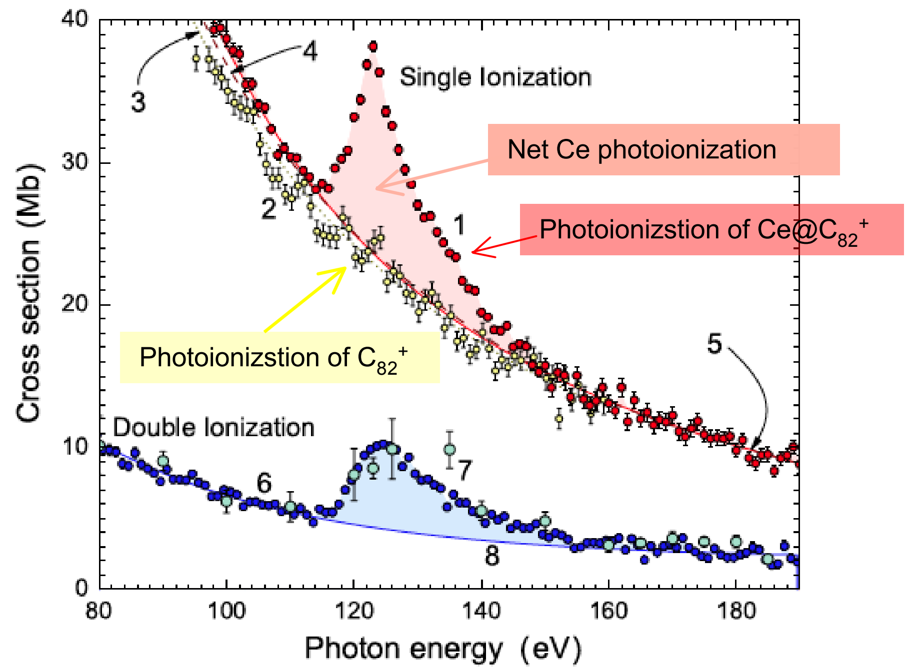
Objective: determine how the electronic structure of a cerium atom is altered by being enclosed in a C_{82}^{+} fullerene cage.

Experiment: measure photoionization of:

Ce^{q+} (isolated cerium ion), C_{82}^{+} (empty fullerene cage), and $Ce@C_{82}^{+}$ (endohedral cerium atom in fullerene cage).

Caged Ce atom looks like Ce^{3+} with energy levels blurred by hybridization.





Mueller et al, Phys Rev Letts **101**, 133001 (2008) and references therein; Amusia, J. Electron Spectrsc. Relat. Phenom. **161** 112 (2007).

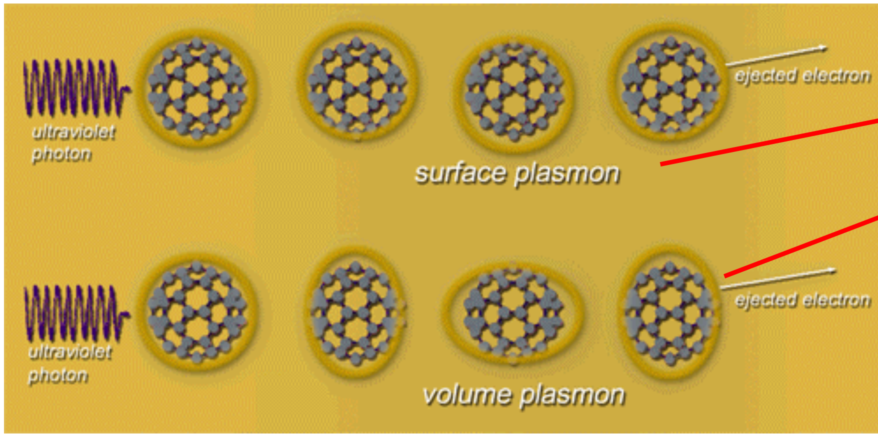
Discussion about nature of plasmon resonances…
ongoing in Physical Review Letters

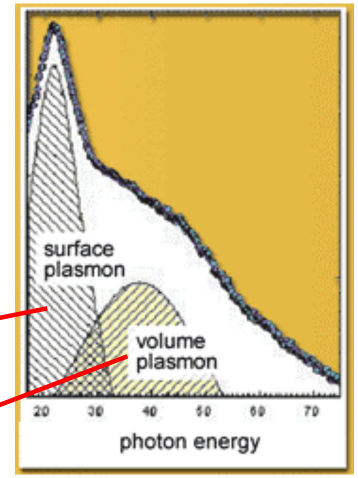
Korol and Solov'yov—Phys. Rev. Letters 98, 179601 (2007)—contend that observed volume plasmon can be interpreted in terms of coupled surface plasmons.

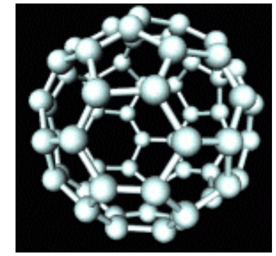
Scully et al.—Phys. Rev. Letters 98, 179602 (2007)—respond that a volume plasmon is associated with a spatial modulation of electron density, rather than a collective excitation with constant electron density.

Theorists are continuing this discussion on the pages of Physical Review Letters. Meanwhile we experimentalists are pleased with our observation of the second (volume plasmon) resonance, which had been overlooked in experiments on neutral C_{60}.

Plasmons: historical view



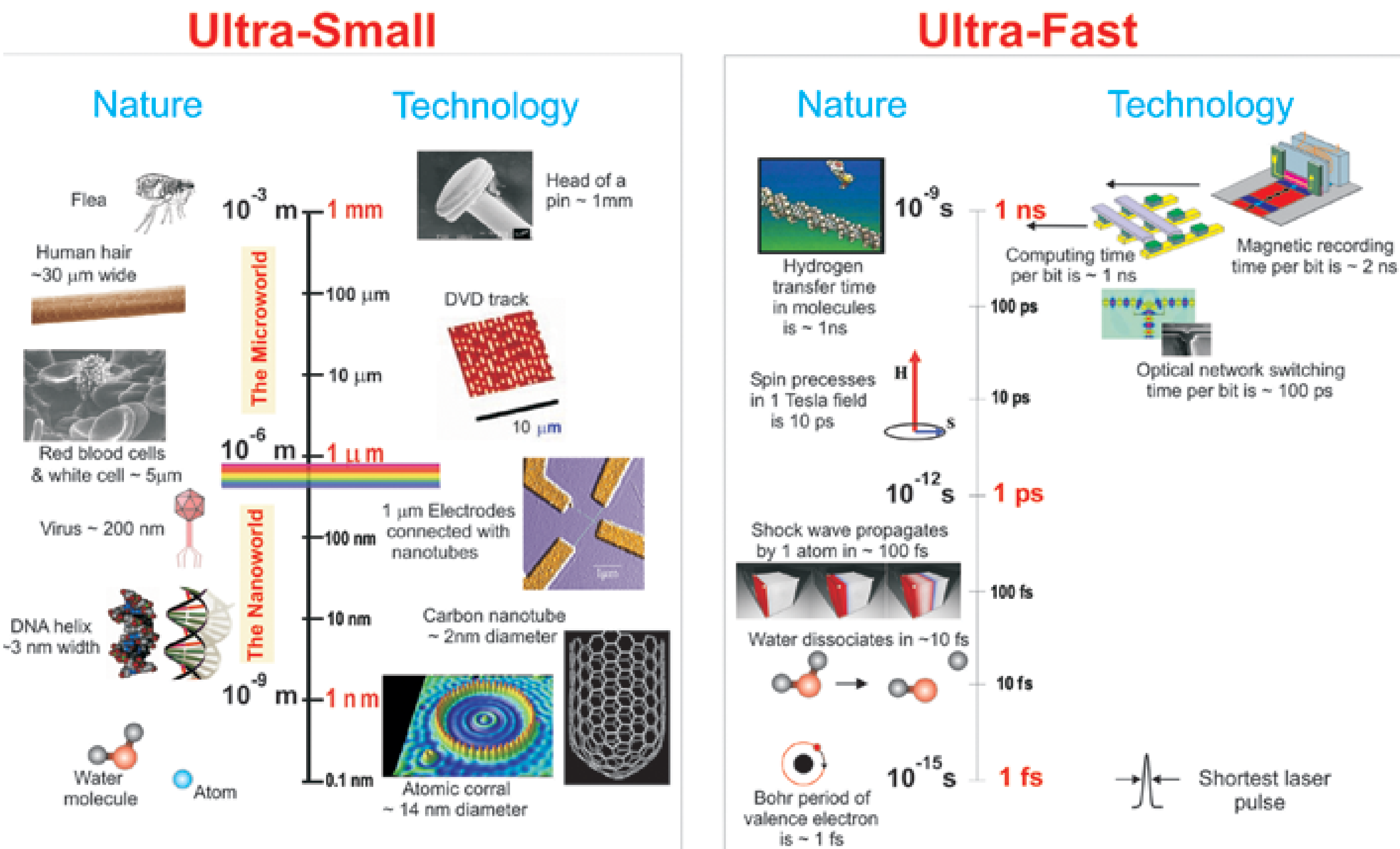




Plasmons confined to the surface of a material can produce obvious effects. **The deep red color in medieval stained-glass windows is actually produced by nanoparticles of gold:** "Electrons at the surface of the nanoparticles slosh back and forth in unison, absorbing blue and yellow light. But longer-wavelength red light reflects off the particles." **The New York Times calls the stained-glass artisans *"the first nanotechnologists."***

Stained-glass window makers in the Middle Ages achieved deep reds by dissolving gold in the molten glass. Surface plasmons on the nanosized particles of metal cause them to reflect red light selectively.

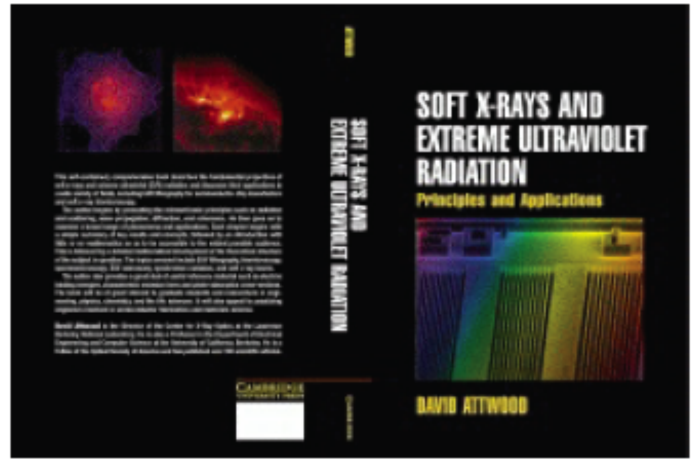
Frontiers in physics

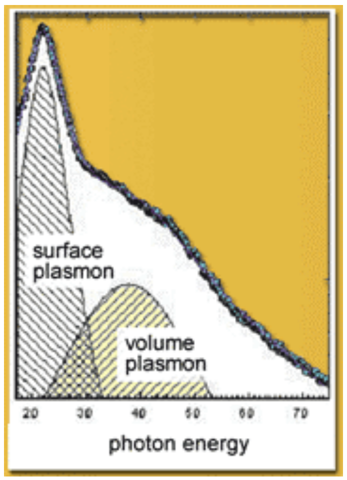


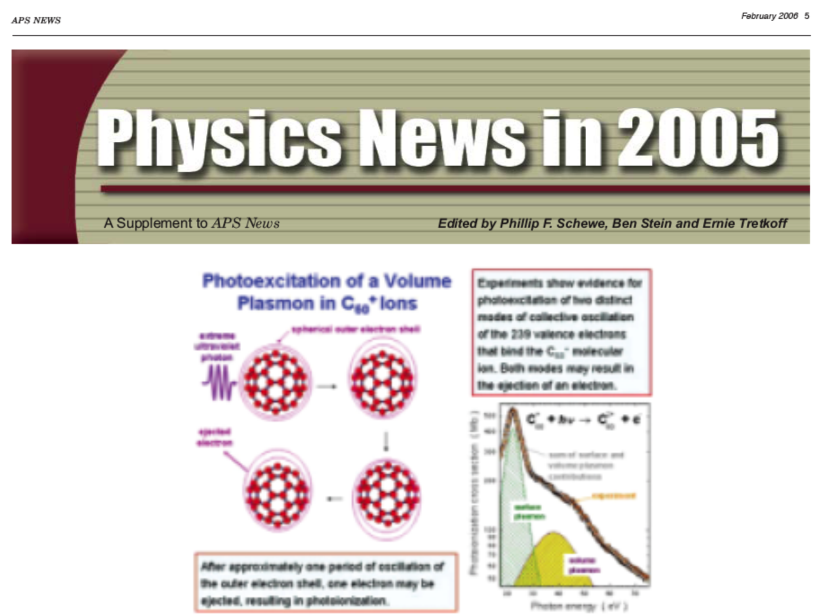
Further references

Soft x-rays and extreme ultraviolet radiation: principles and applications, David Attwood, Cambridge University Press

(www.coe.berkeley.edu/AST/sxreuv)







APS NEWS

February 2006 5

Physics News in 2005

A Supplement to *APS News*

Edited by Phillip F. Schewe, Ben Stein and Ernie Tretkoff

http://www-als.lbl.gov/als/science/sci_archive/103plasmon.html

http://www.lbl.gov/Science-Articles/Archive/sabl/2005/May/06-buckyballs.html

http://www.aps.org/apsnews/0206/

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International team working at ALS

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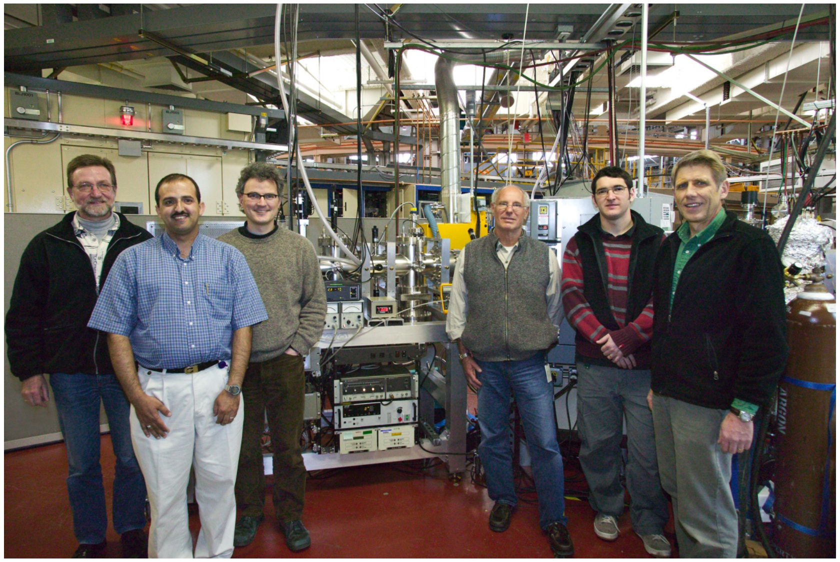
Stefan Schippers and Alfred Müller, Justus-Liebig-Universitaet Giessen

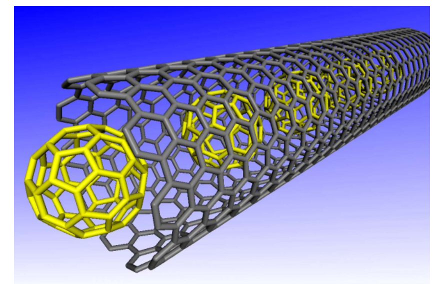
Himadri Chakraborty, Mohamed Madjet, and Jean-Michel Rost, Max Planck Institute, Dresden



"Photoexcitation of a Volume Plasmon in C_{60} Ions," Scully et al, Physical Review Letters **94**, 065503 (2005)

Conclusion:
collective motion of electrons in C_{60}

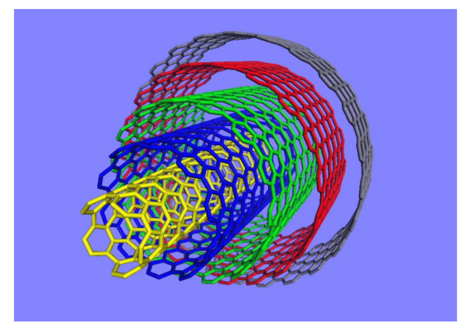
Collective motion (plasmons) are observed in C_{60}, which is intermediate between an atom and a solid. *Behavior characteristic of bulk matter is observed in a molecule with only 240 valence electrons.*



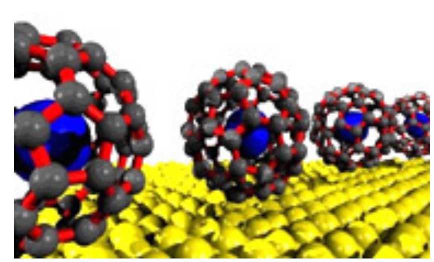
Exciting new science is possible with **nanomaterials**.

A synchrotron light source is a powerful tool for the exploration of the **electronic structure of matter**.

Theory and experiment work together to understand the electronic structure of matter.



fsschlachter@lbl.gov



Fred: diving in Thailand

http://www.lbl.gov/Publications/Currents/archive/
February 16, 2007

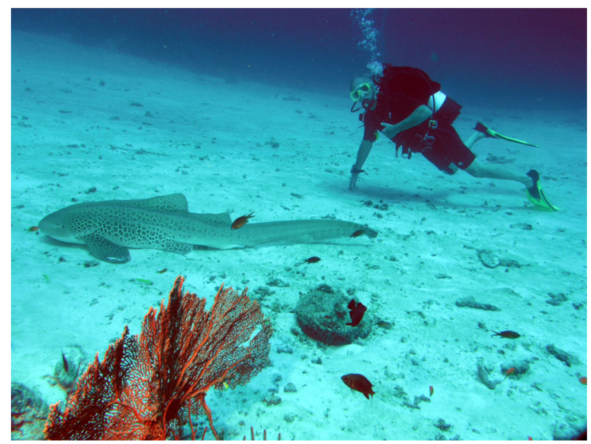
From Buckyballs to Manta Rays: The Diving Adventures of an ALS Beamline Scientist

BY LYN HUNTER

There sat Fred Schlachter on the dark ocean floor, 36 feet below the surface. Just an arm's length away swam a manta ray. Though elated at the sight of this magnificent creature, visions of Steve Irwin — the Australian TV show host who died last fall from a stingray's stab — flashed before him.

Schlachter heads out to the Similan Islands near Thailand for a dive.

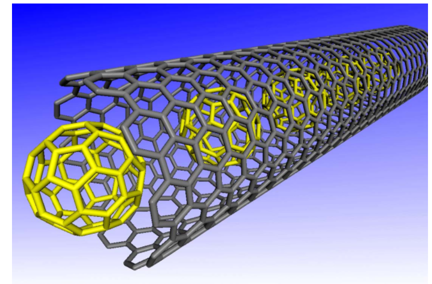
Schlachter is on the faculty at Chiang Mai University, where he lectures in the physics department and mentors a Ph.D student.



Schlachter is careful to leave plenty of distance between himself and a leopard shark in the Andaman Sea.

When he's not diving, the 31-year Lab veteran is assisting ALS users. He researches "how electrons give atoms and molecules their properties, and how big an atom has to be to begin to behave classically, as opposed to quantum mechanically." He was also involved with the search for quantum chaos and collective oscillation of electrons in buckyballs.

Thanks for your attention……



Additional lecture topics:

- Light: a user's guide to the universe (lay audiences)
- Synchrotron radiation: a tool for exploring the electronic structure of matter (multi-hour seminar series)
- Lasers in science and industry: economic impact (www.laserfest.org)
- Over a barrel: revolutionizing the way we power our cars (lay or professional audiences) (RevModPhys 2008)
- The search for quantum chaos.

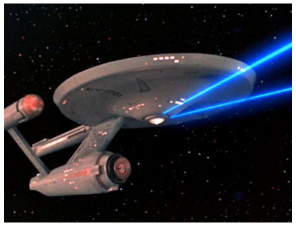
ขอบคุณครับ

fsschlachter@lbl.gov

Chulalongkorn University, September 27, 2010

"Lasers in science and industry: economic impact."

LCLS: x-ray laser



LCLS (Stanford)

ν= 10^{17} Hz

λ~2 A

L= 3.5 kM

P=30 MW

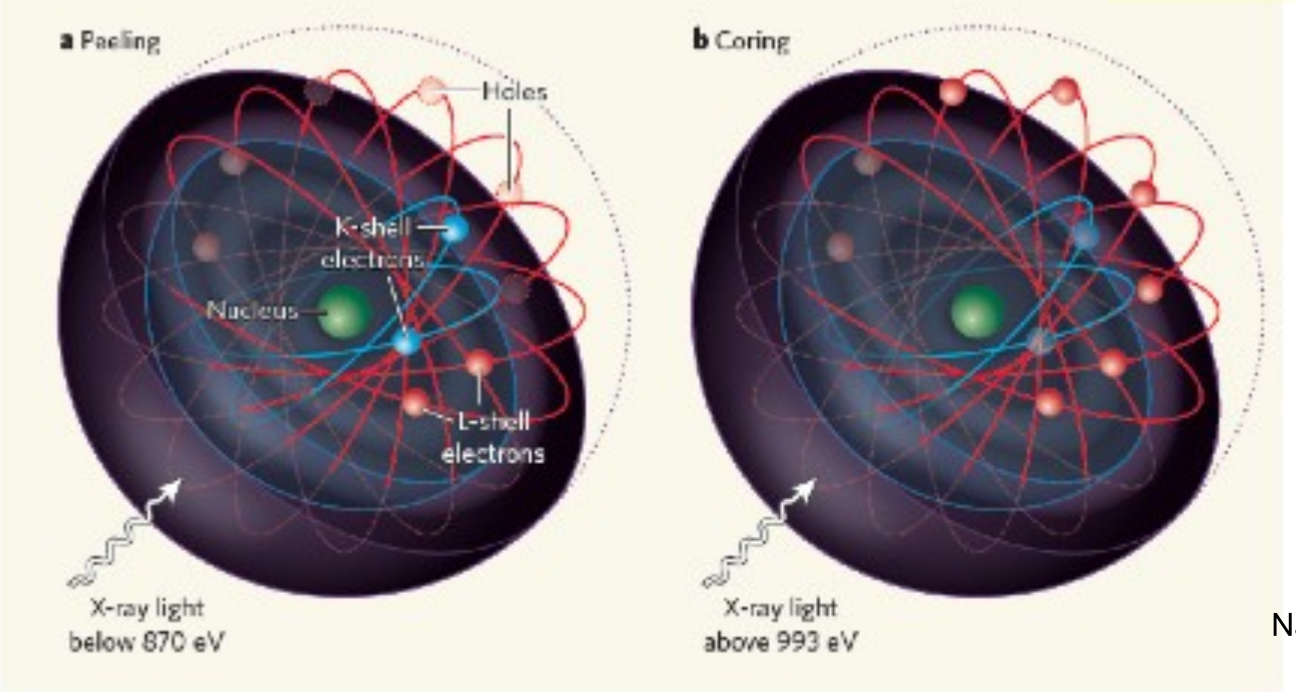
X-ray lasers photograph molecular bonds breaking

X-ray laser: producing hollow atoms

Removing inner-shell electrons from neon atom.

LCLS pulse: tens of femtoseconds

Power 10^{18} watts/cm^2.



Nature vol.**466** July 1, 2010

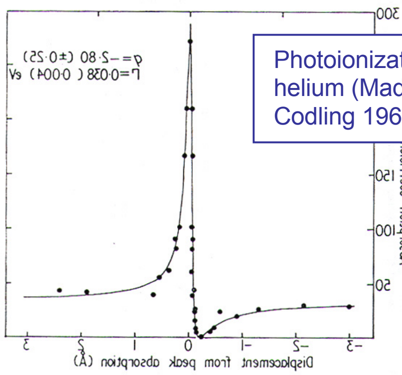
Hollow atoms: Advanced Light Source 1996-2002:

hollow helium: Physical Review Letters **86**, 3747 (2001). Search for quantum chaos is doubly excited atoms of helium.

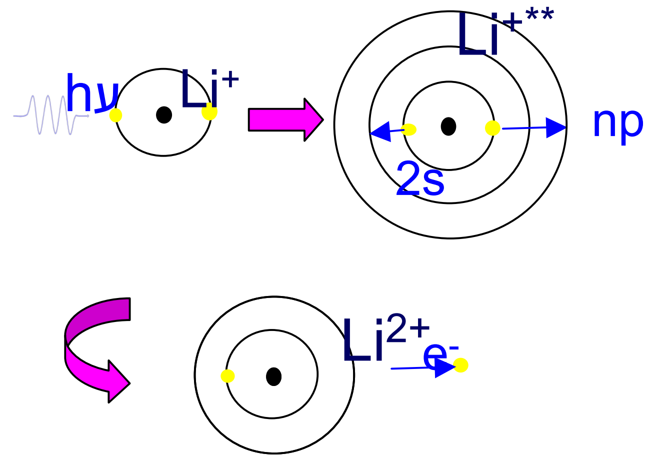
hollow lithium: Physical Review Letters **79**, 1241 (1997). Hollow lithium atomic states.

Photoionization of helium-like Li⁺

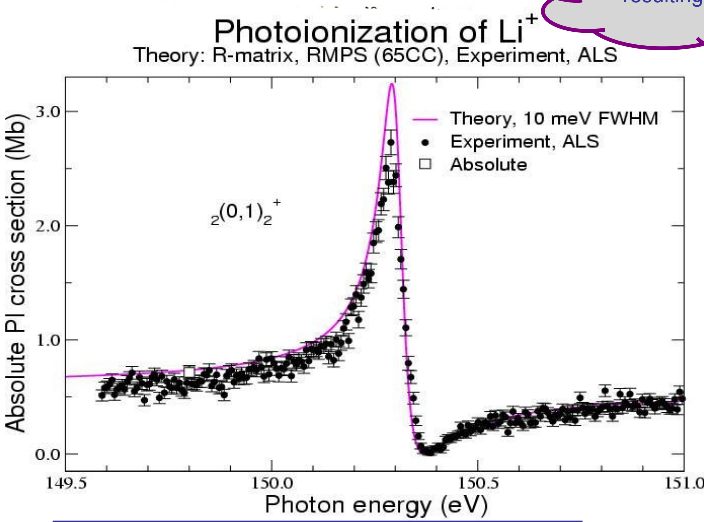
Photoionization of both electrons in He neutrals and Li⁺ ions: the search for quantum chaos



Photoionization of atomic helium (Madden and Codling 1965)



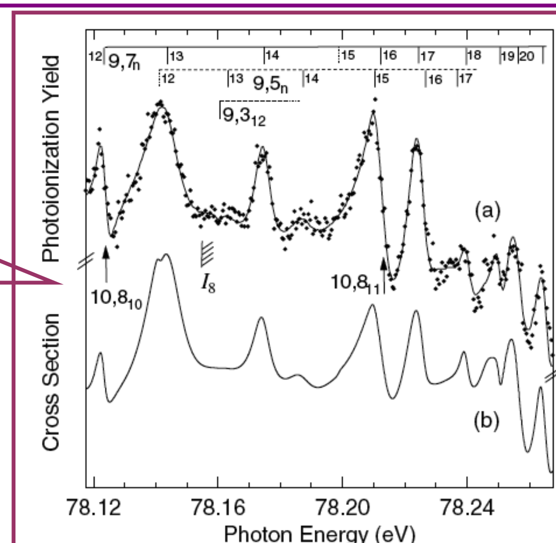
The two electrons are left in excited states, resulting in autoionization



Scully et al, J. Phys. B **39** 3957 (2006)

Ultrahigh spectral resolution measurements of absorption in helium atoms -> quantum chaos

Loss of quantum states in the spectrum of doubly excited helium atoms

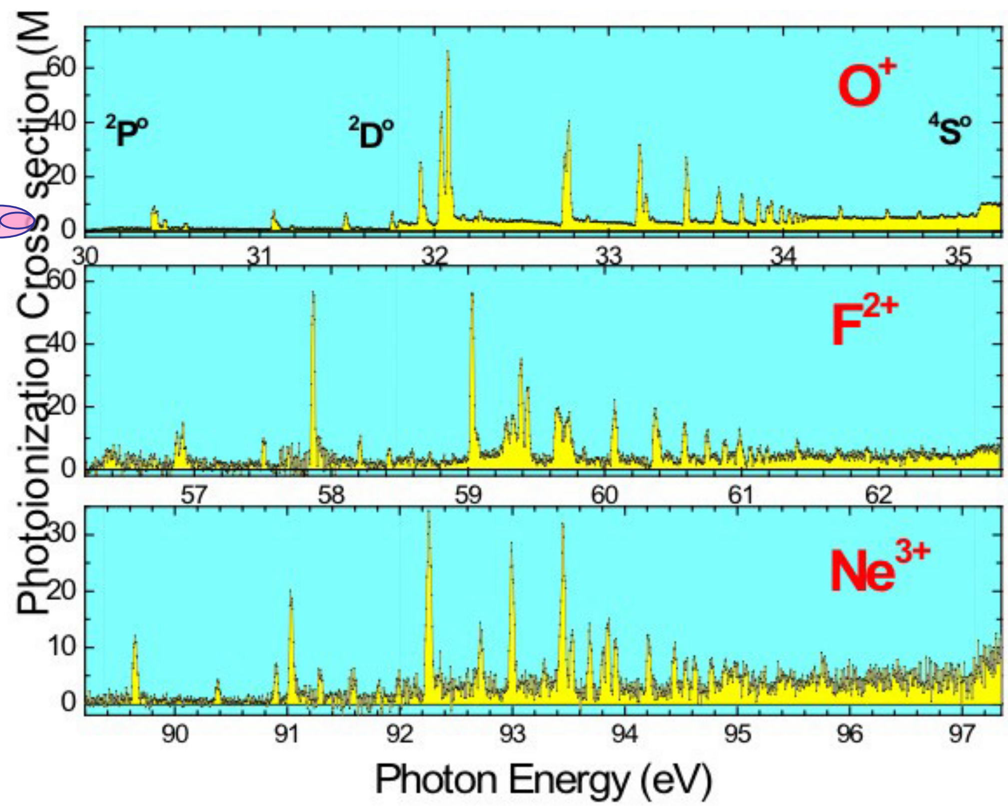


Püttner al, Phys. Rev. Letts. **86**, 3747 (2001)

…photoionization measurements…

Photoionization of ions of the nitrogen isoelectronic sequence

Measurements of photoionization along an isoelectronic (ions with same number of electrons) sequence can reveal systematics in atomic structure.



Aguilar et al, J. Phys. B 38, 343 (2005)

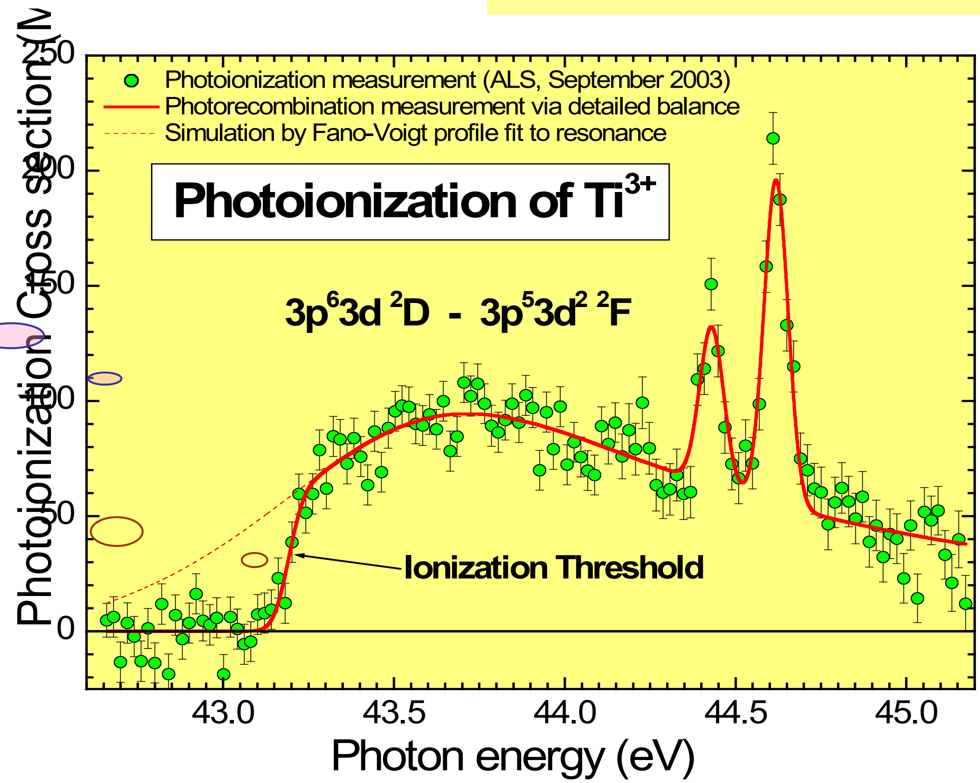
…photoionization measurements…

Ti^{3+} photoionization: a broad resonance lying just above an ionization threshold

A giant dipole resonance 1.5 eV wide lies only 0.2 eV above the ionization threshold, and is therefore truncated.

Truncation of a giant dipole resonance in photoionization of Ti^{3+} ions.

Curve: photorecombination measurement at TSR in Heidelberg inverted using principle of detailed balance



Time-reversal symmetry

Photoionization of Sc^{2+}

S. Schippers et al.
Phys Rev. Lett. **89**, 193002 (2002).

Schippers et al, J. Phys. B **73**, L209 (2004)

Soft x-ray beamline at ALS

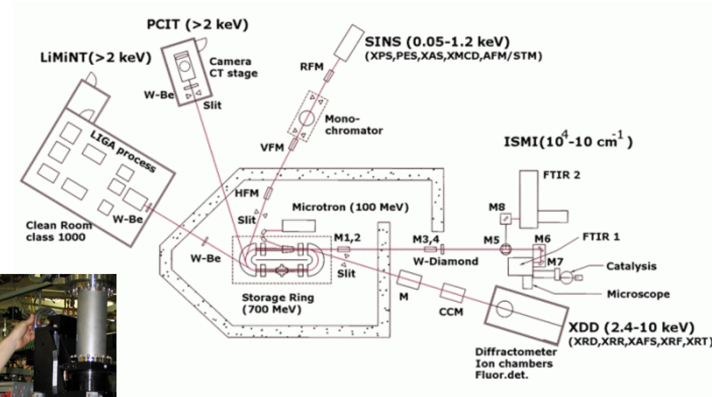
Electron beam 700 MeV

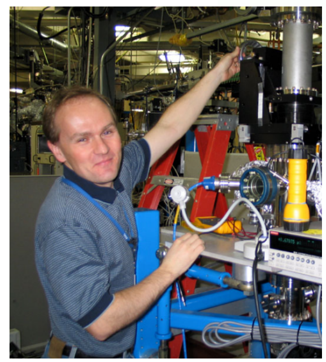
Dipole field 4.5 T

Characteristic energy 1.47 keV

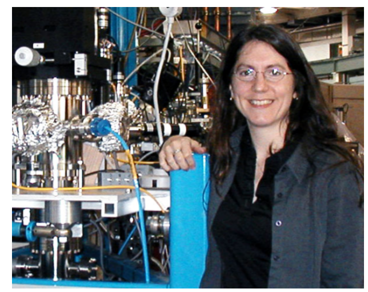
Beamline Specifications

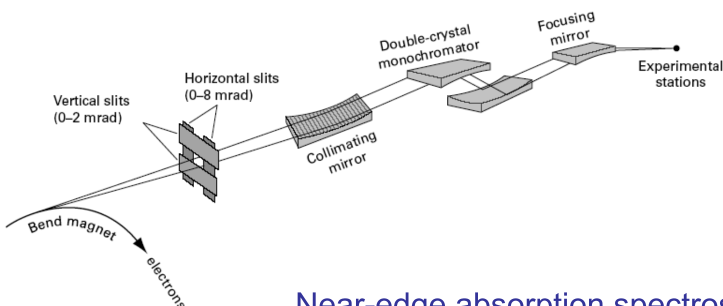
Photon Energy Range (keV)	Photon Flux (photons/s)	Spectral Resolution (E/ΔE)	Spot Size (mm)	Availability
2.2–6.0 [with Si(111) crystals]	$>10^{11}$	3000–8000	<0.5	NOW

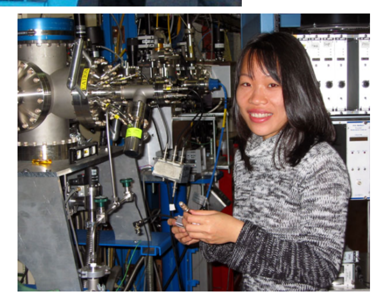




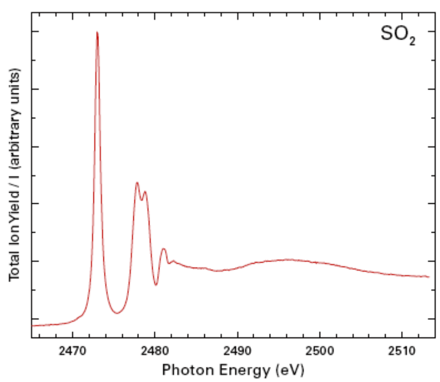
Electron beam 1.9 GeV: 1-T bend magnet. Photon energy range 2.3-5.5 keV with 10^{11} photons/s and a resolving power up to 8000.



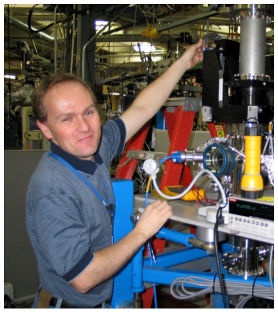




Near-edge absorption spectroscopy

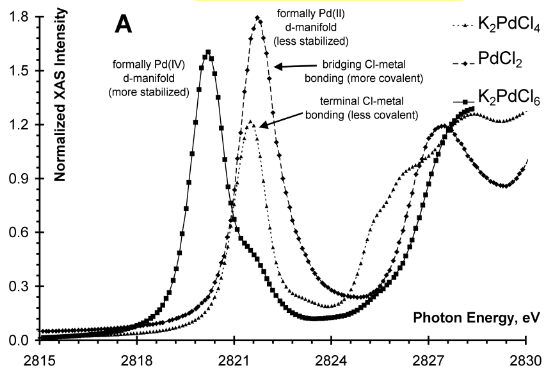


Soft x-ray beamline at ALS: spectroscopy …

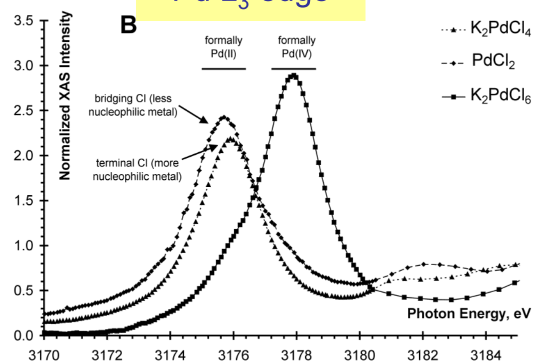


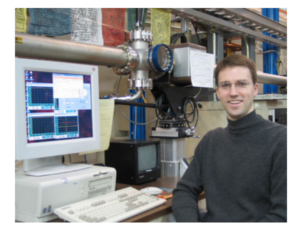
Spectroscopy of Palladium Complexes

Cl K edge

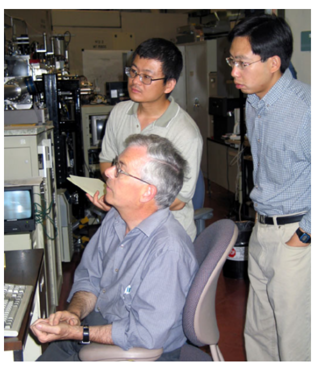


Pd L_3 edge

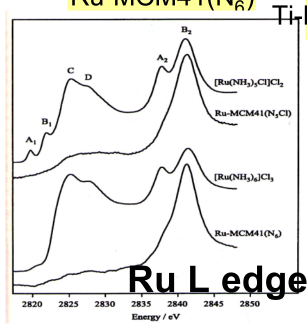




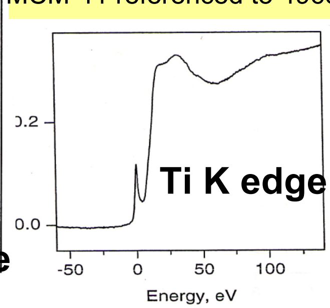
Catalysts: absorption studies of molecular sieves and zeolites



Ru-MCM41(N_6)

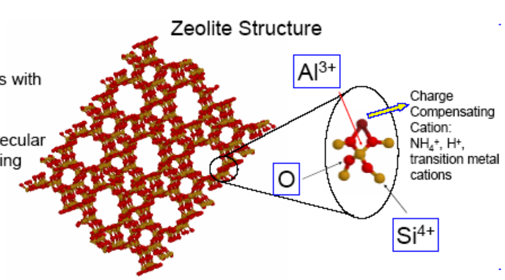


Ti-MCM-41 referenced to 4968 eV

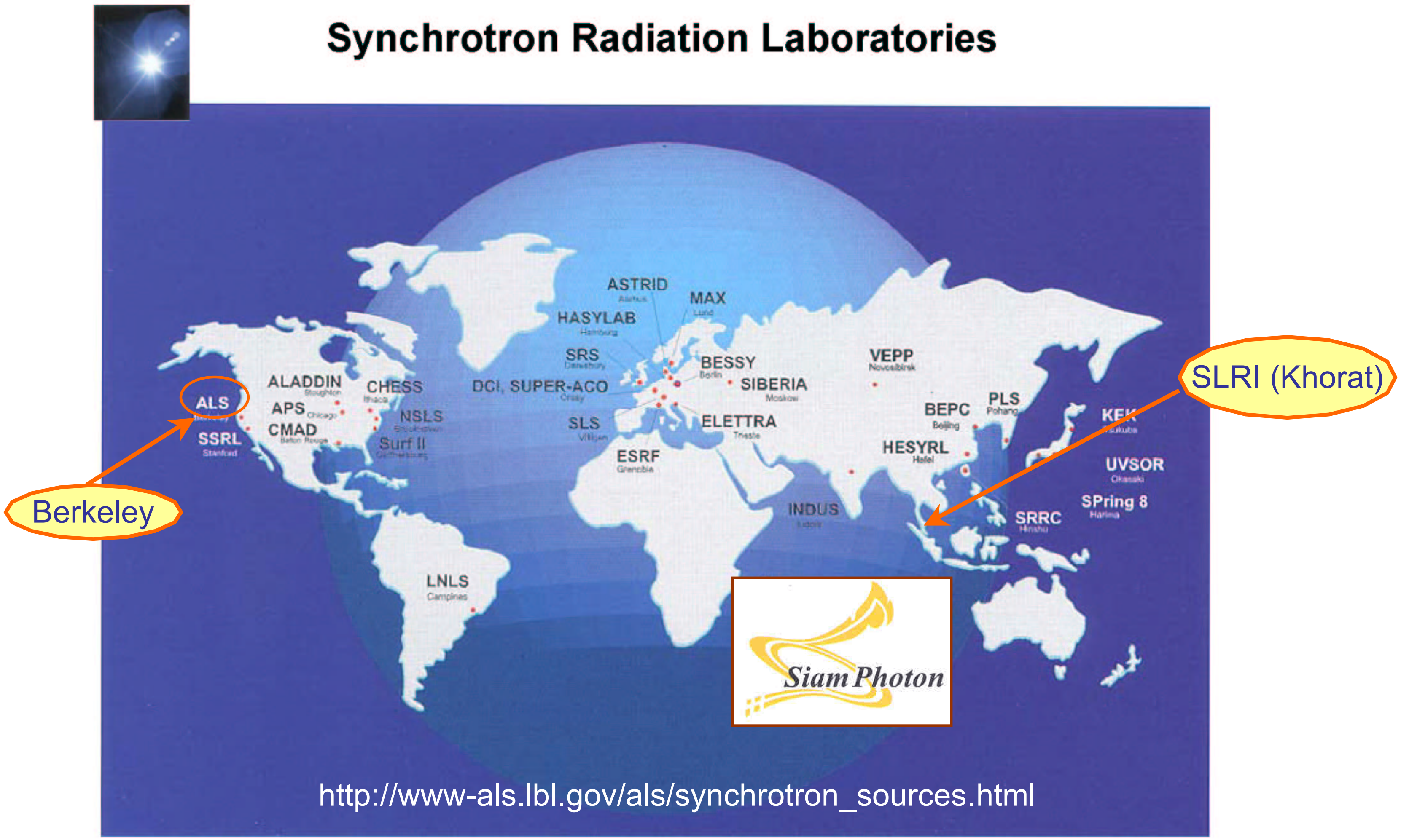


Zeolites

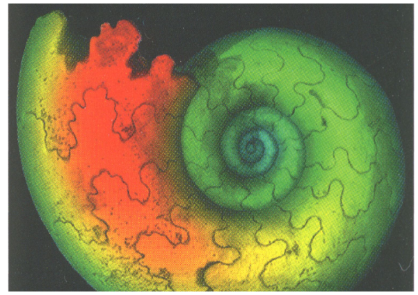
- Crystalline alumino-silicates with interconnecting pores for diffusion of molecules
- Industrial Significance: Molecular sieve, Petrochemical cracking catalyst

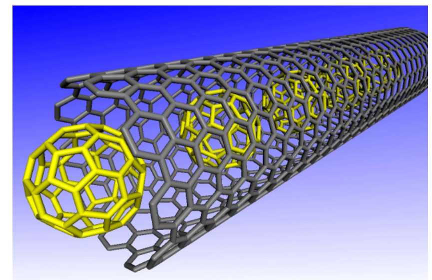


Synchrotron light sources are worldwide



Thanks….





Fsschlachter@lbl.gov