Next big thing in physics

What scientists will be working on in the next decades?

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PHYS-201 “Modern Physics”

Next big thing: accurate description of the nuclear structure

Prof. Todd Averett, experimental nuclear physics

In nuclear physics, much of the field is focused on studying the quark structure of the nucleon. Indeed protons have been known for a century and quarks for a half-century. But still, QCD (quantum chromo dynamics) is unsolved so in a nutshell, we cannot describe properties of the nucleon such as magnetic moment, size, charge distribution, spin, etc in terms of the quarks and gluonic force. To me, this is essential for completing our understanding of all things nuclear physics related: stellar evolution, supernovae (which create ALL elements above iron), neutron stars, fusion, weapons, nuclear power, radioactive decay. Indeed 99.999+% of all visible matter is contained in the nucleus of atoms. Seems important that we understand it!

Next big thing: what is inside a proton?

Prof. Keith Griffioen,
experimental
nuclear physics

Despite living with the proton for a century, we still have not been able to understood its internal structure. The proton is made of two valance up quarks, one valance down quark, a number of quark-anti-quark pairs, and many strong-force-carrying gluons. The strong force is extremely interesting because it has three charges, which we call red, green and blue, and the “color” force between two quarks actually gets larger as you pull them away from each other. Consequently, the quarks in the proton stay close to home, and the proton’s rms radius is less than 1 fm. The project for the coming decade, at Jefferson Lab and elsewhere, is to use electron beams to do tomography of the proton. We want to know (probabilistically) where the quarks are, how they are moving, and how their spins are aligned. We also want to know what the distribution of gluons is like.

Next big thing: what is inside a proton?

This research can be outlined in three current puzzles.

The spin puzzle: Observations of the spin of the quarks in a proton show that it's spin does not come significantly from the quark spin, nor does it come significantly from the gluon spin. This leaves orbital angular momentum, but this runs contrary to our quantum mechanical intuition that ground-states of a system have no orbital angular momentum.

The size puzzle: 60 years of measurements of the proton rms radius have given us values that range from 0.8 to 0.9 fm despite the increasing accuracy of the different techniques (electron scattering, hydrogen spectroscopy, or muon spectroscopy). Either there are unaccounted errors in the measurements, or there is a new particle lurking, which interacts more strongly with the muon than with the electron.

The mass puzzle: Although the Higgs boson generates elementary particle masses, it does not account for the mass of the proton. Three quarks with masses on the order of a few MeV form a proton with a mass of 938 MeV. We physicists think that the gluons, which interact strongly with the quarks and with each other, are responsible for the proton's mass. This pure energy is confined within the proton, but just how this works is still a mystery. To understand the gluons, physicists are proposing a next-generation electron-ion collider that can reach the resolutions necessary to probe these gluons.

So the next time you step on a scale, remember that your mass, and the mass of everything around you, comes overwhelmingly from gluons!

Next big thing: what is the bigger picture?


Prof. Jeff Nelson, experimental neutrino physics

Is the Higgs the predicted Standard Model Particle?

http://www.symmetrymagazine.org/article/march-2012/ten-things-you-may-not-know-about-the-higgs-boson
http://www.symmetrymagazine.org/article/october-2012/what-else-could-the-higgs-be

What is dark energy and what is dark matter?

http://www.symmetrymagazine.org/article/march-2007/explain-it-in-60-seconds-dark-matter
http://www.symmetrymagazine.org/article/january-2013/illuminating-the-dark-universe

Why is the Universe matter dominated? What caused the CP violation? Did neutrinos cause this? If not then it has to be new physics.

http://www.symmetrymagazine.org/article/november-2013/the-early-universe
http://www.symmetrymagazine.org/article/october-2005/explain-it-in-60-seconds

What caused inflation?

http://www.space.com/14699-universe-inflation-cosmic-expansion-theory.html
http://www.symmetrymagazine.org/article/december-2013/baryonic-acoustic-oscillations

Are we part of a multiverse? (which is related)

https://www.google.com/url?q=http://www.space.com/21421-universe-multiverse-inflation-theory.html&sa=U&ei=XBChUvaJJ5booAS23YC4Cg&ved=0CAYQFjAA&client=internal-uds-cse&usg=AFQjCNEcSMmKZt2Mu4QCAQjF_uuI83EdNA

Are neutrinos their own antiparticles?

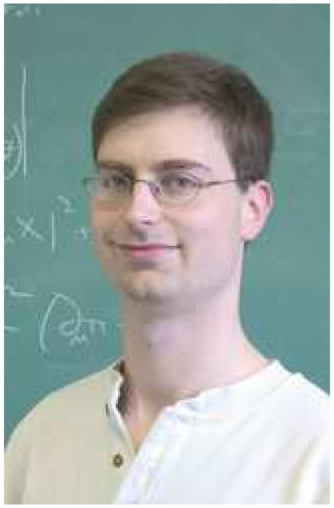
http://www.symmetrymagazine.org/article/august-2013/neutrinoless-double-beta-decay

Next big thing: New physics beyond the Standard model

Prof. David Armstrong, nuclear experiment

We have a very successful mathematically consistent description of the elementary particles, and their interactions (strong, weak, and electromagnetic). With the recent discovery at CERN of the final required particle in the Standard Model (the Higgs boson), things look frustratingly consistent. Why frustrating? Because we are also quite certain that the Standard Model can't be the final theory: it cannot incorporate gravity (we don't know how to make a quantum field theory of gravitation), it doesn't include dark matter or dark energy, etc. So, experimentalists working at the highest energy accelerator (the LHC at CERN) and in a variety of precision experiments using other accelerators or other techniques continue to test the boundaries of the Standard Model, with the hope of finding where it breaks down... and theoretical particle physicists continue to try to develop theories that encompass all of the successes of the Standard Model, but which are in some sense more elegant and simple.

Next big thing: New physics beyond the Standard model



Prof. Josh Erlich, elementary particle theory

Now that the discovery of the Higgs boson has completed the Standard Model of Particle Physics, particle physicists are searching for signs of the new physics that will resolve the (many) remaining puzzles. For example, how did matter win out over antimatter in the early universe (**baryogenesis**)? What is **dark matter**? What is **dark energy**? Why is there not much more dark energy, as would be naively expected by quantum corrections to the vacuum energy (the **cosmological constant problem**)? Why is the Higgs boson not much heavier than it is, as would be naively expected by quantum corrections to the Higgs boson mass (the **hierarchy problem**)?

Next big thing: New physics beyond the Standard model

Prof. Wouter Deconinck, experimental nuclear physics

Dark matter and dark energy make up more than 95% of our universe, but are not part of the Standard Model of particle physics. The most cost-effective approach to resolving these issues appears to be the "precision frontier," a general term for relatively small but incredibly precise experiments that probe fundamental quantities such as the anomalous magnetic moment of the muon, neutrino-less double beta decay, parity-violating electron scattering, electric dipole moments, etc. These experiments cast a much wider net than direct searches, and will break through important sensitivity milestones in the next two decades.

Next big thing: where is the anti-matter?

Prof. Tricia Vahle, experimental neutrino physics

The next big question in neutrinos that I want an answer to is whether or not they violate the charge-parity (CP) symmetry. Quarks violate this symmetry, but its only a little bit. To explain why everything we see is made out of matter, and not antimatter, and in fact to explain why there is any matter at all, we need a much bigger source of CP violation. In the early universe, if there wasn't a source of cp violation, matter and antimatter would be made in equal amounts, and then would annihilate with each other in equal amounts, leaving no matter or antimatter at all. Its possible neutrinos hold the key to this existential question.

http://www.youtube.com/watch?v=Fe4veClYxkE

Next big thing:
Ultracold quantum engineering?

Prof. Seth Aubin, experimental Atomic, Molecular and Optical (AMO) Physics

Ultracold atoms can be engineered to create new devices:

1. Quantum interferometer
Atom interferometer to detect ultra-weak forces.

2. Quantum detector
Entanglement can reduce (squeeze) your detector noise and increase its sensitivity.

3. Quantum simulator
Design/control of many-body Hamiltonians to simulate complicated problems experimentally, e.g. High Tc superconductivity.

4. Quantum computer
Quantum computing will soon be a reality through improvements in quantum interference, entanglement, and control.

Next big thing: Quantum metrology and quantum control

Prof. Eugeniy Mikhailov, experimental Atomic, Molecular and Optical (AMO) Physics

As time progresses we will be able to access measurements of the system at the quantum level. This mean that our measurements will not be contaminated by large classical noise, but quantum fluctuations will be the limit. We already able to distinguish light states at several photon energy levels, observe single atoms and its quantum states. Quantum control of a macroscopic system, i.e. a large system consisted of many atoms, with several energy quanta precision is on its way.

Next big thing: Quantum information and quantum computing

Prof. Irina Novikova, experimental AMO physics

Our developing ability to manipulate quantum states of light and matter leads to fundamentally different approach to handling the information. On one hand, encoding the data into a quantum superposition of just two states promises an enormous economy on the number of the carriers required, as well as absolute security of the network. On the other hand, quantum bits require principally different tools for data manipulation, storage and error correction. Figuring out how to make a practical quantum network and quantum computer will keep many physicists, mathematicians and computer scientists occupied in coming decades.

Relevant papers: Jeff Kimble’s “Quantum internet”
http://ixnovi.people.wm.edu/papers/kimble08.pdf

Next big thing: Bayesian Quantum Mechanics interpretation (QBism)

Prof. emeritus Hans von Baeyer popular science writer, elementary particle theory

I believe that foundations will become an active field through the confluence of two developments:

http://arxiv.org/pdf/1311.5253v1.pdf

http://ixnovi.people.wm.edu/papers/QBism_final.pdf

1. QBism grew out of quantum information theory which will obviously become bigger with quantum computing, quantum cryptography, and quantum tomography. The first hints of new techniques arising from QBism are already on the horizon.

2. The second development is big data. Much of that - climate models, for example - are clearly based on Bayesian rather than frequentist techniques.

E-mail Prof von Baeyer if you have questions!

Next big thing: condensed matter of strongly correlated electron systems

Prof. Shiwei Zhang, condensed matter theory

I think one 'big' topic, a leading challenge, in condensed matter physics is "strongly correlated electron systems". That is, the need to develop the understanding of materials in which the collective effect of electrons, their 'quantumness' together with their interactions, conspire to produce new states and physical phenomena. P.W. Anderson's sentence, "More is different", captures this well. The challenge is theoretical, experimental, and computational. In fact, this topic encompasses more than condensed matter physics.

Next big thing: Topological quantum matter and computation

Prof. Enrico Rossi, condensed matter theory

In recent years physicists have realized that there are many condensed matter systems for which symmetries are not sufficient to characterize their states: these states can only be understood and classified using topological concepts. This has caused the emergence of the field of “topological quantum matter”. For example, we now have systems like “topological insulators”, and “topological superconductors”. Topological superconductors are particularly interesting because their excitations can in principle be used to realize a topological quantum computer. Taking advantage of the unique properties of topological quantum matter to realize novel phenomena of fundamental and technological interest, and a quantum computer is on of the “next big things”.

Relevant papersf
Frank Wilczek’s “Majorana returns”
http://ixnovi.people.wm.edu/papers/Majorana_return434.pdf

Next big thing: unconventional superconductors

Prof. Mumtaz Qazilbash, condensed matter experiment

In addition to the challenge of strongly correlated electrons, a comparable and possibly related problem is that of unconventional superconductivity, i.e. superconductivity not simply mediated by phonons (lattice oscillations). In particular, the reasons behind high-temperature superconductivity are not known. Moreover, we do not have a blueprint for synthesizing superconductors with higher Tc. I expect this problem to keep condensed matter physicists occupied for some time to come.

Next big thing: plasmonics

Prof. Ale Lukaszew, condensed matter experiment

By coupling light to the charges at metal interfaces, plasmonics enables scientists to manipulate photons in a way they never have before: at the sub-wavelength level. With its potential to produce ultra-compact devices that relay information almost instantaneously, plasmonics may be the next big-and small-thing in optical communications. Plasmonic technology has applications in a wide range of fields, including biophotonics, sensing, chemistry and medicine. But perhaps the area where it will have the most profound impact is in optical communications, since plasmonic waves oscillate at optical frequencies and thus can carry information at optical bandwidths.

Next big thing: unitary qubit lattice algorithms

Prof. George Vahala, computational physics

Unitary qubit lattice algorithms are an exciting method of solving nonlinear problems in both classical and quantum physics with schemes that are wonderfully parallelized on classical supercomputers (e.g., over 800K cores) but will also run on future quantum computers. These mesoscopic algorithms, being unitary, are fully time reversible but at the 'macro' level can describe dissipative irreversible systems like fluid and plasma turbulence as well as quantum turbulence. The algorithm involves an interleaving of unitary collision (which entangle on-site qubits) – streaming (spreads this entanglement throughout the lattice) operators.