“All the matter that makes up all the living organisms and ecosystems, planets and stars, throughout every galaxy in the universe, is made of atoms, and 99.9% of the mass of all the atoms in the (visible) universe comes from the nuclei at their centers which are over 10,000 times smaller in diameter than the atoms themselves”

• Why? …should one care?
• What? …are the overarching questions?
• How? …to answer them?
• Where? …are we today?
The Nuclear Landscape and the Big Questions

• Where do nuclei and elements come from? Balantekin, Kistryn
• How are nuclei organized? Harakeh, Casten
• What are practical and scientific uses of nuclei? Olko

TIMESCALE
- from QCD transition (color singlets formed; 10 ms after Big Bang) till today (13.8 billion years later)

DISTANCE SCALE
- from $10^{-15}$ m (proton’s radius) to ~12 km (neutron star radius)
How are nuclei made?

Hot and dense quark-gluon matter

Hadron structure

Hadron-Nuclear interface

Nuclear structure
Nuclear reactions
New standard model

Applications of nuclear science

Physics of Hadrons

Degrees of Freedom

Energy (MeV)

scale separation

quarks, gluons

940 neutron mass

constituent quarks

140 pion mass

baryons, mesons

Physics of Nuclei

protons, neutrons

8 proton separation energy in lead

nucleonic densities and currents

1.12 vibrational state in tin

collective coordinates

0.043 rotational state in uranium
The Grand Nuclear Landscape
(finite nuclei + extended nucleonic matter)

How many protons and neutrons can be bound in a nucleus with Z up to 120?

…current theory predicts around 7000

Experiment:
- stable nuclei
- known nuclei

Theory:
- dip lines

CAUTION
NO BINDING

CAUTION
NO BINDING

N~10^{57}

neutron stars
Isospin Splittings in the Light-Baryon Octet from Lattice QCD and QED
(ab initio calculation of the neutron-proton mass difference)

Neutron = 939.56563 MeV
Proton = 938.27231 MeV
Electron = 0.51099906 MeV

\[ T_n = (887.7 \pm 1.2 \pm 1.9) \text{ s} \]

... but bottle and in-beam experiments give a neutron lifetime that differs by 8 sec!

"The neutron–proton mass difference, one of the most consequential parameters of physics, has now been calculated from fundamental theories. This landmark calculation portends revolutionary progress in nuclear physics." Wilczek, Nature 520, 303 (2015)

\[ \Delta N = n - p \]
\[ \Delta \Sigma = \Sigma^- - \Sigma^+ \]
\[ \Delta \Xi = \Xi^- - \Xi^0 \]
How to explain the nuclear landscape from the bottom up?

**Theory revolution**

- **LQCD**
  - Degrees of Freedom: quarks, gluons
  - Constituent quarks
- **ab initio**
  - Baryons, mesons
- **CI**
  - Protons, neutrons
- **DFT**
  - Nucleonic densities and currents
- **Geometric Algebraic**

**Nucleon and nuclear magnetic moments from Lattice QCD**
S. Beane et al., PRL 113, 252001 (2014)

**Ab-initio approach to reactions (p+4He)**
Hupin et al. PRC 90, 061601 (2014)

**Coupled cluster description of binding energies and radii**
A. Ekstrom et al., 91, 051301 (2015)

**Fusion cross sections from TDDFT**
R. Keser et al., PRC 85, 044606 (2012)

Who could have predicted this 20 years ago?
Nobel Prize 1922
Bohr’s picture still serves as an elucidation of the physical and chemical properties of the elements.

Noble gases (closed shells)
- Ne (10)
- Ar (18)
- Kr (36)
- Xe (54)

Nucleonic shells of the nucleus
- magic nuclei (closed shells)
- 50
- 82
- 126

Bohr's picture still serves as an elucidation of the physical and chemical properties of the elements.
Revision of nuclear structure textbook knowledge

New shell closures at $N = 32 \& 34$?
16O is a textbook doubly-magic nucleus

Measurements of the neutron-rich isotopes 22O and 24O suggest the presence of new magic numbers at N=14 and 16.

A dineutron in 26O? The lifetime could be as large as 10^{-12} s.

Is (doubly-magic) 28O unbound? If so, how much?
In 1954, Hoyle postulated that a 7.65 MeV carbon state. This state plays a crucial role in the hydrogen burning of stars heavier than our sun and in the production of carbon and other elements necessary for life.

**C structure: Ground-state and Hoyle-state**

$^{12}\text{C}$ structure:
- Ground-state and Hoyle-state


In 1954, Hoyle postulated that a 7.65 MeV carbon state. This state plays a crucial role in the hydrogen burning of stars heavier than our sun and in the production of carbon and other elements necessary for life.
Carbon-12 Caught in a Triangle

\[ T_{\text{s.p.}} = 4R/v_F \]
\[ v_F \approx 0.25c \]
\[ T_{\text{s.p.}} \approx 1.3 \cdot 10^{-22} \text{ sec} \]

10^{-22} \text{ sec} = 1 \text{ babysec} = 0.1 \text{ zsec (z=zepto)} = 100 \text{ ysec (y=yocto)}

\[ T_{1/2} = \ln 2 \hbar/\Gamma \]

But what if \( T_{1/2} \lesssim T_{\text{s.p.}} \) ?
Nuclear collective motion

Giant nuclear vibrations

- Isoscalar p-n in phase
- Isovector p-n out of phase

Monopole (GMR)

Dipole (GDR)

Quadrupole (GQR)

by A. Krasznahorkay

Nuclear response to external force

- Dipole polarizability and skins
- Isoscalar dipole and EDM
- Monopole modes, radii and beta decay
- Multipole modes and fission
- Scissors (magnetic) modes
What are the limits of atoms and nuclei? Do very long-lived superheavy nuclei exist in nature?

Structure of nuclei at the limit of mass and charge (Coulomb frustration)
Cosmic origin of superheavy nuclei?
Very relativistic atoms with $Z\alpha \rightarrow 1$

- Around 30 new superheavy isotopes found since 2007
- $Z=114$ (Fl) and 116 (Lv) named in 2012
- $Z=117, 115, 113$ confirmed
- Unique spectroscopic data above $Z>102$
- Chemistry of $Z=106, 112, 114$

IUPAC: Discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number $Z$ not identified before, existing for at least $10^{-14}$ s
| Z=112: Copernicium | Z=114: Flerovium; Z=116: Livermorium |

**Generic IUPAC names:**
- Z=113: Ununtrium, Uut
- Z=115: Ununpentium, Uup
- Z=117: Ununseptium, Uus
- Z=118: Ununoctium, Uuo
The covariance ellipsoid for the neutron skin $R_{\text{skin}}$ in $^{208}\text{Pb}$ and the radius of a $1.4M_\odot$ neutron star. The mean values are: $R(1.4M_\odot)=10$ km and $R_{\text{skin}}=0.17$ fm.
Rare Isotopes and fundamental symmetry tests

Atomic electric dipole moment: The violation of CP-symmetry is responsible for the fact that the Universe is dominated by matter over anti-matter

- Closely spaced parity doublet gives rise to enhanced electric dipole moment
- Large intrinsic Schiff moment
  - $^{199}$Hg (Seattle, 1980’s – present)
  - $^{225}$Ra (Starting at ANL and KVI)
  - $^{223}$Rn at TRIUMF
  - Potential at FRIB (10$^{12}$/s w ISOL target; far future)

Gaffney et al., Nature 199, 497 (2013)
Prospects
High Performance Computing and Nuclear Theory

“High performance computing provides answers to questions that neither experiment nor analytic theory can address; hence, it becomes a third leg supporting the field of nuclear physics.” (NAC Decadal Study Report)

Future: large multi-institutional efforts involving strong coupling between physics, computer science, and applied math
The frontier in experiment and theory: neutron-rich calcium isotopes

Quantified input
Nuclear Forces from EFT

<table>
<thead>
<tr>
<th>LO</th>
<th>NLO</th>
<th>N2LO</th>
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<tr>
<td>N2LO</td>
<td>N3LO</td>
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</table>

Consistency with known data

Extrapolations are tough

Prediction

NNLO_{sat}

SV-min
Nuclei Matter

Our current understanding of nuclei has benefited from technological improvements in experimental equipment and accelerators that have expanded the range of available isotopes and allowed individual experiments to be performed with only a small number of atoms. Concurrent advances in theoretical approaches and computational science have led to a more detailed understanding and pointed toward which nuclei and what phenomena to study, creating conditions for major advances.

Profound intersections

• Astrophysics
• Fundamental Symmetries
• Complex systems
• Computing

How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

• Energy (fission, reactions, decays…)
• Security (stewardship, forensics, detection…)
• Isotopes (medicine, industry, defense, applied research…)
• Industry (radiation, ion implantation…)

Outlook

The study of atomic nuclei makes the connection between the fundamental building block of matter, complex systems, and the cosmos

- Cool
- Deals with fundamental and complex
- Interdisciplinary
- Relevant

- Significant progress and discoveries worldwide in the physics of nuclei and nuclear astrophysics
- Comprehensive and validated theory of nuclei on the horizon
- World-class science program
- Future is exciting

Thank You
Happy birthday, A²!
Backup
Regularities and periodicities in atoms and nuclei
Chemical evolution

mass fraction

mass number

Big Bang
oldest stars
r-process

solar system

supernova

entropy

velocity


S. Rosswog et al., MNRAS 430, 2585 (2013)
Half of the neutron-rich atomic nuclei heavier than iron are built by neutron driven r-process. The final abundances reflect the shell structure of nuclei, which determines the respective nucleosynthesis trajectories.
Theoretical Tools and Connections to Computational Science

1 teraflop = $10^{12}$ flops
1 peta = $10^{15}$ flops (today)
1 exa = $10^{18}$ flops (next 10 years)

Tremendous opportunities for nuclear theory!

<table>
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<tr>
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<th>SPECS</th>
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<th>CORES</th>
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PERFORMANCE DEVELOPMENT

November 2014

http://top500.org
Some nuclei are more important than others

Over the last decade, tremendous progress has been made in techniques to produce and describe *designer nuclei*, rare atomic nuclei with characteristics adjusted to specific research needs and applications.

- Nuclear structure
- Tests of fundamental laws of nature
- Astrophysics
- Applications

Some nuclei are more important than others:

- $^{45}$Fe
- $^{225}$Ra
- $^{18}$F, $^{22}$Na
- $^{149}$Tb