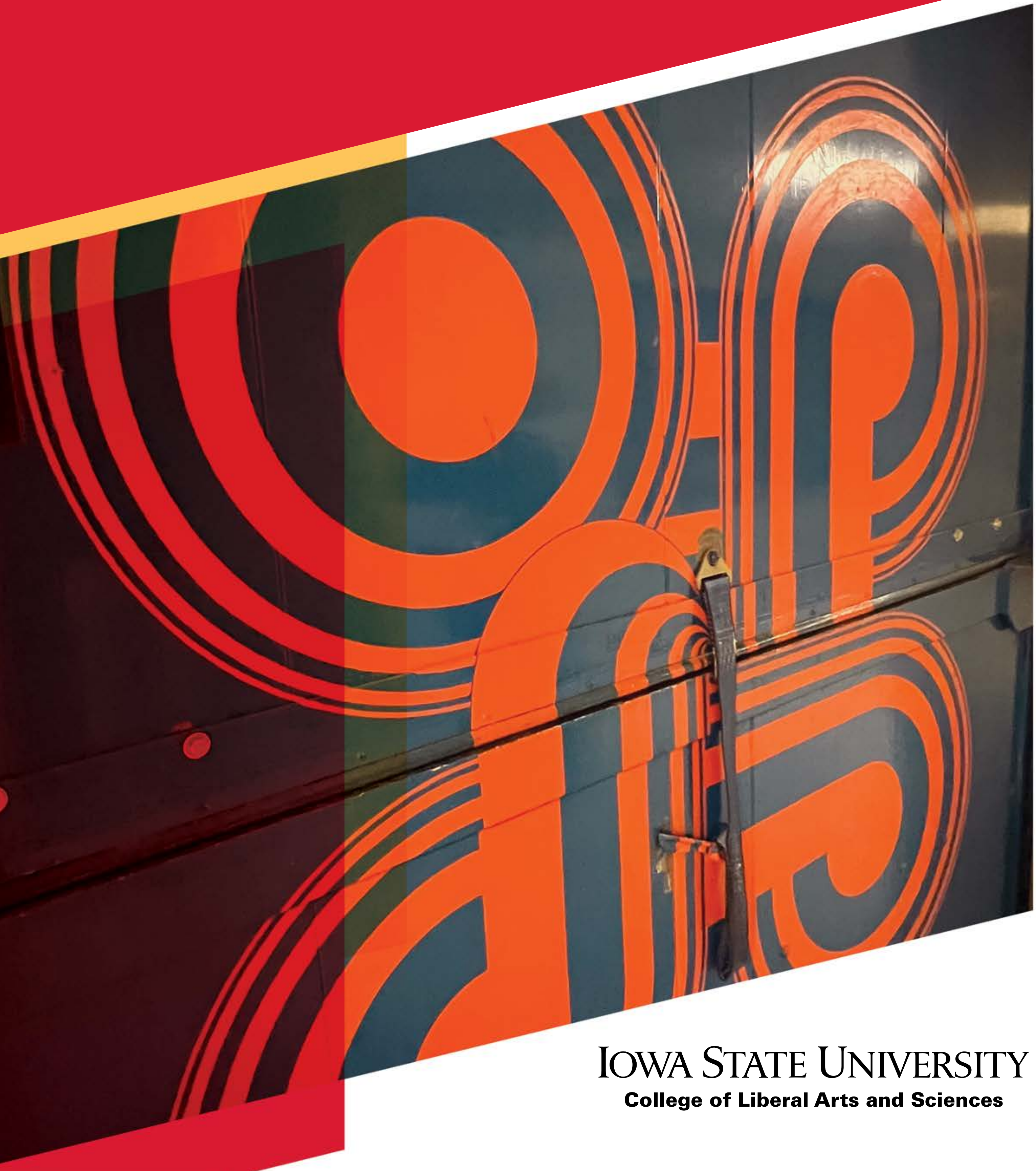
Quanta&Cosmos

Department of Physics and Astronomy | 2023 Newsletter



IOWA STATE UNIVERSITY

College of Liberal Arts and Sciences

A Message from the Chair

Recently, the World Health Organization Director General declared the end of the public health emergency posed by Covid-19. As a result, many of us can breathe a sigh of relief, and demonstrate that cooperation and scientific expertise enabled us to deal with a difficult global situation.

In this context, the Department of Physics and Astronomy has now resumed its normal operations with classes, meetings, seminars, and colloquia being held in person again. Student education through teaching and research experience has reached a level of normality again. Despite this, we will continue to face challenges due to the lost time and gaps in student education because of the pandemic for some time to come.

Higher education in the state of Iowa continues to face challenges from declining state support, forcing students to step in and cover a larger share of the cost of education. As a department, we remain committed to providing excellent instruction for our students and pursuing excellence in research at the national and international levels.

Throughout our department's history, we have enabled generations of Iowans, Americans, and people from all over the world to build a culture of scientific knowledge and appreciation, as well as boost their economic well-being.

As a marker and reminder of the importance of intellectual pursuit, appreciation for science, and civil informed discussion, we will celebrate the centennial of Physics Hall (1923) this year.

I hope that many of you will join us on November 5, 2023, for the centennial celebration of Physics Hall to be held at the Iowa State University Alumni Center starting in the late afternoon. More details will be provided later this summer.

Sincerely,

Frank Krennrich

Frank Krennrich, Professor and Chair, Department of Physics and Astronomy
515-294-5442 | Krennrich@iastate.edu

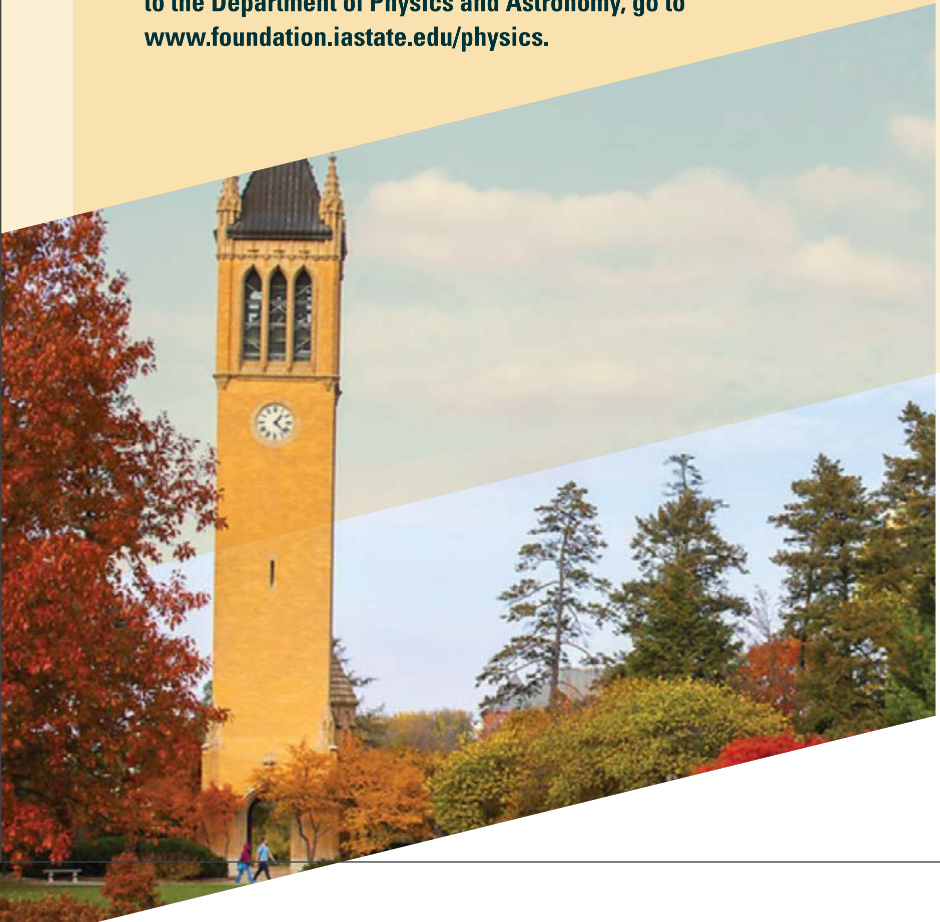
OPPORTUNITIES TO GIVE

We hope that you would designate your contribution directly to the Department of Physics and Astronomy. Please feel free to call Frank Krennrich (515-294-5442), department chair, to discuss possibilities to donate or if you have questions about the different endowment funds.

1) Contributions to the Physics and Astronomy Unrestricted Fund provide the department with the greatest flexibility to finance awards and projects (e.g., a theory coffee room).
2) Contributions to the Zaffarano Lectureship fund allow us to sustain the event over years to come.
3) Inaugural contributions to the Postdoctoral Prize Fellowship in Astronomy and Astrophysics will allow us to establish the fellowship fund.

If you are considering making a significant gift, you could establish a new endowed fund for a purpose that you designate—e.g., the Postdoctoral Prize Fellowship in Astronomy and Astrophysics. For details and guidance, please refer to Michael Gens, Executive Director of Development (call 515-294-0921 or email mgens@iastate.edu).

To donate online and designate your contribution directly to the Department of Physics and Astronomy, go to www.foundation.iastate.edu/physics.



New developments in quantum topological materials

by Adam Kaminski

Progress in understanding the role of topology in quantum materials has allowed the study of exotic elementary particles predicted by high-energy theorists, without the need to resort to hyper-expensive particle accelerators. In 2008, a new field of quantum topological materials emerged. This was based on the realization that electronic bands in certain solids have a nontrivial topology, which leads to the emergence of exotic 2D electronic surface states at the interface between a topological and trivial medium (such as a vacuum).

This effect was first discovered in topological insulators (TI). The surface states of these materials have a characteristic dispersion that has the appearance of two cones connected at their vertices (see Fig.1). According to the Dirac equation, the linear dispersion measured along the cones implies zero rest mass, and the electrons therefore behave like relativistic particles that are known as massless Dirac fermions. The strangeness does not stop there. The spin of these excitations is tied to their momentum, and each state is occupied by a single spin orientation instead of the usual two. Such spin momentum locking makes these materials promising candidates for spintronic devices, which use spin rather than the charge of an electron to store and process information. Instead of moving a charge, one could either flip the orientation of the spin or cause the propagation of the spin along the wire. This theoretically will result in much less dissipation than a moving charge or could even be dissipation-free.

A second important class of topological objects in solids are Weyl Fermions. These objects are chiral and obey the Weyl equation. For a material with 3D Dirac dispersion, if an inversion symmetry or time reversal symmetry is broken (e.g., by applying a magnetic field), the Dirac cones split in momentum space by spin, leading to the formation of two Weyl fermions (see Fig. 2). The spins of the electrons in one case point toward the Weyl point, and outwards in the other, creating two magnetic monopoles in momentum space. Projections of these Weyl points onto the sample surface are connected by a set of *Fermi arcs* in the 2D electron gas that forms at the surface [1]. Fermi arcs are extremely rare features, normally associated with exotic states such as superconductivity, and they may be found in a material's Fermi surface. Electrons at the Fermi surface control many properties including electrical and thermal conductivity and optical properties. The Fermi surface of a metal is the boundary between occupied and unoccupied electron energy states. It normally consists of several three-dimensional shapes such as spheres, ovoids, etc. A Fermi arc in contrast is a disconnected segment. The Fermi arcs in Weyl semimetals display spin momentum locking as discussed in the case of the Dirac fermions above and therefore have potential spintronics applications. Other excitations, such as Majorana Fermions, which are their own antiparticles, are also currently under investigation and these are extremely promising candidates for quantum computing.

Most quantum topological materials are first predicted by calculations and then confirmed by experiment, which somewhat dampens the thrill of experimental discovery. In our lab, we use Angle Resolved Photoemission (ARPES) to measure the electronic properties of materials. Over the years, we have developed a novel tunable laser ARPES spectrometer [2] and closed cycle sample cooling system [3] that allows us to reach liquid helium temperatures for ARPES measurements. We collaborate with colleagues who are experts in crystal structure, materials properties, single crystals growth, and band structure calculations (Paul Canfield, who is usually right, and Linlin Wang, an expert in band structure calculations and can check if Paul is right). Our aim is to discover those systems that are not necessarily predicted by theory. We base our search on rare and promising crystal structures, unusual transport properties, and an old-fashioned intuition. This approach has led to the discovery of new topological systems that have yet to be explained by theorists: Fermi arc nodes in $PtSn_4$ [3] and first weak topological insulator $RhBi_2$ with accessible 2D surface states [4]. More recently, we stumbled upon something even more interesting—the emergence of spin textured Fermi arcs in an antiferromagnet and a new type of magnetic band splitting in an antiferromagnet [5]. These Fermi arcs appear, seemingly out of nowhere, when the sample is cooled

> **Rare-earth monopnictide NdBi (neodymium-bismuth) exhibits a new type of Fermi arc that appears at low temperatures when the material becomes antiferromagnetic—i.e., neighboring spins point in opposite directions. The newly discovered Fermi arcs can be controlled through magnetism and could be the future of electronics based on electron spins.**

below the Neel temperature (T_N). Below this temperature, the sample develops long-range antiferromagnetic (AFM) order, and the magnetic moments at each lattice site point in opposite directions). Because the magnetic moments in antiferromagnets are staggered, they do not produce a net magnetic field that could give rise to Weyl fermions; therefore the Fermi arcs in NdBi must have a different origin. To add to the mystery, these Fermi arcs form in a very unusual way. When the sample is cooled just below T_N, a single, linearly dispersing state emerges. Upon cooling, the sample becomes more magnetically ordered, and this state splits into two, each giving rise to a set of Fermi arcs (see Fig. 3). Unlike in the previously known Zeeman and Rashba band splitting, the bands in NdBi change their curvature, which points to a new effect that is not yet comprehended by theorists.

[1] Lunan Huang et al., Nature Materials **15**, 1155 (2016)
[2] Rui Jiang et al., Rev Sci. Instrum. **85**, 033902 (2014)
[3] Yun Wu et al., Nature Physics **12**, 667 (2016)
[4] Kyungchan Lee et al., Nat. Comms. **12**, 1855 (2021)
[5] Benjamin Schrunk et al., Nature **603**, 610–615 (2022)

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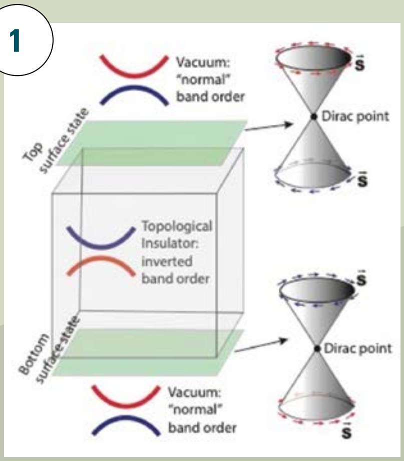

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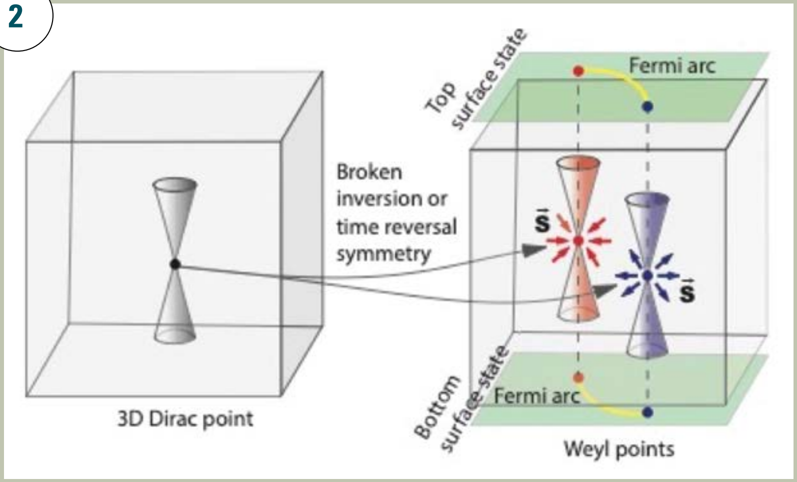

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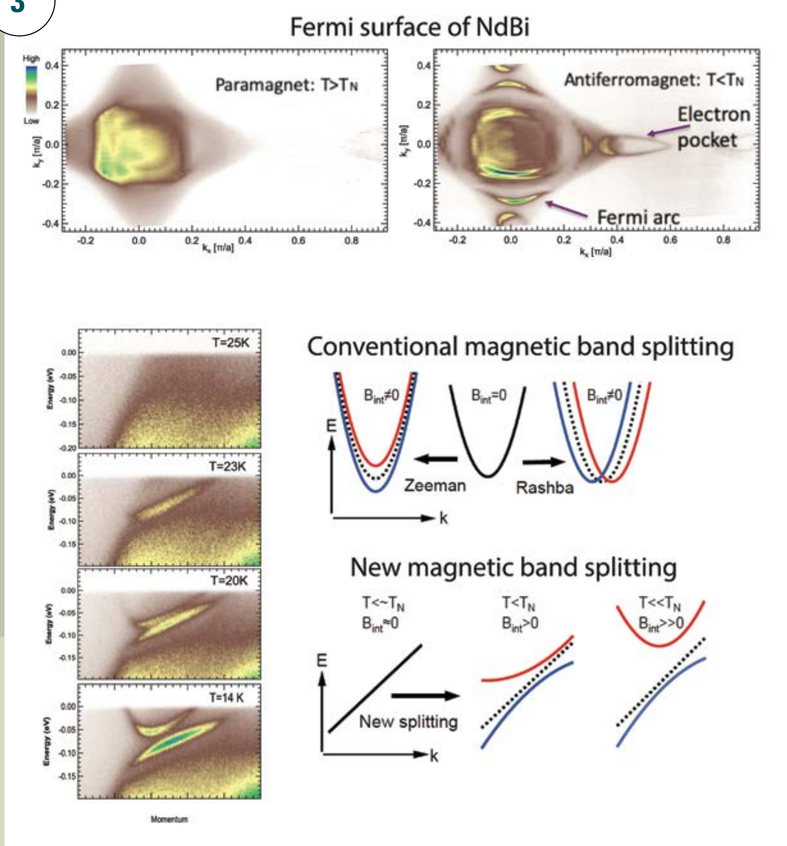


Fig. 1. Schematic representation of TI. The band inversion present in the volume of the TI is topologically different from trivial band order in vacuum; therefore the two are connected at the interface (surface) by a surface state in the form of Dirac cones.

Fig. 2. Breaking of inversion or time reversal symmetry splits spin degenerate 3D Dirac cone into two cones and Weyl points with opposing spin directions. Projections of the Weyl points at the surface of the sample are connected by surface state Fermi arcs.

Fig. 3. Changes in Fermi surface upon transition to AFM state in NdBi. Linearly dispersing state that emerges just below T_N, splits into two bands that change curvature upon further cooling.

Quantum Thermalization, Dynamics, and Memory

by Thomas Iadecola

Equilibrium statistical mechanics is a powerful framework for describing systems of many particles. The equilibrium properties of such a system can be derived by maximizing its entropy subject to the constraints imposed by conservation laws—e.g., those of energy and particles. This formalism is sufficiently general to encompass both classical and quantum systems coupled to thermal reservoirs. However, *isolated* quantum systems evolve under unitary dynamics, which at first glance appears incapable of producing a state with well-defined thermodynamic properties. For example, the entropy of a pure quantum mechanical state is always strictly zero. At the same time, a quantum system coupled to a thermal reservoir can always be recast as a closed quantum system by viewing the reservoir as part of the system. We are thus confronted with the question of how statistical mechanics can emerge in an isolated quantum system.

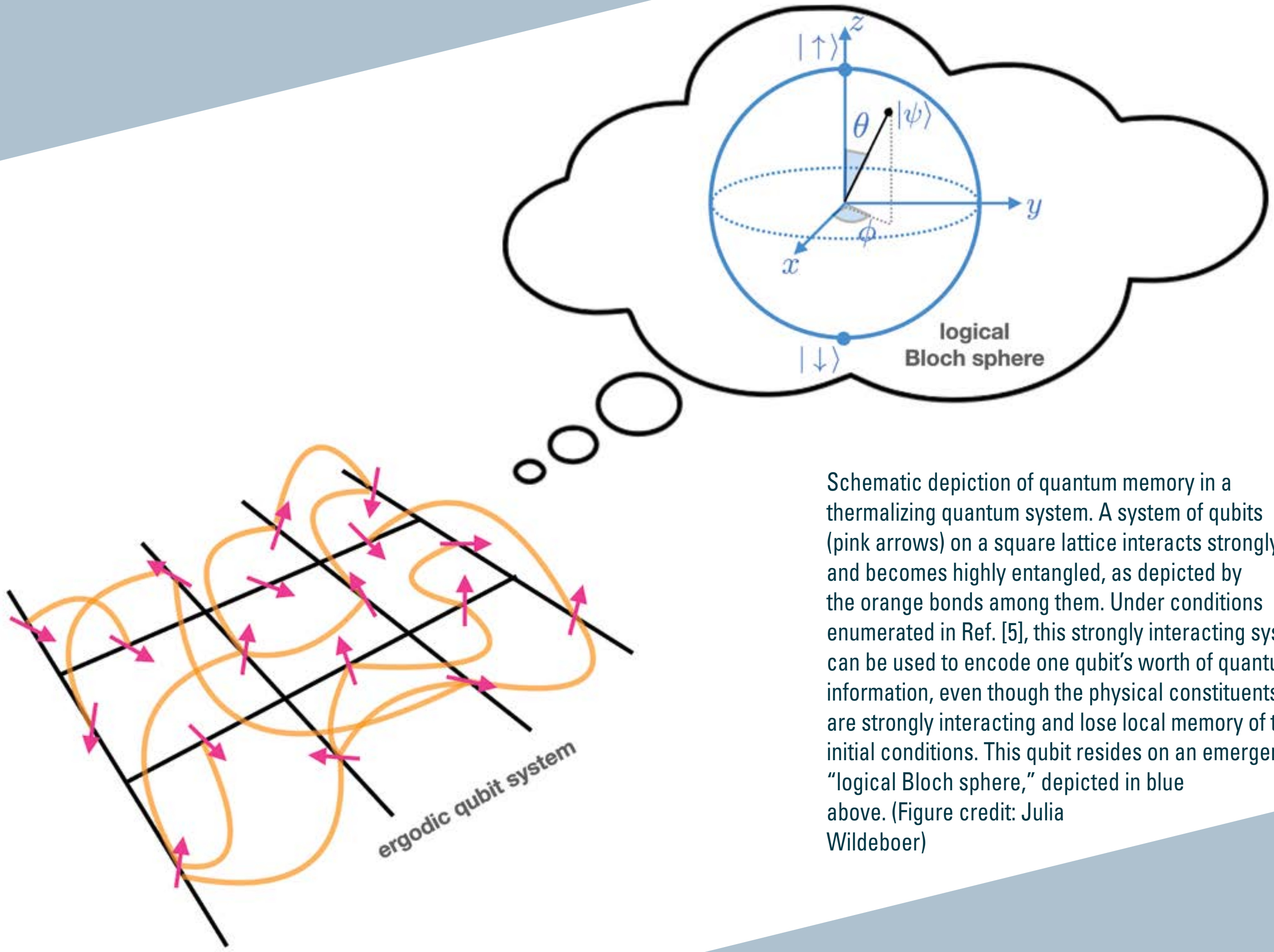
One proposal to answer this question, made in separate works by Deutsch and Srednicki in the early 1990s [1], is known as the eigenstate thermalization hypothesis (ETH). It asserts that the quantum mechanical expectation values of observables in individual eigenstates are continuous functions of energy in the infinite-system-size limit. This hypothesis has profound implications for the dynamics of an isolated quantum system: when such a system is prepared in an initial state that is not an eigenstate, its late-time behavior is still governed by the expectation values of observables in eigenstates with energy close to the energy expectation value of the initial state [2]. An isolated quantum system is then said to *thermalize* when this late-time behavior is consistent with predictions from equilibrium statistical mechanics.

Thermalization is believed to be the default fate of generic isolated quantum many-body systems under unitary evolution, and substantial numerical evidence for this belief has accumulated over the past decade or more. Since the steady state to which a thermalizing system relaxes depends only on macroscopic quantities like the total energy of its initial state, thermalization naturally entails a loss of information encoded in this initial state. A central challenge in the fast-moving field of nonequilibrium quantum dynamics is to identify mechanisms that allow for the preservation of quantum information present in the initial state. Understanding such mechanisms is an important steppingstone toward large-scale quantum computation, which will rely on the use of "quantum memories" to enable sophisticated calculations.

One strategy to preserve memory of the initial state under strongly coupled unitary dynamics is to suppress thermalization altogether. An example of such a strategy is to harness many-body localization (MBL) [3], wherein thermalization is avoided due to strong spatial randomness. MBL enables the preservation of *classical* information in an initial state but can be combined with symmetry-protected or intrinsic topological order [4] to preserve quantum information as well.

However, recent theoretical work in collaboration with Iowa State University postdoc Julia Wildeboer and Dominic Williamson (University of Sydney) has demonstrated that thermalization and quantum memory need not be mutually exclusive. This research, published in *PRX Quantum* [5], leverages an important tool from quantum information theory known as *subsystem codes* [6] to define quantum Hamiltonians whose dynamics possess an exact quantum memory. The resulting models owe their quantum memory properties not to an absence of thermalization, but rather to an interplay of symmetries. The work demonstrates that an appropriate combination of symmetries is sufficient to preserve quantum information in these models and provides explicit examples of Hamiltonians with quantum memory whose structure is compatible with the ETH. It also considers the effect of symmetry-breaking perturbations and demonstrates that the lifetime of the quantum memory can be made parametrically long under certain conditions. The primary example considered in this work is

Research at the interface of quantum statistical mechanics, quantum dynamics, and quantum information science reveals that quantum memory persists in surprising contexts.



Schematic depiction of quantum memory in a thermalizing quantum system. A system of qubits (pink arrows) on a square lattice interacts strongly and becomes highly entangled, as depicted by the orange bonds among them. Under conditions enumerated in Ref. [5], this strongly interacting system can be used to encode one qubit's worth of quantum information, even though the physical constituents are strongly interacting and lose local memory of their initial conditions. This qubit resides on an emergent "logical Bloch sphere," depicted in blue above. (Figure credit: Julia Wildeboer)

simple enough to be realizable on the present-day superconducting qubit architectures, which brings the experimental verification of these ideas within reach.

More generally, these results demonstrate that the intersection of quantum statistical mechanics, quantum dynamics, and quantum information is a fertile ground for exploration. Applying ideas from quantum information theory to quantum dynamics and statistical mechanics has led to remarkable discoveries in recent years. It stands to reason that bringing ideas from the latter to bear on the former will yield new and useful insights as quantum science continues to blossom.

[1] J. M. Deutsch, Phys. Rev. A **43**, 2046 (1991); M. Srednicki, Phys. Rev. E **50**, 888 (1994).
[2] M. Rigol et al., Nature **452**, 854 (2008).
[3] D. A. Abanin et al., Rev. Mod. Phys. **91**, 021001 (2019).
[4] D. A. Huse et al., Phys. Rev. B **88**, 014206 (2013); B. Bauer and C. Nayak, J. Stat. Mech., P09005 (2013).
[5] J. WIldeboer et al., PRX Quantum **3**, 020330 (2022).
[6] D. Poulin, Phys. Rev. Lett. **95**, 230504 (2005); D. Bacon, Phys. Rev. A **73**, 012340 (2006).

ANNIE-LAPPD

by Matt Wetstein

The Neutrino Group at Iowa State is celebrating a major technological milestone: the first deployment of an advanced new kind of light detector called a Large Area Picosecond Photodetector (LAPPD) in a neutrino experiment. LAPPDs are a critical enabling technology for the Accelerator Neutrino Neutron Interaction Experiment (ANNIE), an Iowa State-led effort at Fermilab that studies how neutrinos interact with matter. After two years of development work, ANNIE has observed its first neutrinos with an LAPPD. These photosensors have far-reaching applications, not only for particle physics but also a wide range of applications from medical imaging to national security.

Neutrinos are the most abundant matter particles in the universe, and yet they're also the particles we know the least about. We know that they have mass, but it's so vanishingly small (more than ten million times lighter than the electron) that we cannot yet measure it. As the only neutral massive particles in the Standard Model of physics, neutrinos may uniquely be their own antipartners. Neutrinos are also unusual in the way they transform from one kind to another as they travel, a phenomenon known as "neutrino oscillations."

These strange properties of neutrinos are more than mere intellectual curiosities. Neutrinos may have played a central role in the formation of the early universe. The currently known laws of particle physics are largely symmetric between matter and antimatter. Having been produced in equal amounts, matter and antimatter should have canceled each other out in the early Big Bang, leaving behind an empty universe. The fact that enough matter survived to form planets, stars, and galaxies suggests that there is a yet-unknown mechanism that broke the symmetry. Neutrinos are possible culprits, and in the next decade a large international collaboration is building the Deep Underground Neutrino Experiment (DUNE) in the United States to find out.

We cannot directly observe neutrinos. They can only be detected through their interactions with atomic matter. Because neutrinos are so weakly coupled to the rest of matter, neutrino experiments require incredibly bright neutrino sources and super-massive detectors to shift the odds of detection in our favor. Furthermore, neutrino-nucleus interactions can involve complicated many-body collisions in the nucleus, making it difficult to infer neutrino energy from the detected nuclear fragments.

ANNIE is aimed at better understanding these important details of neutrino-nucleus interactions for future precision neutrino experiments like DUNE. ANNIE is also an R&D effort aimed at developing next-generation

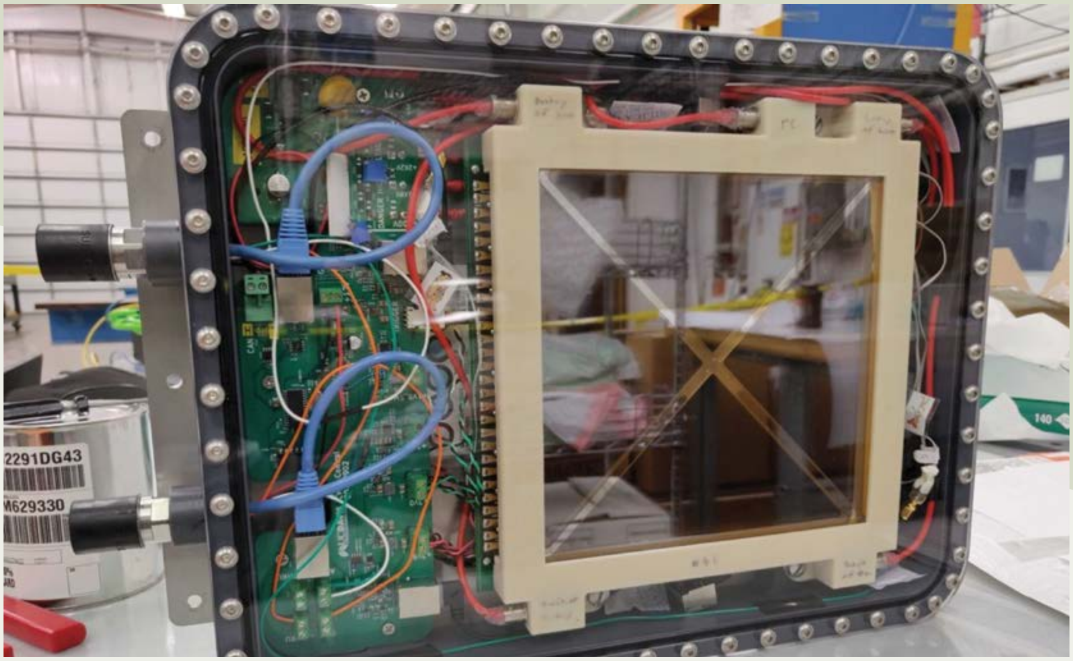


Fig. 1. An LAPPD is an 8-in by 8-in square photosensor. This photo shows the first ANNIE LAPPD enclosed with its power and readout electronics in a waterproof module. This system was largely developed by the Iowa State neutrino group.

Large Area Picosecond Photodetectors are a new kind of imaging photodetector designed to provide exquisite time resolution, roughly 50 picoseconds for a single photon. LAPPDs have broad applications in the field of physics where time resolution is critical.

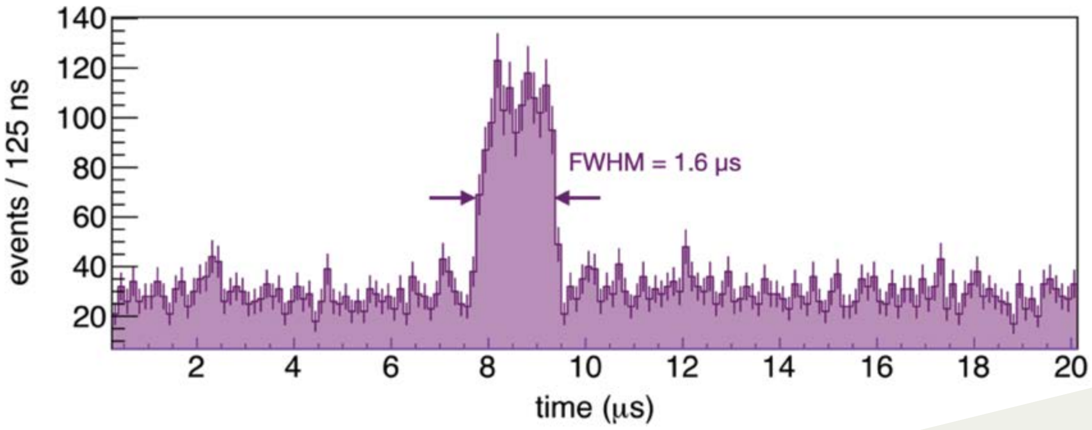


Fig. 2. Neutrino beams produced in an accelerator come in spurts called “spills.” This figure shows the activity in an LAPPD with respect to the timing of the neutrino beam. The 1.6 microsecond spike in activity corresponds to the arrival of the neutrino spill. This is the first-ever observation of neutrinos with an LAPPD.

technologies like LAPPDs. The technologies developed in ANNIE could be scaled for use in massive future neutrino detectors.

LAPPDs are next-generation, high-resolution photosensors combining detailed spatial imaging with the ability to detect the arrival time of single light particles to within 100 trillionths of a second. An LAPPD can measure the time it takes light to travel less than 3cm! By recording the locations and times of photons emitted by neutrino interactions, ANNIE is able to triangulate the location of the neutrino interaction points, determine the directions of high-energy particles, and even estimate the neutrino energies.

LAPPDs are an example of how fundamental questions about the universe can drive technological advances with benefits far beyond basic science. LAPPDs are already being studied in the context of medical imaging, with applications ranging from proton therapies for cancer treatment to groundbreaking time-of-flight PET detectors capable of detecting tumors with significantly lower doses of radioactive tracers. LAPPDs also have potential applications in radiation detection for national security and nuclear nonproliferation.

Using this powerful new technology isn’t as simple as buying an LAPPD and plugging it in. Our group spent the last two years developing a new readout and power system capable of synchronizing these super-fast sensors with each other and with clock signals from GPS satellites. To make things harder, this system had to fit in compact waterproof modules, capable of submersion in the Annie experiment. That system is now deployed and operating successfully.

With one LAPPD in the water and four more to follow this summer, the next two years will be an exciting time for ANNIE and for Iowa State neutrino physics.

Fig. 3. LAPPD-40 in final preparations before deployment in ANNIE.

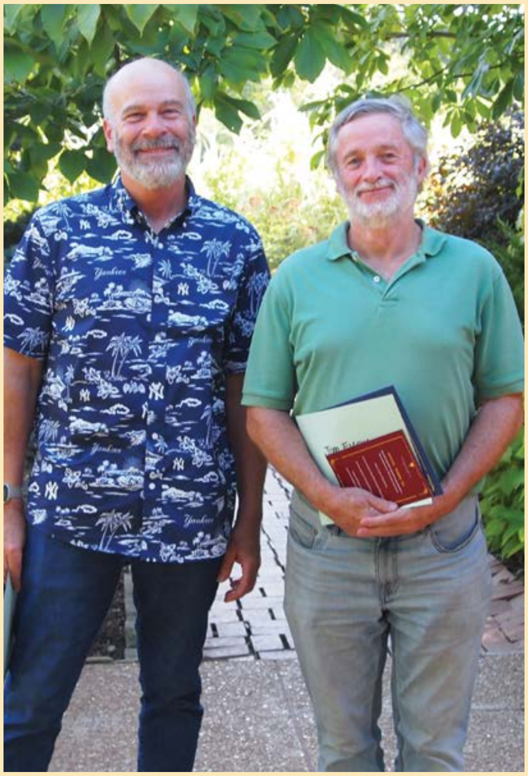
Awards 2022

GRADUATE COLLEGE RESEARCH EXCELLENCE AWARD

Maria Martinez-Casales

DEPARTMENT OF PHYSICS AND ASTRONOMY SUPERIOR SERVICE AWARD

Presented on behalf of the faculty of the Department of Physics and Astronomy to recognize superior service by the scientific and support staff of the department, this recognition is a monetary award of $200 and engraved plaque. This year's recipient is Valerie Arnold.



MOST VALUABLE INSTRUCTOR

The Most Valuable Graduate Instructor Award was presented to James Evans and Steve Kawaler on behalf of the graduate students by Graduate Student Representative Joseph Eix.

GRADUATE TEACHING EXCELLENCE AWARDS

From left to right: Amlan Datta, Abigail Davenport, Juan Schmidt, Steven Doran, Jacob Austin, and (present but not pictured) Matt Lockner.

Awards 2023

GENE RUBY SCHOLARSHIP

Recognizes juniors and seniors for their academic achievement: Michael Blank, Lance Mach, Carsyn Mueller, Andrew Clarke, and Alexander Clarke (left to right).

JUN YE HUIQUING WANG AWARD

Recognizes junior physics majors for their excellent grade point average: Nao Furukawa, Andrew Clarke, and Alexander Clarke (left to right).

JOHN C. AND FAY GISH HILL SCHOLARSHIP

Recognizes students in high-energy or nuclear physics: Noah Brenny (center) with Professor Emeritus John Hill and Fay Gish Hill.

MOST VALUABLE UNDERGRADUATE INSTRUCTOR

The Most Valuable Undergraduate Instructor Award was presented by David Harper, undergraduate student representative to Joseph Shinar.

Awards 2023 *continued*

QIMING LI AND XIAOSHA WANG SCHOLARSHIP

Recognizes graduate students for their outstanding research achievement: Mingyu Xu, Jeremy Hansen, and Brinda Kuthanazhi.

SUPERIOR SERVICE AWARD

Department of Physics and Astronomy Superior Service Award was presented to Kecia Place-Fencl.

MOST VALUABLE GRADUATE INSTRUCTOR

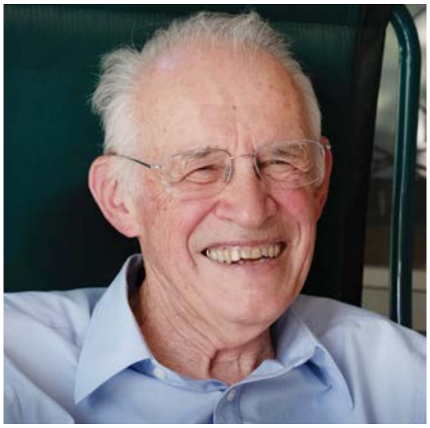
The Most Valuable Graduate Instructor Award was presented by Joseph Eix, graduate student representative to Kirill Tuchin.

Alumni

FRED ADAMS

Born in Redwood City, California, Fred Adams graduated from Iowa State University in 1983 with a BS in physics and mathematics. He went on to receive his PhD in physics from the University of California, Berkeley (in 1988), where his dissertation received the Robert J. Trumpler Award from the Astronomical Society of the Pacific. After serving as a postdoctoral research fellow at the Harvard-Smithsonian Center for Astrophysics, Adams joined the faculty in the Physics Department at the University of Michigan in 1991. Adams was promoted to associate professor in 1996 and to full professor in 2001. He is the recipient of the Helen B. Warner Prize from the American Astronomical Society and the National Science Foundation Young Investigator Award. At the University of Michigan, he has been awarded the Excellence in Education Award, the Excellence in Research Award, and the Faculty Recognition Award, and he was elected to the Michigan Society of Fellows. Adams was subsequently elected to be a fellow of the American Physical Society, elected to Chair of the Division on Dynamical Astronomy of the American Astronomical Society, and he was named as the Ta-You Wu Collegiate Professor of Physics at the University of Michigan.

Professor Adams works in the general area of theoretical astrophysics with a focus on the study of star formation, exoplanets, and cosmology. He is internationally recognized for his work on the radiative signature of the star formation process, the dynamics of circumstellar disks, the development of a theory for the initial mass function, and studies of extra-solar planetary systems. In cosmology, he has studied the inflationary universe, magnetic monopoles, cosmic rays, and cosmic background radiation fields. His work in cosmology also includes explorations of the long-term fate and evolution of the universe, as well as a reexamination of its degree of fine tuning.



CHARLIE DUKE

After growing up in a small North Carolina mountain town and finishing a BS in physics at N. C. State University, Charlie Duke moved to Ames in 1962 to begin graduate school in physics. With Will Talbert as his PhD mentor, he finished in 1967 and continued with postdoctoral years at the Iowa State research reactor TRISTAN facility and at the CERN ISOLDE facility via Aarhus, Denmark. In the fall of 1969, Duke and his wife, along with their two-year old son, moved to Grinnell where he joined the physics faculty at Grinnell College. Their daughter arrived the next spring.

Duke's life at Grinnell College has spanned three separate careers, first and foremost as a physics instructor, second as the academic dean for 11 years followed by a short stint as acting president, and third as a researcher for 10 years as a member of the gamma-ray astronomy VERITAS collaboration working with the Iowa State physics group led by Dave Carter-Lewis and Frank Krennrich. Duke especially appreciates the contributions made by his summer research students to the simulation code developed in collaboration with other VERITAS members. Now, Duke curates the Grinnell College Physics Museum, tutors students, develops python-based quantum mechanics simulations for the introductory modern physics course, and continues as a member of the Iowa State Physics Advisory Council.

1969 Pathdafreldo Contest

Soon after the Zaffarano Physics Adddition opened in 1969, Dan Zaffarano organized a contest to "PAint THose DArn FReight ELevator DOors." The six entries selected were painted on the freight elevator doors in Summer 1969.

GOING UP

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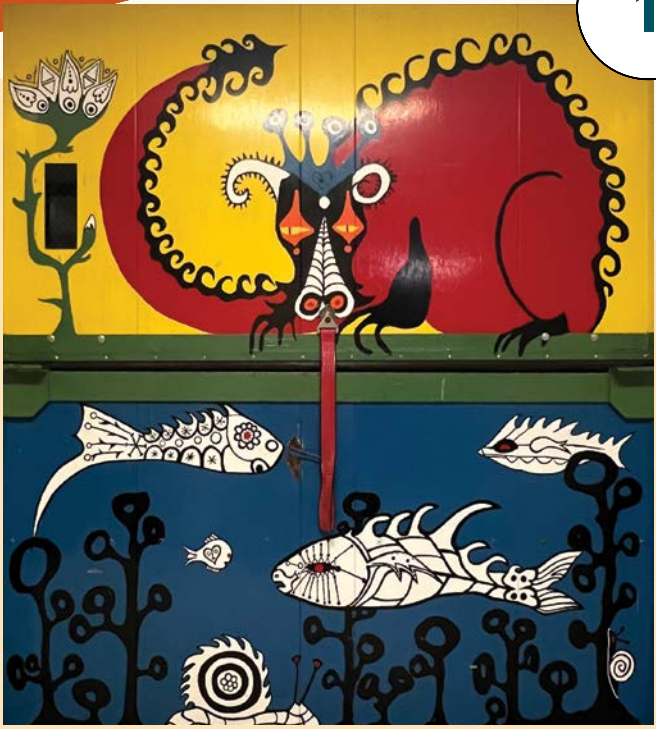

"CHARLIE IN MINNESOTA"
by Professor Klaus Ruedenberg and daughter Ursula

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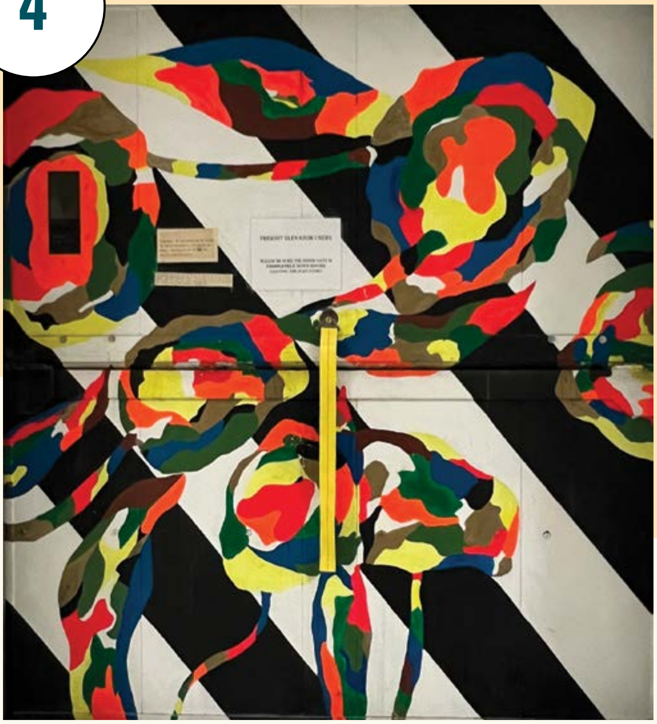

"G4"
by Professor Dan Zaffarano and daughter Elisa

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"SHIBUI"
by Graduate Student Charles Turner and Secretary Dinae Marxer

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"DECONGESTION"

by Graduate Student Jon Larsen and wife Anita

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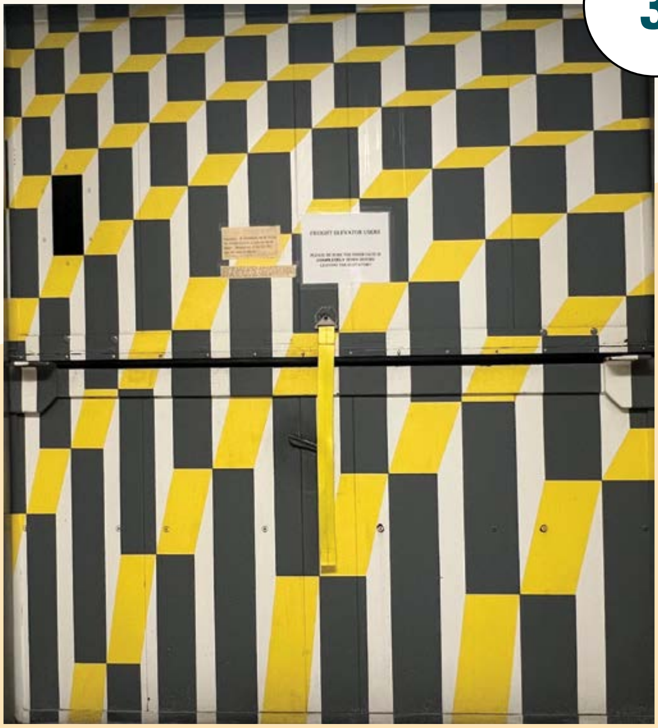

"GORDAN"

by Professor Willard Talbert and Graduate Student (and Reactor Supervisor) Jay Norman

6

"CLYDE"

by Graduate Students John Klinkner and Michael Lind

GOING DOWN

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Quanta & Cosmos is published once a year for the alumni, friends, students, and faculty of the Department of Physics and Astronomy at Iowa State University, an academic department in the College of Liberal Arts and Sciences.

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Adam Kaminski
Thomas Iadecola
Matt Wetstein

CHAIR: Frank Krennrich
EDITOR: Marzia Rosati

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Department of Physics and Astronomy
Ames, Iowa 50011
physastro@iastate.edu | 515-294-5440