Radiations

SPRING
2023

The official publication of Sigma Pi Sigma

The StarShade Challenge

Committed to Student Success

The Medical Imaging Researcher

Science Comes to Life at PhysCon

SPS OUTSTANDING SERVICE AWARD

SPS recognizes faculty and students who exemplify an attitude of service to the discipline of physics and astronomy through actions at the local, national, or international level.

Do you know an SPS or Sigma Pi Sigma member that has had a positive impact on an SPS chapter, a department, or the broader community?

Nominate a member today!

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ΣΠΣ is looking to award individuals who have performed meritorious service to the field of physics and astronomy, to Sigma Pi Sigma, or to your department.

Awards can be bestowed by individual chapters.

Nominate someone today!

www.sigmapisigma.org/awards/service

Recipients receive national recognition and a certificate.

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ON THE COVER

A group of PhysCon 2022 attendees visits the Robert C. Byrd Green Bank Telescope in Green Bank, West Virginia, during a tour of the facilities arranged for the first day of PhysCon 2022. Photo courtesy of Brendan Diamond, zone councilor, Zone 4.

Radiations

SPRING 2023
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Sigma Pi Sigma is an organization of the American Institute of Physics. It was founded at Davidson College, Davidson, NC, December 11, 1921. Member, Association of College Honor Societies. Contact us at sigmapisigma@aip.org; telephone: (301) 209-3007; fax: (301) 209-3082.

Letter from the Assistant Director

An Attitude of Service

by Andrew Zeidell, Assistant Director of Sigma Pi Sigma

"To develop and maintain an attitude of service" is a phrase we all uttered as we took the charge to become members of Sigma Pi Sigma. This charge, based on the mission of Sigma Pi Sigma, means that with the recognition of accomplishment comes the responsibility to serve.

Many of us embodied an attitude of service while leaders in SPS and Sigma Pi Sigma chapters, mentoring classmates, or doing public outreach or advocacy. Some have taken the ethos of service to the heart of their careers and made it the practice of their profession. Some serve by investing in students or volunteering at outreach events, even as they move through their own careers. However we maintain that attitude, we all share a set of values that guide and motivate our service to the physics and astronomy community, and beyond. This dedication to service is foundational to the society.

To encourage a continued attitude of service, here are a few ideas for how Sigma Pi Sigma members can serve the community.

Andrew Zeidell. Photo by SPS.

Nationally

At the national level, Sigma Pi Sigma members can help ensure that the United States has sound science policies. Whether this is by pursuing a career in public service, visiting Congress to share information on issues, or finding volunteer opportunities with organizations like the American Association for the Advancement of Science (AAAS), our expertise and educational

Get Support for Inductions and Chapter Activities

Sigma Pi Sigma Chapter Project Awards of up to $500 are awarded to chapters to support inductions or other engaging activities that include alums or promote Sigma Pi Sigma on campus or to the public. Learn more at **sigmapisigma.org/sigmapisigma/awards/chapter-project**.

background can be powerful tools for impacting society and the future of science.

Another way to contribute at the national level, yet with a uniquely local impact, is to volunteer for the Adopt-a-Physicist program. Adopt-a-Physicist, run by Sigma Pi Sigma and the American Association of Physics Teachers, connects high school physics, astronomy, and general science classrooms to Sigma Pi Sigma members. For three weeks each fall, members share their stories with students from around the United States and abroad, encouraging their interest in science and awareness of its impact.

Locally

Locally, Sigma Pi Sigma members can serve by advocating for science education and science-based policies in their community, getting involved in science outreach projects, and mentoring individual students or teams. Whether it is by serving as judges at regional science fairs or science Olympiads, coaching Science Bowl teams, or volunteering at local outreach events, science professionals can give a profound boost to student confidence. Contacting your local Sigma Pi Sigma or SPS chapter, or a local astronomy or science club, can be a great way to get involved in groups that consistently hold events. These initiatives provide key opportunities for local communities to learn more about physics and astronomy.

Within Sigma Pi Sigma and SPS

Within our Sigma Pi Sigma and SPS community, there are many opportunities to serve. The Physics Congress is a big one that happens every three years. It is truly only possible because of the dedicated efforts of many Sigma Pi Sigma volunteers. From plenary speakers to those running around setting up workshops, they are everywhere. If you're local to a congress, Lunch with the Scientists is a great opportunity to share a meal with aspiring physicists and astronomers, swap stories, and provide encouragement to them. The 2025 Physics Congress will take place October 30–November 1 in Denver, Colorado, and volunteer opportunities will be posted on the Sigma Pi Sigma website as the event approaches.

Another opportunity to give back is through the Alumni Engagement Program, which enables SPS chapters to reach out to alumni members of SPS and Sigma Pi Sigma for mentoring, to serve on panels, and to attend induction ceremonies, colloquia, and outreach events. If you are interested in putting your name into the hat, make sure to stop by our website and fill out the form.

If donating time is not something you can do now, you can still give back in the form of a gift that supports and encourages students through scholarships, career resources, and professional development. For more information, visit **foundation.aip.org/student-programs.html**.

By maintaining a service-oriented approach throughout our lives, we can demonstrate the exceptional standards of membership in Sigma Pi Sigma. Our schools, departments, and society will be aware that we value the pursuit of excellence and enthusiastically support future generations of science-educated professionals. When Sigma Pi Sigma members serve others at any level, we build a sense of community and fellowship, and the society's impact spreads well beyond its membership count. •

Be a Resource for SPS Chapters

Join the SPS and Sigma Pi Sigma Alumni Engagement Program—a database of participants willing to be speakers, panelists, tour guides, and mentors for SPS chapters. Learn more at **spsnational.org/programs/alumni-engagement**.

AIP

The American Institute of Physics is a federation of scientific societies in the physical sciences, representing scientists, engineers, educators, and students. AIP offers authoritative information, services, and expertise in physics education and student programs, science communication, government relations, career services, statistical research in physics employment and education, industrial outreach, and history of the physical sciences. AIP publishes *Physics Today,* the most closely followed magazine of the physical sciences community, and is also home to the Society of Physics Students and the Niels Bohr Library & Archives. AIP owns AIP Publishing LLC, a scholarly publisher in the physical and related sciences. www.aip.org

Member Societies

Acoustical Society of America
American Association of Physicists in Medicine
American Association of Physics Teachers
American Astronomical Society
ACA: The Structural Science Society
AMS: American Meteorological Society
American Physical Society
AVS Science and Technology of Materials, Interfaces, and Processing
Optica (formerly OSA)
The Society of Rheology

Other Member Organizations

Sigma Pi Sigma
Society of Physics Students

Connect with Sigma Pi Sigma

LinkedIn
linkedin.com/groups/142619

Instagram
instagram.com/spsnational

AIP Foundation
foundation.aip.org

The StarShade Challenge

The images from the James Webb Space Telescope (JWST) are stunning. But even as we enjoy them, we—the science community—need to be planning for the future. What should its successors be like?

In collaboration with NASA, SPS and the American Institute of Physics (AIP) are challenging undergraduates to design a giant starshade that can be deployed in space to block starlight. A 100-m shade could be part of a next-generation telescope, and it could help us examine extreme exoplanets from an Earth-stationed observatory.

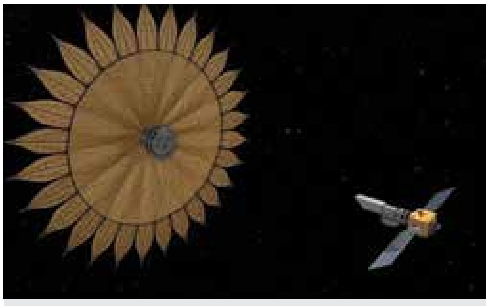
Groups of up to 20 students are eligible for the challenge. Using physics, engineering, and structural analysis, they'll need to ensure that their proposed shade meets critical technical requirements, determine the size of its shadow, and propose a method for deploying it from a rocket. Finally, groups will need to build a 1:100 scale model.

As part of the NASA Innovative Advanced Concepts (NIAC) program, members of the Hybrid Observatory for Earth-like Exoplanets (HOEE) team will meet with groups and help with their designs.

The challenge will take place during the fall 2023 semester. The first 20 groups to register and meet with HOEE staff will receive a $1,000 honorarium for materials, and teams that place in the top three will win up to $10,000 for student travel and research. If you're an alumni member of Sigma Pi Sigma, please consider sharing this information with your SPS and Sigma Pi Sigma chapters! •

Learn more and sign up: aip.org/starshade.

Top: This Hubble Space Telescope image, called Cosmic Cliffs, reveals part of the Carina Nebula (NGC 3372). Bottom: This image from the JWST, Hubble's successor, shows the same area. What will the next generation of telescopes reveal? Top credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); ack. N. Smith (University of California, Berkeley). Bottom credit: NASA, ESA, CSA, and STScI.



This artist's concept shows the geometry of a space telescope aligned with a starshade. The shade blocks starlight to reveal the presence of planets orbiting a star. Image credit: NASA/JPL-Caltech.

Take the StarShade Challenge!

- **Sign-up deadline: September 5, 2023**
- **Sign-up link: aip.org/starshade**
- **Submission deadline: December 15, 2023**
- **First place: $10,000 fund for student travel and research**

The Jocelyn Bell Burnell LEADERSHIP SCHOLARSHIP

Jocelyn Bell Burnell is a luminary in the field of astronomy. She discovered radio pulsars, is a past president of the Royal Astronomical Society and the Institute of Physics, has made groundbreaking discoveries since she was a graduate student, and is a tireless advocate for diversity in science. To acknowledge the importance of her work and her support of our undergraduate community, the SPS and Sigma Pi Sigma Executive Committee voted on December 8, 2022, to permanently name its highest leadership scholarship after Dame Jocelyn Bell Burnell.

Bell Burnell is a dedicated and passionate supporter of the Society of Physics Students and Sigma Pi Sigma. She served as a plenary speaker for the 2012 and 2016 Physics Congresses and led the 2019 and 2022 Physics Congresses as honorary chair. We're thrilled to have her return as honorary chair in 2025, in Denver, Colorado. Bell Burnell generously shares her time at each congress, talking to everyone who wants to chat, take a selfie, or discuss the future of astronomy. She's even helped the SPS staff fill swag bags for attendees.

The SPS scholarship program encourages the study of physics and astronomy and the pursuit of high scholarship, a pillar of Sigma Pi Sigma. Beginning in 2023, the top scholarship awardee will be named the Jocelyn Bell Burnell Leadership Scholarship Award winner and receive a $6,000 scholarship. The winner will be selected based on academic performance and leadership shown in their physics or astronomy department. Scholarship applications are due each year on March 15. For more information, please visit **spsnational.org/scholarships/leadership**. •

Jocelyn Bell Burnell shares dinner with Sylphrena Kleinsasser, a student at Lycoming College and member of the SPS Council, at the 2022 Physics Congress. Photo courtesy of Kleinsasser.

Get Involved with Sigma Pi Sigma

There are many ways to engage with the Sigma Pi Sigma community! Members volunteer at the Physics Congress, serve on panels, share their stories, and help guide the next generation of physicists and astronomers. Here are just a few ways you can get involved—if you have a great idea or volunteer story to share, please, send us a note at **sigmapisigma@aip.org**!

Radiations:

- Suggest topics or submit articles for future issues
- Suggest a colleague to be featured as a Hidden Physicist or in an Alumni Spotlight
- Build community by submitting a Member Note
- Share your nontraditional physics career through Hidden Physicists

Send us a note at **sigmapisigma@aip.org** with the subject "Radiations," or submit a Hidden Physicist story or Member Note at **sigmapisigma.org**.

Adopt-a-Physicist:

- Connect with high school physics, astronomy, and science students
- Participate in online message boards discussing physics and astronomy, careers, school, work-life balance, and more

Sign up this fall at **adoptaphysicist.org**.

Alumni Engagement Program:

- Connect with Sigma Pi Sigma members and SPS alumni
- Provide tours, job shadowing, mentorship, and professional development
- Offer to be a speaker at local events or serve as a panelist

Sign up at **spsnational.org/programs/alumni-engagement**.

Other Opportunities:

- Start or join a social media group for your chapter
- Participate in local job and career fairs
- Connect with local physics and astronomy departments
- Reach out to nearby chapters for collaboration

Short on time? Consider financially supporting students through scholarships, career resources, and professional development at **foundation.aip.org/student-programs.html**.

Your Support Makes a LASTING IMPACT

by Brad Conrad, Director of Sigma Pi Sigma

Thanks to the generous donations of Sigma Pi Sigma members and friends of SPS, undergraduates from more than 75 universities received financial assistance to attend the 2022 Physics Congress last October in Washington, DC. Without your critical support, many would have missed this transformative event.

The Physics Congress, hosted by Sigma Pi Sigma, gave these students and hundreds more a unique—and fun—collective opportunity for personal and professional growth. The event brought together more than 1,000 physics and astronomy students from 257 colleges and universities. At least 60 students came as the only student from their school, making new friends and lifelong connections along the way.

Throughout 2022, Sigma Pi Sigma supported students from another 25 departments as they traveled to meetings of AIP Federation Member Societies and Affiliates, and funded 18 regional meetings for undergraduate physics and astronomy students.

Students from Rhodes College's SPS chapter bond at the 2022 Physics Congress.

Travel Support Matters

Physics and astronomy departments are small when compared to most other majors—in 2022, departments in the United States averaged just six to seven undergraduates per year. As an undergraduate I knew that there were physics majors at other schools, but it was an abstract concept. How would I ever meet them? My first meeting—a combined SPS Zone 2 and New York Section of the American Physical Society meeting—changed the course of my life professionally and personally. It helped me figure out that I needed to try graduate school and that I belonged in this community. It got me interested in a variety of topics unrelated to my undergraduate research. It opened many doors for me. I'm eternally grateful to those who made it possible for me to attend: my SPS advisor John Andersen and those who donated to my department. I'm proud that Sigma Pi Sigma helps so many students achieve this milestone every year.

Presenting research results at a conference is one of the most important professional development activities we can offer students as they prepare for future careers. Effectively and succinctly communicating with peers and future colleagues is a skill that will benefit students for a lifetime. And through these experiences, students often gain insight into how their research connects to that of other groups or entire fields of study of which they were unaware. Science that occurs in a vacuum runs the risk of failing to advance the field and our shared understanding of the universe. For many, attending meetings illustrates what it means to be part of the scientific community in ways that a classroom cannot.

SPS Awards For Travel

Support that helps undergraduate students become active members of the physical science community speaks to the heart of the society. Since its inception at Davidson College in 1921, Sigma Pi Sigma has encouraged excellence within the field and the fellowship that comes from gathering with colleagues. These ideals live on through our support of undergraduate travel to conferences. Today, SPS is proud to offer three types of Sigma Pi Sigma–supported travel assistance to students:

1. **Travel Awards** support undergraduates presenting their scholarly work at regional, national, or international conferences of AIP Federation Member Societies and Affiliates.
2. **Chapter Reporter Awards** support undergraduates or groups of undergraduates attending national conferences. After concluding their trip, recipients write about their experiences for an SPS or Sigma Pi Sigma publication.
3. **Research Reporter Awards** support undergraduates traveling to conduct research at a national laboratory, international laboratory, or observatory.

These awards are possible because of the generosity of Sigma Pi Sigma members and friends of the Society of Physics Students.

Sigma Pi Sigma also supports regional meetings across North America, called SPS zone meetings. Zone meetings offer many of the same opportunities as national or international conferences but on a smaller scale and with an undergraduate focus. Registration and lodging are typically inexpensive, increasing accessibility. And by presenting research at a regional meeting, students can meet local potential collaborators, employers, and graduate schools, and make new friends they're likely to encounter again and again. They can also hone their communication skills in a less intimidating environment than a national or international meeting.

Looking to the Future

This year will bring many more meetings and students in need of travel support. And looking further ahead, Sigma Pi Sigma and the 2025 Executive Program Committee are already well on their way to planning the 2025 Physics Congress, which will take place October 30–November 1 in downtown Denver, Colorado. We're anticipating more than 1,300 attendees for three days of professional development and networking with plenary speakers Jocelyn Bell Burnell (University of Oxford), Donnell Walton (Corning Inc.), Eric Cornell (University of Colorado Boulder and JILA), and Julianne Pollard-Larkin (MD Anderson Cancer Center).

This event only happens every few years, and we want as many students as possible to be part of the action! But some simply cannot afford to attend PhysCon, or other physics and astronomy meetings, without a helping hand. As the Sigma Pi Sigma community, we can be that helping hand. We can give students the opportunity to make connections that will last a lifetime by contributing to the Annual Fund and the Congress Centennial Endowment Fund at **foundation.aip.org**.

Linked but distinct, the societies of Sigma Pi Sigma and SPS are volunteer driven and donor supported. With your help we can ensure that future generations have experiences that mirror the comments of the students featured here. We each have a part to play in making the community more accessible and welcoming, and I invite you to join us in supporting the next generation and the next 100 years of Sigma Pi Sigma. •

A student checks out the effects of diffraction glasses in the 2022 Physics Congress Exhibit Hall.

Plenary speakers Renee Horton (left) and Julianne Pollard-Larkin (right) enjoy the 2022 Physics Congress.

Rush Holt, a former congressman and SPS chapter advisor, gives a plenary talk during the 2022 Physics Congress. All photos by SPS.

"As a first-generation college student, I am learning as I go. The college experience has been amazing for me. There is so much to learn, and I am excited to have the honor of being taught under incredible faculty and through my friends. Upon earning my bachelor's degree in applied physics and mathematics, I would like to start working in a research laboratory while also pursuing a master's degree in physics. I also have an interest in continuing on to earn a PhD. Thank you for believing in me."

- Matthew, an SPS member who received a donor-supported scholarship and travel award

"I am a junior pursuing a degree in physics education, with the intent of teaching high school physics. I want to convey to my students the importance of physics in life, as well as how fun it can be! I also want to teach my students how to advocate for themselves and hopefully inspire some of them to pursue physics and engineering as a career."

- Katie, an SPS member who received a donor-supported SPS award

Fall 2022 SPS CHAPTER AWARDS

Congratulations to the winners of the Fall 2022 SPS Chapter Awards. These awards are made possible in part by generous contributions from Sigma Pi Sigma members. For examples of past award-winning projects, visit **spsnational.org/awards/chapter-awards**.

FUTURE FACES OF PHYSICS

Future Faces of Physics Awards are made to SPS chapters to support projects that promote physics and astronomy across cultures and the recruitment and retention of people from groups historically underrepresented in physics.

Rhodes College
Rhodes College Egg Drop
Grace Nehring (Leader)
Brent Hoffmeister (Advisor)

Saint Joseph's University
The Stuff in Space
Joseph Popp (Leader)
Roberto Ramos (Advisor)

Stony Brook University SUNY
Peer Mentorship and Physics Cafe
Evan Trommer (Leader)
Dominik Schneble (Advisor)

University of Central Florida
Advocating for Traditionally Underrepresented Groups in Physics
Madisyn Brooks (Leader)
Costas Efthimiou (Advisor)

University of North Alabama
Future Face of Physics Trivia for Underrepresented Groups
Madison Guth (Leader)
Mel Blake (Advisor)

SPS CHAPTER RESEARCH

SPS Chapter Research Awards support local chapter research activities that are imaginative and likely to contribute to the strengthening of the SPS program.

Benedictine University
The Fundial: Fostering Community Through Guiding Principles of Physics
Jeffrey Korbitz (Leader)
Matthew Wiesner (Advisor)

Calvin University
Our First Radio Telescope
Jenny Feng Lau (Leader)
Paul Harper (Advisor)

Florida Polytechnic University
Photodegradation and Environmental Stability of Microencapsulated Thermochromic Materials for Energy Saving Applications
Daniil Ivannikov (Leader)
Sesha Srinivasan (Advisor)

Old Dominion University
Introductory Astronomy Research
Jonathan Rose (Leader)
Perry Nerem (Advisor)

Rhodes College
From Ideas to Orbit: Fabrication and Assembly of Custom Satellite Hardware
Damien Nguyen (Leader)
Brent Hoffmeister (Advisor)

University of Central Florida
Abnormal Shadow Distributions from Relativistic Light Sources
Olivia Bitcon (Leader)
Costas Efthimiou (Advisor)

Sigma Pi Sigma Outstanding Service Award

These awards recognize individuals and groups who have performed meritorious service to the field of physics, to Sigma Pi Sigma the organization, its members, or to a local Sigma Pi Sigma chapter. Both members and chapters can nominate candidates. Learn more and nominate someone at sigmapisigma.org/sigmapisigma/awards/outstanding-service.

MARSH W. WHITE

Marsh W. White Awards are made to SPS chapters to support projects that promote interest in physics and astronomy among students and the general public. The award is named in honor of Dr. Marsh W. White for his years of service to Sigma Pi Sigma and the community.

Adelphi University
Lab for Kids
Zahin Ritee (Leader)
Matt Wright (Advisor)

Brigham Young University
Physics Demonstrations for Underserved Elementary Students
Matthew Ricks (Leader)
Benjamin Frandsen (Advisor)

Indiana University of Pennsylvania
The Annual IUP Physics Olympics
David Lane (Leader)
Andrew Zhou (Advisor)

Mount Holyoke College
The Observatory Open Hours: Celestial Safari!
Mysha Khan (Leader)
Spencer Smith (Advisor)

Rhodes College
Rhodes College Rites to Play
Grace Nehring (Leader)
Brent Hoffmeister (Advisor)

Saint Joseph's University
Physics on the Move
Kayla Dickert (Leader)
Roberto Ramos (Advisor)

Stony Brook University SUNY
Engaging High Schoolers in Electromagnetism
Christopher Siebor (Leader)
Dominik Schneble (Advisor)

Tarleton State University
Observatory Outreach
Stephen Bardowell (Leader)
Melissa Lewis (Advisor)

University of Central Florida
Electrifying Interest in Physics
Maximillian Daughtry (Leader)
Costas Efthimiou (Advisor)

University of North Alabama
STEM Day
Harmonie Wildharber (Leader)
Mel Blake (Advisor)

University of Southern Mississippi
Promotion of Physics in the Hattiesburg Community
Braden Hudson (Leader)
Michael Vera (Advisor)

University of Virginia
Let the Cat Out of the Box: Charlottesville High School Outreach
Ethan McKeever (Leader)
Jency Sundararajan (Advisor)

SIGMA PI SIGMA CHAPTER PROJECT

Sigma Pi Sigma Chapter Project Awards support inductions or chapter events that include alumni or expand recognition of the society.

Florida Polytechnic University
Inaugural Inductees' Insights Sharing
Daniil Ivannikov (Leader)
Sesha Srinivasan (Advisor)

Saint Joseph's University
Saint Joseph's University Sigma Pi Sigma (ΣΠΣ) Induction Ceremony
Nathaniel O (Leader)
Roberto Ramos (Advisor)

University of Colorado Boulder
Boulder Branch Sigma Pi Sigma 2022-2023 Induction Ceremony
Alexander Fix (Leader)
Keith Ulmer (Advisor)

University of North Alabama
Induction Ceremony
Madison Guth (Leader)
Mel Blake (Advisor)

University of Virginia
Lighting the Way with Lighthouse Instruments: UVA Sigma Pi Sigma Annual Luncheon
Ethan McKeever (Leader)
Jency Sundararajan (Advisor)

Apply for a Sigma Pi Sigma Chapter Project Award

Sigma Pi Sigma Chapter Project Awards of up to $500 are awarded to chapters to support inductions or other engaging activities that include alums or promote Sigma Pi Sigma on campus or to the public. Applications are due November 15. For more information and award proposal templates, visit sigmapisigma.org/sigmapisigma/awards/chapter-project.

FEATURE

Centennial panelists (L-R) Eric Cornell, Jim Gates, Jocelyn Bell Burnell, and John Mather. Photo by Ashauni Lennox.

Science Comes to Life at PhysCon:
Scholarly Adventures in Washington, DC

by Fabrizio Vassallo, SPS Reporter, Denison University

In a letter to a physics aficionada who had enjoyed his lectures, Richard Feynman suggested that she should "study hard what interests [her] the most in the most undisciplined, irreverent and original manner possible."[1] Feynman's advice to combine the complicated, the abstract, the scholarly side of physics with its creative, messy, adventurous side is often hard to reconcile with the strict environment that seems to characterize the sciences. At the 2022 Physics Congress, however, attendees saw those two different strands of physics harmonized in every talk, workshop, special event, and meal. For a moment, join me in recapping some of those adventures, some of which you could experience at the next congress.

On the scholarly side of things, you can hardly do better than attending a plenary session given by some of the foremost faces of science in the last half-century, including two Nobel laureates, a presidential advisor, and perhaps *the* most renowned female astronomer alive, full stop. A thousand people gathered to witness this event, which would properly kick things off in one of the hotel's ballrooms—a place grandiose enough to have been taken out of a British royal castle, with a slightly nerdy spin provided by the huge recreation of the James Webb Telescope's primary mirror at one end. Despite the daunting officialism of it all, once Dame Jocelyn Bell Burnell stood up to answer the plenary question, "Where will physics and astronomy be in 100 years?" all of that faded away to give place to the cool science we were there to learn and discuss. Hearing each of the speakers—Dame Bell Burnell and Drs. John Mather, Jim Gates, and Eric Cornell—present their views about the future of science, often mixing technical discussions with jokes and funny anecdotes, we got a sense that regardless of the titles and prizes they had accumulated, they were just like us—driven, curious scientists looking to share their research, experience, and love for physics and astronomy with like-minded people. This idea would be reinforced throughout the next few days as I interacted one-on-one with the likes of Drs. Gates and Cornell in the hotel hallways, something

Fabrizio Vassallo. Photo courtesy of Vassallo.

I definitely wasn't expecting would happen when I flew to Washington, DC, from the small town in Ohio where I attend college.

If the difference between that environment and my tiny liberal arts university in Granville, Ohio, wasn't shocking enough, one of the first events of the conference was a field trip to the University of Maryland, College Park. Its physics department is known around the world as one of the best in atomic, molecular, and optical physics. Although I wasn't sure I would find this tour interesting, it turned out to be one of the highlights of my trip. This was my first time seeing an elite research institution from the inside, touring fascinating places such as the Lathrop Nonlinear Dynamics Lab, where they have a 3-meter-tall model of the Earth that looks equal parts daunting and incredible. Everyone was so nice to us visitors, from the university staff coordinating the event to the students that acted as our guides. This visit helped me decide that I want to go to a grad school with a similar culture and environment—one that combines a friendly atmosphere with a wealth of research areas at the absolute cutting edge.

A student presents research at the 2022 Physics Congress poster session. Photo by SPS.

If the trip had ended there, after just those two events, I would've called it a success. But there's more. My last day in DC turned out to be the epitome of the undisciplined and irreverent attitude toward science that Feynman encouraged. Saturday started off intensely with the core event of my conference experience: the poster session. I went into it with a mix of anxiousness and excitement; although I'd presented a poster before, I'd never presented at such a big event. Despite my initial wariness, it went well. Multiple people, ranging from undergraduates to experts in my field, stopped by to ask about my research, sometimes pushing me to the limit of my understanding with probing questions, which I truly appreciated. And that was it, PhysCon was over for me.

Holding on to my successful work, albeit with a bittersweet feeling, I decided to make the best of the rest of the day. For me, that meant hunting for bookstores. I took the metro downtown, explored the city, and walked for hours from one bookstore to the next. The day ended at a store in The Wharf, where I found a biography of the late Stephen Hawking and read at a little table by the docks. As the hours flew by, I reflected on the spontaneous nature of what I was experiencing and on my connection to physics as I read about Hawking's own inspiring relationship with the same subject.

That day—well, the whole event—taught me about making friends in science, interacting with elite physicists, and presenting a technical poster to a wide-ranging audience. But it also taught me about the approach I want to have toward science. As I started my trip back to Columbus, I realized that I now understood what Feynman had meant in that letter. PhysCon very well could have been a one- or two-day event completely crowded with technical presentations of all sorts, but it was the harmonious intertwining of the scholarly with the creative, the structured with the unexpected, and the abstract with the adventurous that made the event great. So that's my main takeaway from this experience: science doesn't happen, like they might have you believe, in dull rooms with people in lab coats writing equations endlessly on blackboards. Science happens best when we approach it "in the most undisciplined, irreverent, and original manner possible." •

A full-scale model of the James Webb Space Telescope's primary mirror looms in the background as PhysCon attendees discuss the most pressing needs in physics and astronomy today. The model was made by SPS advisor Toni Sauncy and her chapter at Texas Lutheran University. Photo by SPS.

References

1. Richard Feynman, *Perfectly Reasonable Deviations from the Beaten Track: The Letters of Richard P. Feynman*, ed. Michelle Feynman (New York: Basic Books, 2005), 206.

FEATURE

Pack Snacks, and Don't Be Terrible

A Q&A with Sarah Hörst, Plenary Speaker at the 2022 Physics Congress

by James Hirons, Makayla Teer, Ryan Rodriguez, and Elyzabeth Graham, SPS Reporters, Texas A&M University - Commerce

Sarah Hörst is an associate professor of earth and planetary sciences at Johns Hopkins University. She specializes in the complex organic chemistry occurring in the atmosphere of Titan, as well as elsewhere in the universe.

Who fostered your curiosity at an early age?

My parents. My dad was a doctor, and my mom had one of these fairly typical stories for women of her generation. She majored in biology and wanted to go to grad school, but that wasn't really a thing for women. When I was little, she had a bookstore.

My mom missed doing science so she started working at a small biological research institute. She was a research assistant because she only had a bachelor's degree. My mom went to grad school to get her PhD when I was seven and she was 41. She got her PhD when I was 13—I did the references for her dissertation. I would come home from school, and there'd be a stack of papers sitting next to the computer. I would just sit there and type in references for her.

Both of my parents were very into STEM, which was a big privilege and really helped make the path easier for me.

What was the driving force behind your pursuit of atmospheric chemistry?

I had done summer research with my undergrad advisor, looking at the Galilean satellites. During the school year, he sent me an email asking me to come by his office. I get in there and he starts buttering me up, "We have this project, and we immediately thought of you!" It turned out that I had to go to the telescope on campus every single night for like nine months, looking for clouds on Titan. Clouds on Titan are very bright. You don't even need to take pictures; you can just look at how bright Titan is to see if there are clouds.

Sarah Hörst gives a plenary talk on Titan at the 2022 Physics Congress. Photo by SPS.

Voyager flew by Titan and couldn't image the surface because the atmosphere was so thick. It's this place that's so interesting based on the few things that we know about it, but it's so averse to giving up its secrets. From then on, I was really interested in Titan.

As a woman in STEM, what is the biggest challenge you faced during your educational career?

One thing that was really hard was the lack of role models. I went to Caltech for my undergrad. I didn't take a single class in my planetary science major from a female faculty member—not a single class. I took a total of two undergraduate STEM classes from female faculty members, one in mechanical engineering and one in physics. I also had a literature major, and half of those professors were women. And it was like, "What message are you trying to send here?"

My class had the highest percentage of women that had ever been admitted to Caltech; we were 37 percent when we started and 25 percent when we graduated. In grad school it wasn't a lot better. Every single one of our core classes was taught by a male faculty member. I was 25 or 26 before I took a class from a female planetary scientist.

There were two female faculty members in my PhD department. Neither one of them—and this is not a knock on them—was living a life that I envisioned for myself. I was thinking, "Okay, so these women who are complete badasses and amazing are doing this thing, but they're not doing it the way that I want to. Is there room for me?"

I didn't work for a woman until my postdoc. That was such a game changer for me. She was doing science the way that I wanted to. It wasn't cutthroat. It wasn't competitive. It was us in her office looking at data and laughing. When we're learning, we model the behavior we see from other people. If you don't have a person to model yourself after, it's a lot harder to figure out how to do what you want to do.

What is the best piece of advice you've been given in your career?

The first thing that comes to mind is to make sure you pack snacks.

One of the things that my undergraduate research advisor helped me to see early on is that being happy is really important.

NASA's Cassini spacecraft captured this less-than-revealing picture of a hazy Titan on September 15, 2017. Credit: NASA/JPL-Caltech/Space Science Institute.

What changes would you like to see in the physics, astronomy, and planetary science community?

That one's easy. We need to fix our issues with diversity and inclusion 1,000 percent. We are selfishly missing out on talent, and that's preventing us from doing the things that we say we want to do. But more from a human perspective, we need to not be so terrible.

What do you wish someone had told you earlier in your career or education that you want students to know?

It's going to be okay, whatever that means. It's true—it will be okay. •

This interview has been edited for length and clarity.

Got Snacks?

SPS provides $300 in financial support for chapters to start food cabinets for hungry physics and astronomy students. Chapters use funds for items that are freely accessible to all department undergraduates and are encouraged to fundraise to restock and maintain the food cabinet. Applications are accepted on a rolling basis. For details see spsnational.org/scholarships/FFHPS.

SPS reporters from Texas A&M University - Commerce commemorate their interview with Sarah Hörst (second from left). Photo courtesy of the reporters.

Be a Role Model for Physics and Astronomy Students

Join the SPS and Sigma Pi Sigma Alumni Engagement Program—a database of participants willing to be speakers, panelists, tour guides, and mentors for SPS chapters. Learn more at spsnational.org/programs/alumni-engagement.

Help high school physics classes understand the joys of studying physics and astronomy and the career opportunities they provide—sign up for Adopt-a-Physicist! Physicists are "adopted" by up to three classes and interact for a set, three-week session, making lively, in-depth discussions possible. Learn more at sigmapisigma.org/sigmapisigma/adopt-physicist.

FEATURE

Committed to Student Success

Gary White and Willie Rockward Receive Seagondollar Service Awards

by Kendra Redmond, Editor

Gary White and Willie Rockward both hail from Louisiana and are now physics professors on the East Coast. Colleagues describe both as passionate physics professors and excellent mentors. Neither really planned on majoring in physics, and neither is wary of a road trip with students.

At the 2022 Physics Congress, the SPS and Sigma Pi Sigma Executive Committee recognized White and Rockward for another commonality: an exemplary level of commitment and service to the societies. For this they each received a rare Worth Seagondollar Service Award.

Gary White: Expanding Opportunities

When asked to declare a major at Northeast Louisiana University, White wasn't sure what to do. "I wanted to major in science, but a campus advisor told me that it wasn't possible to do all of science," he says. So he asked, "How do you get in that observatory?" The advisor replied, "Well, you'd have to major in physics, probably."

Physics was a great fit. The small department didn't have an active SPS chapter, but White was inducted into Sigma Pi Sigma there. "I didn't really register what Sigma Pi Sigma was," he says, "but I thought it was a good idea to join."

After earning a PhD in physics from Texas A&M University, White interviewed for a professorship at Northwestern State University of Louisiana (NSU). "By noon they had offered me the job," he says. He didn't realize then he'd be the *only* physics professor at NSU.

In addition to teaching, White advised NSU's fledgling SPS chapter. By leveraging award money from the SPS office, he often secured matching funds from the school. This significantly expanded opportunities for his students.

In a particularly memorable experience, White and a dozen students road tripped to Atlanta, Georgia, for an American Physical Society March Meeting. That was the first time many of them had crossed the state line, and seven presented research.

After a few years at NSU, White was elected to the SPS Council, and he eventually became president. Then the SPS and Sigma Pi Sigma director position opened. Although it meant moving to Washington, DC, "The impact you could have in that kind of job made me want to go," White says.

When he became director in 2001, White further expanded opportunities for students. A highlight of his tenure was growing the Physics Congress into what it is today. The 2004 Congress, White's first as director, brought a few hundred people to the testing ground of the first atomic bomb, the Trinity Site in New Mexico. The 2008 Congress, hosted at Fermilab in Illinois, exceeded expectations.

"We had something like 800 people register, and Fermilab told us they could only hold 600," White says. "I remember driving there a few weeks before the congress, we were scrawling out plans on the floor of the van for how to fit everyone," he recalls. "But it worked out beautifully."

Gary White (above) and Willie Rockward (right) show off their new Worth Seagondollar Award medals. Photos by SPS.

The SPS Summer Internship Program blossomed under White's leadership. Each summer, more than a dozen physics and astronomy undergraduates come to Washington, DC, to work in policy, research, industry, or communication. The experience helps students see "the breadth of what they can do with their degree," White says.

As director, White prioritized building partnerships, increasing diversity, and raising the profile of students. Inspired by the trip to Atlanta, he also helped secure undergraduate research sessions at several national meetings.

In 2012, after more than ten years as director of SPS and Sigma Pi Sigma, White passed the torch. He is currently editor of the academic journal *The Physics Teacher*, and an adjunct physics professor at George Washington University in Washington, DC. And, of course, he's the SPS advisor.

About Worth Seagondollar

L. Worth Seagondollar spent 40 years as a Sigma Pi Sigma advisor, first at the University of Kansas and then at North Carolina State University. As Sigma Pi Sigma president in the 1960s, he was instrumental in the society's merger with the American Institute of Physics Student Sections, which created the Society of Physics Students. In 1996 he was the first recipient of the award named in his honor.

Willie Rockward: Investing in the Future

"Physics was not my first choice, was not my first love—it wasn't even on my radar," Rockward says. Two factors brought him to physics. First, his mother would only let him play high school football if he earned high grades in math and science. Second, he dreamed of playing football at Grambling State University. The school offered him a scholarship—in physics.

He made the football team, but didn't stay long. "After about two or three weeks of practicing against the number one defense, a linebacker hit me so hard that I said, 'Okay, I'm sticking with physics,'" he says. Rockward joined SPS at Grambling and was inducted into Sigma Pi Sigma there.

His department chair often brought students to SPS zone meetings. "I remember going to one at the University of Texas at Dallas—we had a great time. We presented our research and met with other chapters," Rockward recalls.

He went on to get a PhD in physics at Georgia Institute of Technology and become a physics professor at Morehouse College, a historically black men's college in Atlanta. The department chair made him advisor of its struggling SPS chapter.

Inspired by his own experience, Rockward began taking students to SPS zone meetings to present research. White, then SPS director, saw the impressive Morehouse contingent at a zone meeting. He complimented Rockward, then nudged him. "You should consider running for SPS zone councilor."

"I threw my name in the hat—and it was the only one," Rockward laughs. As zone councilor he set up a zone meeting rotation in his region. Georgia, Alabama, and Florida took turns hosting zone meetings, and every fifth year, Puerto Rico. "We had the very first SPS zone meeting outside of the continental United States, and it was fabulous," he says.

Rockward eventually became president of Sigma Pi Sigma, serving for two terms. During that time, he encouraged members to support physics and astronomy undergraduates with their time and money.

"At every council meeting, Steve Feller, then chair of the Congress Planning Committee, would stand up and challenge the council to give to SPS," he recalls. "That still resounds in my mind, because if you really believe in an organization, you have to be willing to invest in it," he says.

A highlight of Rockward's presidency was helping to establish the Congress Centennial Endowment Fund, which supports student travel to the Physics Congress in perpetuity. "We encouraged people to give in increments of powers of ten," he says. And Rockward and the SPS Council led by example.

In 2018 Rockward moved from Morehouse to Morgan State University in Baltimore, Maryland, where he is chair of the physics and engineering physics department. He's working with its new SPS advisor to build up the chapter, and he's the Sigma Pi Sigma advisor.

"What keeps me invested in the society is seeing the breadth of the physics community. I get to see students—the upcoming generation, I get to see my colleagues, and I get to see my mentors, the people who were there before me," he says. "Some of the students who started with me are now coming into SPS as zone councilors." •

Learn more about the Congress Centennial Endowment Fund at foundation.aip.org/student-programs.html or scan this QR code.

Welcoming SIGMA PI SIGMA Back to Campus

Clemson's SPS chapter and members of its graduate student association enjoy a fun night at the movies. Photo courtesy of the chapter.

by Ben Perez, Contributing Writer

During a regular cleanup, David Sanders, president of Clemson University's SPS chapter, stumbled across a dusty box in the lounge labeled "Sigma Pi Sigma." Upon opening it, he found a set of pins with "ΣΠΣ" on them. He asked the chapter's then SPS president what they were, but she had no idea. "I think they're from an organization we had a long time ago," she said. That answer didn't satisfy Sanders, so as any scientist would, he dug deeper.

Sanders soon rediscovered the physics and astronomy honor society and wanted to bring the prestigious organization back to Clemson. He emailed the SPS office for help, and within the day, Brad Conrad, director of SPS and Sigma Pi Sigma, responded with the paperwork and a list of things to do. "We will be in touch with your advisor, and then we will figure the rest out from there," he told Sanders.

After the t's were crossed and the i's dotted, Clemson's Sigma Pi Sigma chapter was officially revived. It had been a ten-year hiatus.

Conrad was thrilled. "Undergraduate student groups like Sigma Pi Sigma and SPS are integral to the success of a student's career," he says. "When students pick up the mantle of leadership, they support each other and future generations of students. Each year of initiates is a resource for all of the physics and astronomy students to come."

The chapter hopes to expand and build strong relationships with other Sigma Pi Sigma chapters. The students want their chapter to feel like part of the bigger network of Sigma Pi Sigma chapters and members, which they can tap into to learn, grow, and find collaborators.

The physics students have great expectations for their chapter and plan to build on this initial momentum. "It will take years to get where we want to go, but we have a great group of undergraduates behind us to carry the torch once we seniors graduate," says Sanders.

Chad Sosolik, Clemson's Sigma Pi Sigma advisor, is poised to aid in their mission. "He has always been there to support us, even when we come to him with our crazy ideas," Sanders says. When a new idea hits, Sosolik humors the students, talks through the idea with them, and helps them plan a few experiments to see whether it's crazy or they are really onto something, according to Sanders.

When it comes to the honor society, the students plan to build something lasting. If all goes well, Clemson's Sigma Pi Sigma chapter won't be relegated to a forgotten box gathering dust ever again.

Editor's Note

In last fall's Chapter Spotlight, we inadvertently swapped the photos of two of Sigma Pi Sigma's newest chapters. Our sincere apologies to the chapters at the University of Alabama at Birmingham and Saint Mary's College - Notre Dame. We are so happy that you are part of the society!

Saint Mary's College - Notre Dame (IN)

University of Alabama at Birmingham

MICHAEL HINGSON

Creating a More Inspired, Inclusive Society

by Ben Perez, Contributing Writer

Michael Hingson was born to extremely supportive parents. They wanted him to be anything he chose and fostered a love for curiosity early on.

"I was always fascinated by science and looked up to my father. He was an electronics engineer, and whenever I could, I loved helping him repair TVs," Hingson says. "Yeah, I got zapped a few times, but, as my father always said, I had to learn sometime. And eventually, I did."

By age six Hingson could do algebra in his head, thanks to his dad. At 14 they got their amateur radio licenses together. "I remember cracking up talking to my father over the radio asking him, 'Oh, how's the weather over there?' Knowing well and good we were only a few rooms apart," he reminisces.

His story may not sound unusual for a physicist, but Hingson has an extra challenge: He's blind. Hingson was born with retinopathy of prematurity, a disease that can occur in premature babies when blood vessels grow abnormally in the retina and cause loss of vision. Because of this, many people have written him off. But he can accomplish the same tasks as sighted people, he just needs different tools.

Hingson learned to read Braille at an early age, and if Braille books weren't available, a parent or volunteer would read him the information he wanted to know. He uses a guide dog to help him navigate the world, along with technology such as AIRA, a "visual interpreter" that helps translate the visual world into an auditory one.

Using such tools, Hingson continued his education and graduated from the University of California, Irvine, with a bachelor's and master's degree in physics and a teaching certificate. That's where he was inducted into Sigma Pi Sigma. "I would have been Phi Beta Kappa, too, if we'd have had a chapter of that honor society when I attended," he says.

He'd planned to pursue a career in teaching, but like many scientists, Hingson's career path didn't follow a linear progression. He began working with the National Federation of the Blind, and that's where he got into sales. Forty-one years later, Hingson has built quite a career in the field, first selling technology and now selling himself as a motivational speaker. Although he doesn't do hard science anymore, he applies many of the skills he learned as a physics student—paying attention to details, being methodical, taking all factors into consideration, and exploring all paths to a new venture.

A defining day in Hingson's life was September 11, 2001. He was working in one of the World Trade Center towers when terrorists attacked; he descended 78 floors to safety with the help of his guide dog, Roselle. He immortalized their story in his *New York Times* best-selling book *Thunder Dog: The True Story of a Blind Man, His Guide Dog, and the Triumph of Trust*. Soon after, he started receiving invitations to speak about his experience that day, his life, and dealing with change.

Today, Hingson has turned most of his attention to speaking, inspiring and motivating audiences around the world with his story and the life lessons he's learned along the way. He also serves as the chief vision officer for accessiBe, an Israeli company whose products help make websites more inclusive. Inclusion doesn't only apply to race, gender, and religion, but also to people of all abilities, Hingson says. "That last one often gets left out of the conversation, but if we truly want to be an inclusive society, then it means making society accessible for everyone."

Michael Hingson and his guide dog. Photo by Josie Reynoso.

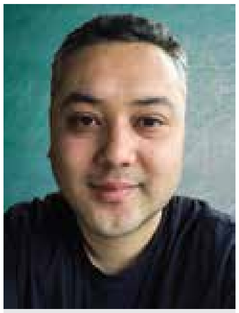
Looking ahead, Hingson wants to do everything he can to build a better world. That includes traveling, speaking, educating, and consulting. He is working on a new book, *A Guide Dog's Guide to Being Brave*, and hosts the podcast "Unstoppable Mindset," where inclusion, diversity, and the unexpected meet. "Honestly, I have so many interests I want to pursue. I can't afford to retire now," he says.

To learn more about Michael Hingson, his book, and his speaking career, visit MichaelHingson.com or email him at speaker@michaelhingson.com.

The Medical Imaging Researcher

by Pragalv Karki, Research Scientist, Mayo Clinic of Rochester

Hello and namaste. I am originally from Nepal, a small country renowned for being the birthplace of Buddha, the home of the Himalayas, and a sovereign nation throughout history. Nepal's breathtaking mountains and waterfalls always inspire a sense of calm in me.



Pragalv Karki. Photo courtesy of Karki.

After reading Carl Sagan's *Cosmos* in high school, I became fascinated with physics. One of the things from the book that amazed me was how the ancient Greek mathematician Eratosthenes calculated the earth's radius using simple geometry. Following high school, I decided to pursue an undergraduate degree in physics in the United States at Minnesota State University Moorhead (MSUM). I found the faculty to be exceptionally compassionate. In the final year of my degree, I was inducted into Sigma Pi Sigma in recognition of my academic performance and involvement with the Society of Physics Students' outreach activities. I am extremely grateful to the organization and the faculty for that.

As if the Minnesota cold wasn't enough, I enrolled at the University of North Dakota for a graduate degree. My PhD advisor and the faculty provided me with comprehensive training in theoretical and computational methods. Consequently, I was able to explore broader areas for postdoctoral positions. My first postdoc was at the University of Oregon (UO) and involved developing theoretical and computational frameworks in phononic metamaterials. It was during my time at UO that I became familiar with the field of biophysics. By the time I applied for my second postdoc, I had become so interested in the field that I mostly applied for positions related to biophysics.

Surprisingly, however, this change did not lead to a position in biophysics but rather a position as a medical imaging researcher at the Mayo Clinic in Rochester, Minnesota. I am a member of a group led by the inventor of an imaging technique called magnetic resonance elastography (MRE). MRE is an MRI-based technique that allows in vivo assessment of a tissue's viscoelastic properties by applying acoustic waves. Clinically, the technology is used in the diagnosis of liver diseases.

My research focuses on applications of MRE to brain disorders such as normal pressure hydrocephalus, Alzheimer's disease, and Parkinson's disease. The goal of our research is to solve fundamental problems in medical imaging by combining data science, medicine, biology, and physics. In a large group of approximately 20 researchers, I am the only traditional physicist among a group of doctors, medical physicists, engineers, and data scientists. Physics and physics-based computational methods are critical in several aspects of the technology.

A physics education provides a broad range of skills. My degree in physics combined with my computational skills enabled me to make these career transitions. During my PhD program, I not only learned physics, but I also learned how to learn. That gives me confidence in learning new subjects and techniques. Every single day I find myself incredibly enthused to be working on challenging problems that could improve health care and benefit others at the best hospital in the United States and beyond. •

Not a Physics or Astronomy Professional?

Help Sigma Pi Sigma document and share the career paths of "hidden" physicists and astronomers. Nominate a friend by emailing us at sps@aip.org, or share your career story at sigmapisigma.org/radiations/hidden-physicist-submission-form.

Coupled Oscillations in Diverse Phenomena

Part 3: Neutrino oscillations

by Dwight E. Neuenschwander, Physics Professor, Southern Nazarene University

Parts 1 and 2 of this article appeared in the Spring and Fall 2022 issues of Radiations *and are available at www.sigmapisigma.org/sigmapisigma/radiations/archive. Numbering in Part 3 continues from the previous parts.*

Editor's note: We inadvertently created a new—and meaningless—matrix notation when we published Part 2. Our sincere apologies to author Dwight Neuenschwander and to you, our readers. The version available on our website has been corrected.

The Backstory

The neutrino ν ("little neutral one") was postulated by Wolfgang Pauli in 1930 to save the principles of energy and angular momentum conservation in beta decay. Without knowing about the neutrino, an observed reaction seemed to be $n \rightarrow p + e^-$. Consider energy: for the decay of a free neutron, in the neutron's rest frame the conservation of energy gives

$$m_n c^2 = (m_p + m_e)c^2 + K_e + K_p \tag{44}$$

where *K* denotes kinetic energy, and by conservation of momentum [6],

$$p_p = p_e. \tag{45}$$

Equations (44) and (45) together imply a unique kinetic energy for the emitted electron. Most neutrons reside in nuclei, and for the beta decay that turns, say, boron-12 into carbon-12, in the absence of neutrinos the unique kinetic energy of the electron would be 13.37 MeV. However, the actual kinetic energies of the electrons emitted in boron-12 beta decay range across the continuum from zero to 13.37 MeV. As Pauli realized, the presence of a third emitted particle offers an infinite number of ways to partition the kinetic energy and momentum, allowing the continuum of electron kinetic energies while preserving energy conservation. This third particle must have zero charge, since electric charge is conserved and the charges are already accounted for. Furthermore, it would have to interact ever so weakly since it slipped under the detection threshold of original instrumentation, suggesting the neutrino has very little if any mass. (According to neutrino reaction cross sections eventually measured, if a beam of neutrinos was sent through a block of lead a light-year thick, most of them would emerge out the other side!) The very weakness of neutrino interactions allows observations so far to give only upper bounds to the particle's observables, such as its mass and magnetic dipole moment; typically, these quantities are taken to be zero, which, if not exactly correct, are good approximations.

The neutrino (actually the antineutrino $\bar{\nu}$) was first detected in 1956 when a team led by Frederick Reines and Clyde Cowan took advantage of the high antineutrino flux of the new Savannah River nuclear power plant to compensate for the particle's low-probability interactions. Beta decays coming from the byproducts of the fission include the abundant reaction

$$p \rightarrow n + e^- + \bar{\nu}.$$

Then and now, neutrinos and antineutrinos are detected indirectly by detecting the particles they produce in reactions. According to theory, the antineutrino from beta decay can drive the reaction,

$$\bar{\nu}_e + p \rightarrow n + e^+.$$

The position immediately annihilates with an electron to produce two 0.511 MeV gamma-ray photons, and in the Reines-Cowan experiment the neutron is absorbed by cadmium (with which the newly developed organic liquid scintillator detector was spiked) to produce a 9 MeV photon. The delay of a few microseconds between the production of the 0.511 MeV and 9 MeV photons allows a delayed-coincidence detection of the photons through an array of photomultiplier tubes [7].

As we presently understand the zoo of elementary particles, the fermions that participate in the strong and weak forces are the quarks, and the fermions that do not participate in the strong force are the leptons, whose most common representatives are the electron and its corresponding neutrino. There are three "flavors" (as they are whimsically called) of quarks and leptons; only the leptons concern us here [8], and the three lepton flavors are the electron e^- and its neutrino ν_e; the muon μ^- and its neutrino ν_μ; and the tau τ^- and its neutrino ν_τ—and their antiparticles. They all carry spin ½; the electron, muon, and tau carry negative charge (their antiparticles carry positive charge). The electron's mass is about ½ MeV/c^2, the muon mass about 106 MeV/c^2, and the tau mass about 1777 MeV/c^2. Lepton flavor is so far evidently conserved (approximately if not exactly so) [9]; electron-type neutrinos go with electrons, muon neutrinos with muons, and tau neutrinos with taus. The appearance of neutrinos is the hallmark of the weak interaction in reactions such as

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (46a)$$

$$\nu_\tau + n \rightarrow p + \tau^- \quad (46b)$$

$$\mu^- + p \rightarrow \nu_\mu + n \quad (46c)$$

and so on.

The Solar Neutrino Problem

In the mid-1960s the famous "solar neutrino problem" surfaced. In the sun's core electron-type neutrinos are produced in the first step of the proton-proton cycle of nuclear fusion, $p + p \rightarrow H_1^2 + e^+ + \nu_e$. Since neutrinos interact so weakly, they escape the sun at once, and each one carries no more than about 20 MeV of energy. Some of them pass through Earth. The neutrino detector in the Homestake Mine in South Dakota first raised the alarm about the solar neutrino problem. Headed by Raymond Davis, the experiment, which ran from 1970 to 1994, featured a large tank of dry-cleaning fluid, carbon tetrachloride CCl_4. It detects solar neutrinos through the reaction

$$\nu_e + n \rightarrow p + e^-. \quad (46d)$$

When this reaction occurs in a chlorine nucleus, it becomes the nucleus of the noble gas argon, which bubbles out to be collected. After several years of data collecting, the observed flux of neutrinos was about 2/3 short of the prediction, even when the solar models took into account other fusion channels such as the CNO cycle in addition to the *p-p* cycle.

The fact that neutrinos from the sun carry less than 20 MeV but the muon and tau masses are 106 and 1777 MeV/c^2, respectively, means that even if the neutrino could, somehow, produce the reaction, $\nu + n \rightarrow p + \mu^-$; in other words, if muon neutrinos were somehow in the mix of incoming solar neutrinos, they would still not have enough energy to make the muon appear in the chlorine-to-argon reaction. The insensitivity of the CCl_4 to muon neutrinos was suggestive. The most promising solution, first published by Bruno Pontecorvo in 1957 [10], could explain the discrepancy while allowing conservation of lepton number and lepton flavor in interactions (particles and antiparticles have opposite signs of these numbers). Pontecorvo suggested the possibility that a neutrino oscillates between flavors as it travels freely, not interacting with anything! In other words, a ν_e traveling freely might change into a ν_μ, then into a ν_τ, or back into a ν_e. *This is a coupled oscillator problem*. The coupling and the frequency of this oscillation depend on two neutrino species having a mass *difference.*

To model this business mathematically, the moment of epiphany comes with realizing that when *propagating freely* the neutrino state is a *mass* eigenstate, but when *interacting* the neutrino state is a *flavor* eigenstate. The flavor eigenstates are what we mean when saying a neutrino is an electron neutrino ν_e, or a muon neutrino ν_μ, or a tau neutrino ν_τ. The mass eigenstates are superpositions of the flavor eigenstates, and, conversely, the flavor eigenstates are superpositions of mass eigenstates—which means that "the" mass of a ν_e or ν_μ or ν_τ particle is not well defined. Be that as it may, the mass and flavor eigenstates form two complete sets of basis vectors in the abstract space of all neutrino states. We will consider the role of neutrino mass in flavor-changing from two perspectives: (1) as an eigenvalue problem, and (2) from a rotation-of-axes perspective. Of course, the approaches are two ways of doing the same thing, but it may be instructive to examine both, not only for our understanding of neutrinos, but also to deepen our appreciation of what eigenvectors and eigenvalues are all about.

(1) Neutrino state eigenvectors

For simplicity, let's consider only two neutrino species. Begin with two mass eigenstates: neutrino state ν_1 carries a definite mass m_1, and neutrino state ν_2 carries a definite mass m_2. To reiterate, these neutrinos do not have a unique flavor; they are superpositions of two flavors.

The quantum wave function $\nu_n(t)$ of a freely propagating neutrino may be written with the usual quantum phase factor for a free particle of momentum *p* and energy *E* where, assuming for simplicity that the particle moves in only one spatial dimension *x*,

$$\nu_n(t) = A_n e^{i(px - Et)/\hbar} \quad (47)$$

where *n* = 1 or 2, and where A_n is a constant.

Since the neutrino masses are very small if not zero, we may assume these particles move through the lab frame with speeds $v \approx c$. Therefore $x \approx ct$. The momentum *p* can be extracted from the relativistic energy-momentum relation for a free particle,

$$E^2 - (pc)^2 = (mc^2)^2. \quad (48a)$$

Since *m* is small, using a binomial expansion gives

$$E \approx pc + \frac{(mc^2)^2}{2pc} \tag{48b}$$

and again, since *m* is small, we may use $p \approx E/c$ in the denominator of Eq. (48b):

$$E \approx pc + \frac{(mc^2)^2}{2E}. \tag{48c}$$

In solving Eq. (48c) for *p* and recalling $x \approx ct$, Eq. (47) becomes

$$\nu_n(t) \approx A_n e^{-i\omega_n t} \tag{49}$$

where

$$\omega_n \equiv \frac{(m_n c^2)^2}{2E\hbar}. \tag{50}$$

These two neutrino states, each of definite mass, can be arranged as a vector in the abstract space inhabited by two neutrino species. In the two-dimensional "mass basis" an arbitrary neutrino state is

$$|\nu_{mass}\rangle = \begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}A_1 e^{-i\omega_1 t}\\ A_2 e^{-i\omega_2 t}\end{pmatrix}. \tag{51}$$

Requiring all the mass to reside *somewhere* among neutrino species 1 and 2 gives the constraint

$$\langle \nu_{mass}|\nu_{mass}\rangle = 1 \tag{52a}$$

which with Eq. (51) yields

$$|A_1|^2 + |A_2|^2 = 1 \tag{52b}$$

so the A_n can be parameterized as

$$A_1 = \cos\theta \tag{52c}$$

$$A_2 = \sin\theta \tag{52d}$$

for some real number θ.

We are saying that the state of a freely propagating neutrino is an eigenstate of a Hamiltonian H_{free} whose eigenvalues include the masses m_n. That Hamiltonian would be

$$H_{free} = \hbar\begin{pmatrix}\omega_1 & 0\\ 0 & \omega_2\end{pmatrix} \tag{53}$$

because in the Schrödinger equation the states of Eq. (49) give $H_{free}|\nu_n\rangle = \hbar\omega_n|\nu_n\rangle$.

The neutrinos of definite flavor in the weak interactions, ν_e, ν_μ, and ν_τ, are not eigenstates of H_{free}. They can, however, be written as superpositions of the definite-mass neutrino eigenstates. Considering that we are using only two neutrino species, say ν_e and ν_μ [11], using Eqs. (51) and (52c-d) we may write for the electron neutrino

$$\nu_e(t) = a_1\nu_1(t) + a_2\nu_2(t)$$

$$= a_1\cos\theta\, e^{-i\omega_1 t} + a_2\sin\theta\, e^{-i\omega_2 t} \tag{54a}$$

and for the muon neutrino

$$\nu_\mu(t) = b_1\cos\theta\, e^{-i\omega_1 t} + b_2\sin\theta\, e^{-i\omega_2 t} \tag{54b}$$

where a_n and b_n are constants.

These neutrino states, along with $\nu_\tau(t)$, are flavor eigenstates of the weak-interaction Hamiltonian. The weak interactions can preserve flavor, such as

$$\mu^+ + \mu^- \to \nu_\mu + \bar{\nu}_\mu \tag{55a}$$

or they can change flavor without violating any lepton flavor conservation laws (the particle and antiparticles of the same flavor have opposite-sign lepton numbers), such as

$$\mu^+ + \mu^- \to \nu_e + \bar{\nu}_e. \tag{55b}$$

For generic interactions that allow both flavor-preserving and flavor-changing events, we can parameterize the neutrino interaction Hamiltonian (still in two-dimensional neutrino state space) as

$$H_{int} = \begin{pmatrix}H_{ee} & H_{e\mu}\\ H_{\mu e} & H_{\mu\mu}\end{pmatrix} \equiv \begin{pmatrix}\alpha & \beta\\ \beta & \alpha\end{pmatrix}. \tag{56}$$

These matrix elements will depend on the weak force parameters such as the Fermi coupling constant G_F. The diagonal elements describe weak interactions that preserve lepton flavor, such as the reaction of (55a) and scattering events like $\nu_e + e^- \to \nu_e + e^-$. The off-diagonal elements describe weak interactions where the incoming and outgoing neutrinos have different flavors, such as reaction (55b) or $\nu_e + e^+ \to \nu_\mu + \mu^+$. But note that we have seen this sort of Hamiltonian before.

To find out what the a_n and b_n in Eqs. (54) are, the eigenvalue problem for H_{int} falls readily to hand, because its eigenvectors are the electron and muon neutrinos.

To proceed, for the Hamiltonian of Eq. (56) we parameterize its eigenstates as

$$|\nu_{int}\rangle = \begin{pmatrix}p\\ q\end{pmatrix} e^{-i\lambda t/\hbar} \tag{57}$$

where p and q are independent of time. Now the Schrödinger equation becomes

$$H_{int}|\nu_{int}\rangle = \lambda|\nu_{int}\rangle. \quad (58)$$

Our task is to find the eigenvalues λ through the application of the theorem of alternatives and then use these eigenvalues in Eq. (58) to find the eigenvectors normalized to unit magnitude. But this is mathematically identical to the ammonia molecule problem, so we have done this before. It follows that $\lambda = \alpha \pm \beta$, and the corresponding normalized time-independent portion of the eigenvectors of Eq. (51) are

$$\binom{p}{q}_{\lambda=\alpha+\beta} = \frac{1}{\sqrt{2}}\binom{1}{1} \quad (59a)$$

and

$$\binom{p}{q}_{\lambda=\alpha-\beta} = \frac{1}{\sqrt{2}}\binom{1}{-1}. \quad (59b)$$

Let us suppose that the $\alpha + \beta$ eigenvalue belongs to the electron neutrino. This means that Eqs. (59a) and (54a) at t = 0 are the same state, so that

$$\frac{1}{\sqrt{2}}\binom{1}{1} = \binom{a_1 \cos\theta}{a_2 \sin\theta} \quad (60)$$

and therefore $\frac{1}{\sqrt{2}} = a_1\cos\theta$ and $\frac{1}{\sqrt{2}} = a_2\sin\theta$, suggesting as *a* solution (not *the* unique solution, remember the theorem of alternatives) $a_2 = a_1 \equiv a$, which then requires $\sin\theta = \cos\theta = 1/\sqrt{2}$ and $\theta = \pi/4$. Restoring the time dependence by letting t be nonzero in Eq. (54a), we have the electron neutrino wave function expressed as superpositions of the mass eigenstate wave functions:

$$\nu_e(t) = \frac{a}{\sqrt{2}}(e^{-i\omega_1 t} + e^{-i\omega_2 t}). \quad (61a)$$

Carrying out the same procedure by identifying the $\alpha - \beta$ eigenvalue with the muon-type neutrino produces

$$\nu_\mu(t) = \frac{b}{\sqrt{2}}(e^{-i\omega_1 t} - e^{-i\omega_2 t}). \quad (61b)$$

Given the $1/\sqrt{2}$ in both flavor eigenstates, it appears that in the abstract space of neutrino states the flavor eigenstates are rotated by 45 degrees relative to the mass eigenstates. Let

$$\omega_2 = \omega_1 + \delta. \quad (62)$$

Then the flavor eigenstates can be written

$$\nu_e(t) = \sqrt{2}\, a\, e^{-i(\omega_1 + \delta/2)t} \cos\left(\frac{\delta t}{2}\right) \quad (63a)$$

$$\nu_\mu(t) = \sqrt{2}\, ibe^{-i(\omega_1 + \delta/2)t} \sin\left(\frac{\delta t}{2}\right). \quad (63b)$$

The probability of a neutrino being an electron neutrino at time t is

$$P_e(t) = |\nu_e|^2 = 2a^2\cos^2\left(\frac{\delta x}{2c}\right) \quad (64a)$$

and the probability of it being a muon neutrino at time t is

$$P_\mu(t) = |\nu_\mu|^2 = 2b^2\sin^2\left(\frac{\delta x}{2c}\right). \quad (64b)$$

If these were the only two neutrino flavors, then as long as the neutrino exists,

$$1 = P_e(t) + P_\mu(t) = 2(a^2 + b^2) \quad (65)$$

or $a^2 + b^2 = ½$, which allows these coefficients to be parameterized as $a = \frac{1}{\sqrt{2}}\cos\phi$ and $b = \frac{1}{\sqrt{2}}\sin\phi$ for some angle ϕ to be fit to data.

(2) Rotation of axes

Return to the concept that any two neutrino flavor states are a superposition of states of definite mass:

$$\binom{\nu_e}{\nu_\mu} = \begin{pmatrix} a_1 & a_2 \\ b_1 & b_2 \end{pmatrix}\binom{\nu_1}{\nu_2} \quad (66)$$

which can be abbreviated as

$$|\nu_{flavor}\rangle = \Lambda|\nu_{mass}\rangle \quad (67)$$

where

$$|\nu_{flavor}\rangle = \binom{\nu_e}{\nu_\mu} \quad (68a)$$

$$|\nu_{mass}\rangle = \binom{\nu_1}{\nu_2} \quad (68b)$$

and Λ is the square matrix in Eq. (66). So long as the neutrino exists—whatever its flavor and mass—we require

$$\langle\nu_{flavor}|\nu_{flavor}\rangle = \langle\nu_{mass}|\nu_{mass}\rangle. \quad (69)$$

The adjoint (denoted with †, the transpose and complex conjugate) of Eq. (66) gives

$$\langle\nu_{flavor}| = \langle\nu_{mass}|\Lambda^\dagger. \quad (70)$$

Now Eq. (69) becomes

$$\langle \nu_{mass} | \Lambda^{\dagger}\Lambda | \nu_{mass} \rangle = \langle \nu_{mass} | \nu_{mass} \rangle \quad (71)$$

which requires

$$\Lambda^{\dagger}\Lambda = \tilde{1} \quad (72a)$$

(one says that Λ is "unitary"), which in detail requires

$$\begin{pmatrix} a^*_1 & b^*_1 \\ a^*_2 & b^*_2 \end{pmatrix}\begin{pmatrix} a_1 & a_2 \\ b_1 & b_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}. \quad (72b)$$

This condition implies

$$|a_1|^2 + |a_2|^2 = 1 \quad (72c)$$

$$|b_1|^2 + |b_2|^2 = 1 \quad (72d)$$

and

$$a^*{}_2 a_1 + b_1 b^*{}_2 = 0. \quad (72e)$$

All of these constraints are consistent with

$$\Lambda = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \quad (73)$$

Now Eq. (66), informed by Eq. (73) and with Eq. (49) showing the time dependence explicitly, becomes

$$\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_1(0)e^{-i\omega_1 t} \\ \nu_2(0)\, e^{-i\omega_2 t} \end{pmatrix}. \quad (74)$$

The transformation from neutrino states of definite mass to states of definite flavor is merely a rotation of axes in the abstract two-dimensional space of neutrino states.

Our goal is to predict the probability that a neutrino which begins its life at time $t = 0$ as an electron neutrino will turn into a muon neutrino at time $t > 0$. In other words, we intend to calculate $|\langle \nu_\mu(t)|\nu_e(0)\rangle|^2$. To prepare the way, the time dependence of the mass eigenstates can be factored out of Eq. (74) as follows:

$$\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} e^{-i\omega_1 t} & 0 \\ 0 & e^{-i\omega_2 t} \end{pmatrix}\begin{pmatrix} \nu_1(0) \\ \nu_2(0) \end{pmatrix}. \quad (75a)$$

This gives, at $t = 0$, the relation

$$\begin{pmatrix} \nu_e(0) \\ \nu_\mu(0) \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_1(0) \\ \nu_2(0) \end{pmatrix} \quad (75b)$$

[which could be shown from Eq. (74), but the matrix with the exponential elements will prove useful]. In other words,

$$|\nu_{flavor}(0)\rangle = \Lambda |\nu_{mass}(0)\rangle \quad (76a)$$

from which it follows that

$$\Lambda^{-1}\, |\nu_{flavor}(0)\rangle = |\nu_{mass}(0)\rangle. \quad (76b)$$

From Eq. (72a) we see that $\Lambda^{-1} = \Lambda^{\dagger}$, therefore

$$\Lambda^{\dagger} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}. \quad (77)$$

Now we can write $|\nu_{flavor}(t)\rangle$ in terms of $|\nu_{flavor}(0)\rangle$. Putting Eqs. (75a), (76b), and (77) together, we have

$$\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \end{pmatrix} = \Lambda \begin{pmatrix} e^{-i\omega_1 t} & 0 \\ 0 & e^{-i\omega_2 t} \end{pmatrix} \Lambda^{\dagger} \begin{pmatrix} \nu_e(0) \\ \nu_\mu(0) \end{pmatrix}. \quad (78)$$

Writing out the matrix multiplication is a bit of work; to simplify the result it helps to use Eq. (62), $\omega_2 = \omega_1 + \delta$. The top component of Eq. (78) is, in Dirac bracket notation,

$$|\nu_e(t)\rangle = e^{-\omega_1 t}\left[U|\nu_e(0)\rangle - i\sin(2\theta)\sin\left(\frac{\delta t}{2}\right)|\nu_\mu(0)\rangle\right] \quad (79a)$$

where $U \equiv \cos^2\theta + e^{i\delta t}\sin^2\theta$. The bottom component of Eq. (78) is

$$|\nu_\mu(t)\rangle = e^{-\omega_2 t}\left[-i\sin 2\theta \sin\left(\frac{\delta t}{2}\right)|\nu_e(0)\rangle + U|\nu_\mu(0)\rangle\right]. \quad (79b)$$

Let a neutrino start out as an electron neutrino at $t = 0$. The amplitude for it to become a muon neutrino at time $t > 0$ follows by multiplying $\langle \nu_\mu(t)|$ of Eq. (79b) with $|\nu_e(0)\rangle$ and using the orthonormality of the flavor states; therefore,

$$\langle \nu_e(0)|\nu_\mu(t)\rangle = ie^{i\zeta t}\sin(2\theta)\sin\left(\frac{\delta t}{2}\right) \quad (80a)$$

where $\zeta = \omega_1 + \frac{\delta}{2}$. The corresponding probability follows,

$$P_{e\to\mu}(t) = \sin^2(2\theta)\sin^2\left(\frac{\delta t}{2}\right). \quad (80b)$$

Similarly, the probability for a neutrino that is a muon neutrino at $t = 0$ to become an electron neutrino at $t > 0$ is

$$P_{\mu\to e}(t) = |\langle \nu_e(t)|\nu_\mu(0)\rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{\delta t}{2}\right). \quad (80c)$$

If $\delta \neq 0$, in other words, if $m_1 \neq m_2$, then *electron neutrinos and muon neutrinos can change back and forth into each other—neutrino oscillations occur* [11]. The spatial period of the oscillation—how far a neutrino travels before it changes from one flavor to the other—can be found by using $t = x/c$ to convert the neutrino's travel time to the distance traveled. The wavelength λ of the oscillation can then be read off the phase in Eqs. (80), recognizing $\delta/2c$ as a wavenumber $k = 2\pi/\lambda$, which gives

$$\frac{\delta}{2c} = \frac{2\pi}{\lambda}. \quad (81a)$$

From Eq. (62), $\delta = \omega_2 - \omega_1$, which by Eq. (50) says

$$\delta = \frac{1}{2E\hbar}[(m_2c^2)^2 - (m_1c^2)^2]. \quad (81b)$$

Now Eq. (81a) gives, for the distance between neutrino flavor-changing events,

$$\lambda = 8\pi\hbar c\left(\frac{E}{(m_2c^2)^2 - (m_1c^2)^2}\right) \approx 1\times10^{-5}\text{ m eV}\left(\frac{E}{(m_2c^2)^2 - (m_1c^2)^2}\right). \quad (81c)$$

Data for electron- and muon-type neutrinos says $(m_2c^2)^2 - (m_1c^2)^2 \approx 7.5\times10^{-5}\text{ eV}^2$. At $E = 20\text{ MeV}$, these numbers give in Eq. (81c) a distance $\lambda_{e\leftrightarrow\mu}$ = 1300 km (780 miles) for electron-muon oscillations. The value of $(m_2c^2)^2 - (m_1c^2)^2$ for muon- and tau-type neutrinos is $2.4\times10^{-3}\text{ eV}^2$, which at 20 MeV gives $\lambda_{\mu\leftrightarrow\tau}$ = 32 m. Data suggest that the mixing angle θ for electron-muon neutrino oscillations is about $33.9°$ and about $45°$ for muon-tau oscillations [12].

How to Catch a Neutrino

The Reines-Cowan and Davies experiments were sensitive to electron-type neutrinos. Other options were soon forthcoming. In 1974 Howard Georgi and Sheldon Glashow and others predicted proton decay as a consequence of "grand unified" theories, which put quarks and leptons in a common family and allowed transitions between them. These theories predict a proton lifetime on the order of 10^{31} years. We can't wait for 10^{31} years to see if a proton decays in the reaction $p \to e^+ + \pi^0$, but in a collection of 10^{31} protons, there should be about one decay per year. A thousand tons of matter would have about 5×10^{32} protons and, if the theory is correct, about 50 of them per year should decay [13]. Assemble a thousand tons of transparent matter (pure water), surround it with photomultiplier tubes, and watch for the Cherenkov radiation (light emitted by a charged particle moving at the speed *v*, where *c/n* < *v* < *c* with *n* the medium's refractive index), a "shock wave" cone of light that can be detected by photomultiplier tubes.

Several such detectors were built in the early 1980s, but the idea was not new. In 1954 Frederick Reines, Clyde Cowan, and Maurice Goldhaber, using part of the detector with which they detected the antineutrino two years later, put a lower bound of 10^{22} years on proton decay, and a 1974 proposal by Reines and William Kropp presciently envisioned a 10-kiloton proton decay detector—which was turned down for "lack of theoretical motivation" at that time [14]. Subtracting neutrino backgrounds offered a serious challenge to these experiments; for example, elastic scattering of neutrinos by electrons, $\nu_e + e^- \to \nu_e + e^-$, could produce an electron with enough energy to emit Cherenkov radiation.

So far proton decay has not been observed. But with such massive detectors in place that are sensitive to neutrino events, serendipitous results ensued. In 1998 a group working with a detector deep in a mine in Kamiokande, Japan, first published evidence for oscillations in "atmospheric neutrinos" [15], neutrinos produced when cosmic rays from the sun collide with nuclei in the upper atmosphere to produce muons and muon neutrinos. The discovery was made by "Super-Kamiokande," which uses Earth's diameter as a baseline: solar or atmospheric neutrinos pass through us from above in the daytime and come up through the floor at night. Super-Kamiokande reported, "The number of the upward going neutrinos was only half of the number of the down going neutrinos. This is because the muon neutrinos passing through the earth turn into tau neutrinos" [14] (recall that the muon-tau oscillation length is quite short). Super-Kamiokande produced the first hard evidence for $\mu - \tau$ neutrino oscillations in *atmospheric* neutrinos but not conclusive verification of oscillations in *solar* neutrinos.

In 1984 the neutrino detection story took another turn when Herb Chen pointed out the advantages of using hydrogen-2 as the detector medium [16]. In a charged current interaction (similar to the Homestake reaction, but with deuterons instead of chlorine nuclei), the neutrino collides with the neutron in hydrogen-2, turning it into a proton and electron: $\nu_e + \mathrm{H}_1^2 \to p + p + e^-$. Since *E* < 20

MeV for solar neutrinos and the muon mass = 106 MeV/c^2, only electron neutrinos participate here, although this reaction is detectable since the electron carries 5–15 MeV of energy. But there is also a neutral current interaction that can proceed with any lepton flavor:

$$\nu_\rho + \mathrm{H}_1^2 \to n + p + \nu_\rho \tag{82}$$

where $\rho = e, \mu$, or τ. This possibility led to the founding of the Solar Neutrino Observatory (SNO) near Sudbury, Ontario. SNO is a 12-meter-diameter acrylic sphere containing 1000 tons of heavy water, surrounded by photomultiplier tubes to detect Cherenkov radiation. The heavy water was loaned to the experiment by Atomic Energy of Canada. The sphere containing heavy water was surrounded by another sphere containing ordinary water.

In a reaction (82) the neutron that emerges can react with a second deuteron to make helium-3 and a 6 MeV photon: $n + \mathrm{H}_1^2 \to \mathrm{He}_3^3 + \gamma\ (6\ \mathrm{MeV})$. One could collect the helium (analogous to how the Homestake experiment collected the noble gas argon), but the photons are detected immediately by the array of photomultiplier tubes. Neutrons that escape the heavy water sphere enter the shell of ordinary water, where some of them collide with hydrogen-1 to drive the reaction $n + \mathrm{H}_1^1 \to \mathrm{H}_1^2 + \gamma(2.2\ \mathrm{MeV})$ to produce more signals for the photomultiplier tubes. The SNO results of 2001 were firm evidence for neutrino oscillations in solar neutrinos [17].

The 2015 Nobel Prize in Physics was awarded to Arthur McDonald, director of SNO, and Takaaki Kajita, leader of the group at Kamiokande, for the observation of neutrino oscillations. The humble coupled oscillator touches a lot of physics!

References

[6] The energies released in beta decays tend to be a few MeV. Compared to the electron's mass of 0.511 MeV/c^2, one might want to use the relativistic expression for the electron's kinetic energy when relating it to momentum, whereas the neutron and proton masses are ≈ 1 GeV/c^2, so Newtonian kinetic energy can be used for them.

[7] "The Reines-Cowan Experiments: Detecting the Poltergeist," *Los Alamos Sci*. 25 (1997): 4–27. See https://library.lanl.gov/cgi-bin/getfile?00326606.pdf. The title refers to experiments in the plural because it also gives a thorough description of Reines's original idea (1951) to bury a neutrino detector deep under ground zero of a nuclear bomb test site.

[8] The three families or "flavors" of quarks are the "up" *u* and "down" *d;* "charm" *c* and "strange" *s*; and "top" *t* and "bottom" *b*. Ordinary matter (what we see on the Periodic Table) is made of "first-generation" quarks and leptons: *u* and *d* quarks (proton = *uud*, neutron = *ddu*), and the leptons e^- and ν_e. The second generation consists of *c, s*, and the muon and ν_μ; the third generation of *t, b,* and the tau and ν_τ.

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[12] Data from K. A. Olive et al., *Particle Data Group* (2010). These figures (rounded) are also presented in Paul Tipler and Robert Llewellyn, *Modern Physics* (San Francisco: Freeman, 2008), 610.

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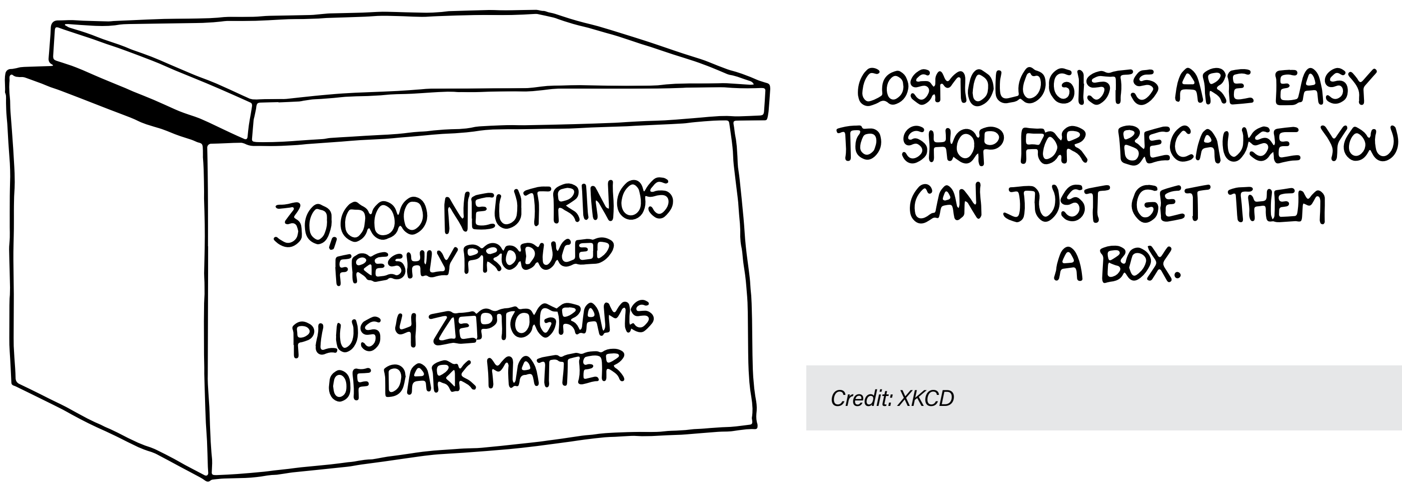
[17] SNO's homepage: https://falcon.phy.queensu.ca/SNO/. See also https://en.wikipedia.org/wiki/Sudbury_Neutrino_Observatory.



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