Opportunities in Nuclear, Particle and Astrophysics

Examples of China-US Collaborations

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University of Wisconsin &
APS Committee on International Scientific Affairs
"... One day in the early Spring of 1956, Professor T. D. Lee came up to my little office on the thirteenth floor of Pupin Physical Laboratories. He explained to me, first, the $\tau$-$\theta$ puzzle. If the answer to the $\tau$-$\theta$ puzzle is violation of parity—he went on—then the violation should also be observed in the space distribution of the beta-decay of polarized nuclei: one must measure the pseudo-scalar quantity $\langle \sigma \cdot p \rangle$ where $p$ is the electron momentum and $\sigma$ the spin of the nucleus.
Discovery of Parity Violation

Between experimental runs in Washington, I had to dash back to Columbia for teaching and other research activities. On Christmas eve, I returned to New York on the last train; the airport was closed because of heavy snow. There I told Professor Lee that the observed asymmetry was reproducible and huge. The asymmetry parameter was nearly -1. Professor Lee said that this was very good. This result is just what one should expect for a two-component theory of the neutrino.
Neutrinos are the most abundant particles in the Universe besides photons.
Matter in the Universe

- Dark Energy: 70%
- Dark Matter: 25%
- Heavy Elements: 0.03%
- Ghostly Neutrinos: ~0.3%
- Free Hydrogen and Helium: 4%
- Stars: 0.5%
Neutrinos and the Early Universe

- 380,000 yrs ago
- Now

Diagram showing the evolution of the universe from the Big Bang to the present day, with key stages labeled: Big Bang, Inflation, Quark Soup, Big Freeze Out, Parting Company, First Galaxies, Modern Universe.
Matter - Antimatter in the Universe

- Big Bang
- Inflation
- Quark Soup
- Big Freeze Out
- Parting Company
- First Galaxies
- Modern Universe

Radius of the Visible Universe:
- 0
- $10^{-32}$ Sec.
- 1 Second
- 300,000 Years
- 1 Billion Years
- 12-15 Billion Years

Age of the Universe:

Matter vs. Antimatter:
- 10,000,000,000
- 10,000,000,000
- US
- 1

Matter
- Anti-Matter
Quantum Universe

• Are there undiscovered principles of nature: new symmetries, new physical laws?
• What is dark matter?
• What are neutrinos telling us?
• What happened to the antimatter?

Exploring the Heart of Matter

• What is the structure of matter?
Signs of Dark Matter

Rotation Curve of Galaxies

Gravitational Lensing

Bullet Cluster Merger

Large Scale Structure Formation & CMB Spectrum

DAMA annual modulation - DM Signal?
A World of Dark Matter Searches

Homestake:
- LUX

Soudan:
- CDMS
- CoGeNT

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- CDMS
- CoGeNT

Canfranc:
- ANAIS
- ArDM
- Rosebud

SNOLAB:
- DEAP/CLEAN
- PICASSO
- COUPP

Boulby:
- DRIFT

Modane:
- EDELWEISS

Kamioka:
- XMASS

YangYang:
- KIMS

Jinping:
- Panda-X
- CDEX

South Pole:
- DM-ICE

Gran Sasso:
- CRESST
- DAMA/LIBRA
- DarkSide
- XENON
- WARP

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A World of Dark Matter Searches

The only “underground” laboratory in the Southern Hemisphere

JinPing:
- Panda-X
- CDEX

South Pole:
- DM-ICE

The deepest underground laboratory in the world
DM-Ice Dark Matter Search

A Direct Detection Experiment

WIMP-nucleon scattering, look for nuclear recoil

Test the DAMA Annual Modulation Signal with an experiment in the Southern Hemisphere.

500 kg-year NaI detector sensitivity
(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.

Use same target material NaI(Tl)

DM-Ice sensitivity
DM-Ice Dark Matter Search

A Direct Detection Experiment

WIMP-nucleon scattering, look for nuclear recoil

\[
\text{WIMP} \rightarrow \text{nuclear recoil}
\]

Detector

250–500 kg NaI(Tl), loosely-packed inside pressure vessel for coincidence veto, R&D with SICCAs

Location

South Pole, ~ 2500 m deep in the ice, near the center of IceCube for additional veto, Antarctic support through United States Polar Program and NSF

arXiv:1106.1156
Direct Detection Dark Matter Search

- A multi-stage liquid Xe based Dark Matter experiment at China JinPing Lab (location: Sichuan Province)
- Deepest dark matter facility, covered with 2,500m of marble
- PandaX-1: Time Projection Chamber (TPC) design optimized for low mass dark matter
- PandaX-2: increase the fiducial mass: optimized for large mass dark matter
PandaX-1a:
• exposure: 25 kg x 300 days
• start Nov 2012

PandaX-2 (ton-scale):
• exposure: 1,200 kg x 600 days
• start 2015

MOU between U-M & SJTU
signed in September 2011

Member institutions:
• Shanghai Jiao Tong University (SJTU)
• Shanghai Institute of Applied Physics
• Shandong University
• Peking University
• University of Michigan (U-M)

first US collaborators at Jinping Laboratory
Search for Neutrinoless Double Beta Decay

Understanding the Nature of Neutrino Mass with $0\nu\beta\beta$

Are neutrinos their own antiparticles? Are neutrinos Majorana particles?

Observation of $0\nu\beta\beta$ would indicate lepton number violation

Experimental Signature of $0\nu\beta\beta$
- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable $2\nu\beta\beta$ background
Search for Neutrinoless Double Beta Decay

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$Q = (2527.518 \pm 0.013) \text{ keV}$

$(^{130}\text{Te}) \geq 2.8 \times 10^{24} \text{ y (90\% C.L.)}$

probing livetimes longer than age of Universe
CUORE Search for $0\nu\beta\beta$

Cryogenic Underground Observatory for Rare Events

Source = Detector

Bolometric Search with $^{130}\text{Te}$

Use as calorimeter to watch for events of energy $E=Q_{\beta\beta}$

packed array of 988 bolometers with ~ 200 kg of $^{130}\text{Te}$

- Operated at Gran Sasso laboratory
- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator operated at ~ 10mK
- Shielded by several lead shields

TeO$_2$ crystals developed by

- Good energy resolution
- Large source mass
- High efficiency
Towards Future Bolometric 0νββ Experiments

### Sensitivities at 1σ after 5 years of livetime

<table>
<thead>
<tr>
<th>Configuration</th>
<th>bkg [c/keV/kg/y]</th>
<th>(T_{1/2}^{1\sigma}) [10^{26} y]</th>
<th>(m_\nu) [1σ sens] [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoricino</td>
<td>0.18</td>
<td>0.029 (90%CL)</td>
<td>350-720</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoricino + CUORE-0</td>
<td>0.06</td>
<td>0.12* (90%CL)</td>
<td>170-350*</td>
</tr>
<tr>
<td>CUORE baseline</td>
<td>0.01</td>
<td>2.0</td>
<td>42-87</td>
</tr>
<tr>
<td>R&amp;D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUCIFER (ZnSe 95% enrich)</td>
<td>0.001</td>
<td>2.7</td>
<td>42-89</td>
</tr>
<tr>
<td>CUORE 80% enriched</td>
<td>0.01</td>
<td>4.7</td>
<td>27-57</td>
</tr>
<tr>
<td>CUORE enriched w/ TeO₂ SSB</td>
<td>0.001</td>
<td>14</td>
<td>16-33</td>
</tr>
<tr>
<td>CdWO₄ enriched 1000 crystals</td>
<td>0.001</td>
<td>8</td>
<td>21-29</td>
</tr>
<tr>
<td>ZnSe enriched 1000 crystals</td>
<td>1e-4</td>
<td>41</td>
<td>11-23</td>
</tr>
</tbody>
</table>

EXO 1ton w/ Ba⁺ tagging: \(<m_{\beta\beta}> < 12 - 25 \text{ meV (1}\sigma\rangle \) (*) after 2 years live time

Majorana/GERDA 1-ton: \(<m_{\beta\beta}> < 15 - 38 \text{ meV (1}\sigma\rangle \)  

Crystal R&D critical for potential upgrade options of CUORE
Tonne Scale $^{76}$Ge $0\nu\beta\beta$

Majorana (US)

- $^{76}$Ge offers an excellent combination of capabilities and sensitivities.
- Two international collaborations, GERDA and MAJORANA, are currently involved in $^{76}$Ge based measurements. Cooperative Agreement to jointly pursue a future tonne scale experiment.
- Collectively GERDA and MAJORANA will show feasibility for proceeding towards tonne-scale experiment.

GERDA (Europe)

Have held discussions with Chinese groups about their interest in joining a potential future experiment. → SJTU recently hired junior faculty
Depth and Shielding for Tonne scale $^{76}\text{Ge}$ $0\nu\beta\beta$

Depth of Underground Laboratories

- **In-situ** production and decay of unstable isotopes in Ge and Ar are the limiting depth-dependent backgrounds for GERDA.
- Cosmogenic decays of $^{77}\text{mGe}$ predominantly by pure $\beta$-emission, can be difficult to reject with analysis cuts.

Depth is an important factor in reducing backgrounds.

China’s Jinping Underground Laboratory (7500 mwe) significantly deepest lab worldwide.

(c.f. Gran Sasso (3300 mwe), Homestake (4100 mwe), SNOLAB (6000 mwe))

Conceptual laboratory and shield designs for tonne scale $^{76}\text{Ge}$
g-2 Experiment

Measure the muon anomalous magnetic moment to 0.14 ppm

BNL E821

Future Goals

Goal: 0.14 ppm

Expected Improvement

2010 e⁺e⁻ Thy

• New team built from E821 experts, augmented by significant new strengths
• Obtain more muons
  • x10 µ/p
  • x20 stat/year
• Control systematic errors

Shanghai Institute of Ceramics makes most of the world’s PbW04 and PbF2 and other crystals. Consider use of PbF2 in new experiment g-2.

SJTU faculty involved
Exploring Nuclear Structure

Solenoidal Large Intensity Device (SoLID)

**International collaboration** (8 countries, 50+ institutes and 190+ collaborators)
- Rapid Growth in US-China Collaboration (2 grants from NSFC + MOU)
- Chinese Hadron collaboration (USTC, CIAE, PKU, Tsinghua U, +)
  - large GEM trackers
  - MRPC-TOF

Five experiments approved for SoLID with two having Chinese collaborators as co-spokesperson (Li from CIAE and Yan from USTC)
Parity-violating Deep Inelastic Scattering:
- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins over large range kinematics
- Test of Standard Model
- Quark structure:
  - charge symmetry violation
  - quark-gluon correlations

Parity Violation with SoLID

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} \left[ a(x) + Y(y) b(x) \right] \]

- \( b(x) \): weak coupling
- \( a(x) \): quark structure information

Exploring Nuclear Structure
SoLID Collaborators from China

1. China Institute of Atomic Energy
2. University of Science and Technology of China
3. Huang Shan Xue Yuan
4. Huazhong University of Science and Technology
5. Peking University
6. Institute of High Energy Physics Chinese Academy of Sciences
7. Tsinghua University
8. Institute of Modern Physics Chinese Academy of Sciences
9. Shandong University
International Nature of Physics and New Scientific Opportunities

• China and the US both pursue research at the frontiers of particle, nuclear, and astrophysics.
• Unique expertise and facilities create opportunities for collaboration.
• International collaboration have enabled recent discoveries.
• Exchange and partnership are the basis for future endeavors, and we look forward to creating future scientific opportunities.