Center for Ultra-Low Background Experiments at DUSEL

Barbara Szczerbinska (DSU)

For CUBED Collaboration

Collaboration List

- **Senior Investigators (total: 19):**

1: The University of South Dakota (Y. Sun, C. Keller, D. Mei, C. Yang, V. Guiseppe)
2: South Dakota State University (R. McTaggart, J. Rauber)
3. Dakota State University (B. Szczerbinska)
4. South Dakota School of Mines & Technology (W. M. Roggenthen, D. Medlin, S. Howard, H. Hong, A. Petukhov, Xinhua Bai)
5. Augustana College (A. Alton)
6. Black Hills State University (M. Zehfus, K. Keeter, Dan Durben)
7. Sanford Lab (J. Heise)

- **Advisory committee (Chair: Yuen-Dat Chan)**

1. Los Alamos National Laboratory (S. Elliott)
2. Lawrence Berkeley National Laboratory (K. Lesko, Y-D. Chan)
3. University of North Carolina (J. Wilkerson)
4. Princeton University (C. Galbiati)
5. Brown University (R. Gaitskell)
6. Sanford Lab (J. Alonso)

- **Involved National Collaborations:**

1. Majorana Collaboration
2. LUX Collaboration
3. MAX Collaboration

Collaboration Picture
(The first collaboration meeting in May 19-20th 2009)

CUBED Mission

- Bring together the current South Dakota faculty to develop a critical mass of expertise necessary for SD's full participation in large-scale collaborations planned for DUSEL
- Increase the number of research faculty members in South Dakota to complement and supplement existing expertise in nuclear physics and materials sciences
- Train and educate undergraduate and graduate students as a way to develop the scientific workforce of the state

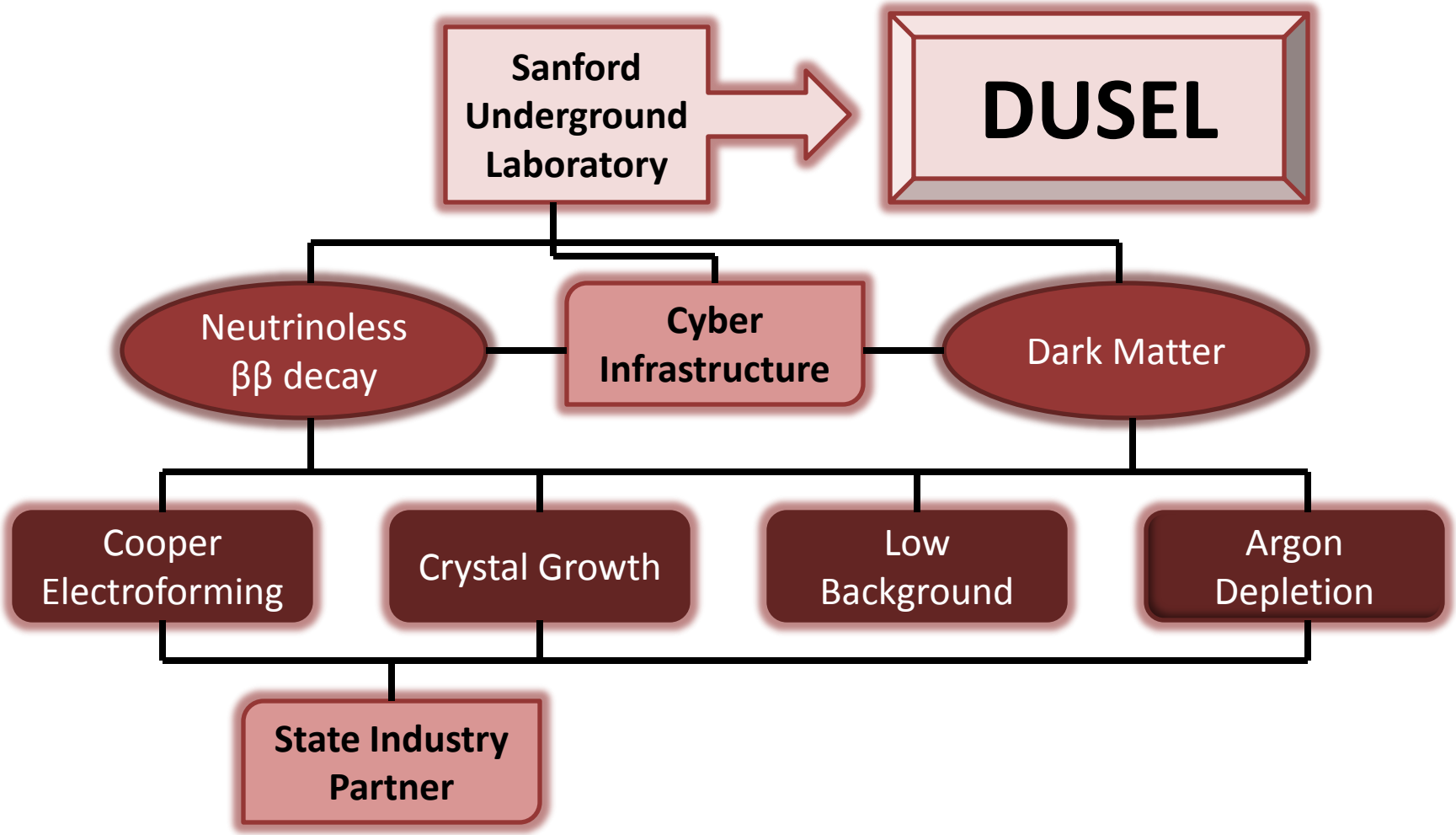
CUBED Research Objectives

- **Low background counting facility driven by physics, biomedical research, Homeland security**

- **Super clean materials production demanded by DUSEL projects:**
  - Underground Crystal Growth
  - Underground Copper Electroforming
  - Purification/Depletion of Noble Gases

- **P5 (Particle Physics Project Prioritization Panel) Report research foci**
  - Detection of neutrinoless double beta decay (High Purity Germanium)
  - Direct detection of dark matter (Argon & Xenon)

Road Map


Sanford Underground Laboratory
DUSEL
Neutrinoless ββ decay
Cyber Infrastructure
Dark Matter
Cooper Electroforming
Crystal Growth
Low Background
Argon Depletion
State Industry Partner

P5 Report - Chapter 4 - The Deep Underground Science and Engineering Lab DUSEL – June 2, 2008

"**The Deep Underground Science and Engineering Laboratory** would offer a major new facility for US particle physics. Located in the Homestake mine in Lead, South Dakota, DUSEL would be an underground laboratory housing a wide spectrum of experiments. When the first parts of the laboratory begin operation around 2013, DUSEL would be a key element in the US particle physics program. A large detector for **long-baseline neutrino physics** would be part of **the initial suite of experiments**, as would detectors for **dark matter** and **double beta decay experiments.** "

Project background

- **Direct detection of dark matter**
  - Mass of Weekly Interacting Massive Particles
  - Cross section of WIMPs
- **Neutrinoless double beta decay**
  - Effective Majorana mass of the electron neutrino
  - Neutrino's absolute mass scale
  - Particle-antiparticle nature
- **Extremely rare processes require:**
  - Large mass exposure
  - Small internal background
  - Sufficient shielding against external background
  - Deep underground site

Targeted Background Levels

- **Neutrinoless double-beta decay**
  - less than 1 count/ton/year in order to probe the quasi-degenerate neutrino mass region as low as 100 meV
- **Direct dark matter detection**
  - less than 1 count/ton/year to be sensitive to WIMP-nucleon cross-section of $10^{-46}\ cm^2$

Potential Background Sources

- **Natural radioactivity**
  - ^{238}U, ^{232}Th, ^{40}K
  - ^{39}Ar in Ar
    - Requires material purification
    - Veto detectors for backgrounds from surroundings
- **Muon-induced backgrounds**
  - Deep underground site
- **Cosmogenic isotopes**
- **Neutrino elastic and quasi-elastic scattering can also be a background for very rare physics processes**

Cosmogenic Activation

- Isotopes produced in *Ge* by fast cosmic-ray neutrons create backgrounds in next generation double beta decay and dark matter experiments

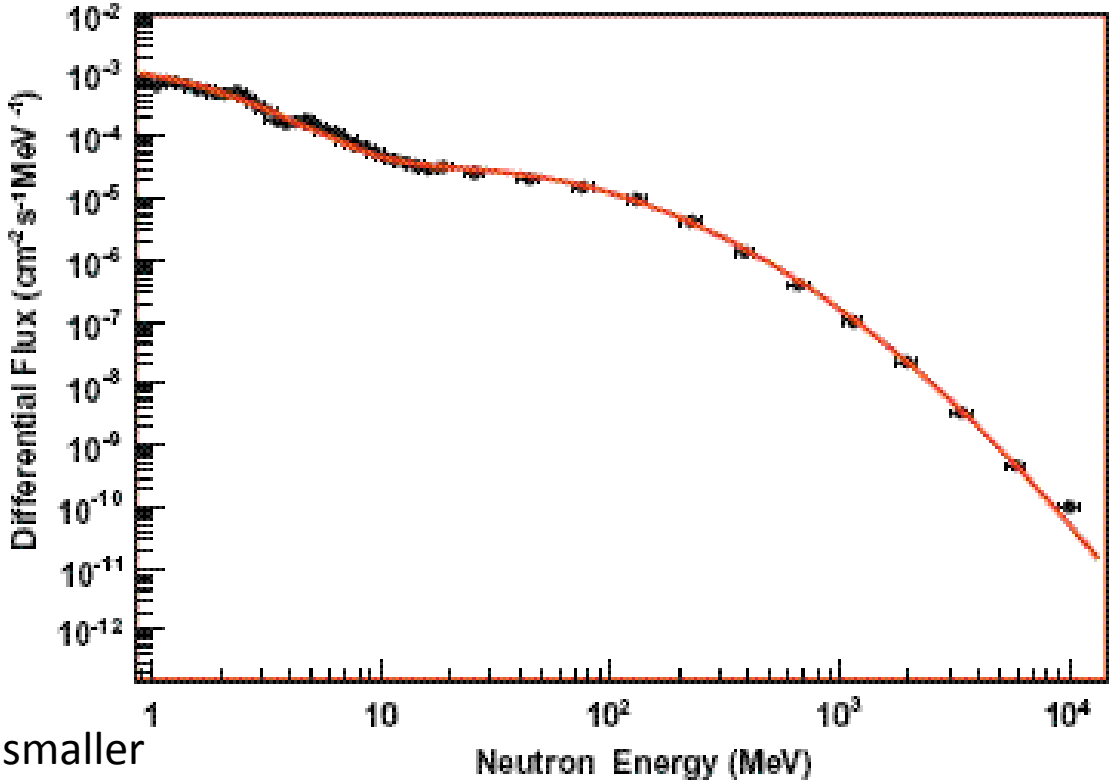
- **Production rate** of the radioactive isotope

$$R_i = \sum_j N_j \int \phi(E)\sigma_{ij}(E)dE$$

  - N_j the number of target nuclear isotopes *j*
  - $\phi(E)$ the cosmic **neutron flux**
  - $\sigma_{ij}(E)$ **neutron excitation function** for a product *i* at target *j*

Measured neutron flux at sea level

- Neutron flux measured by different groups
- Early measurements might be incorrect or of marginal quality [J.F. Ziegler IBM J. Res. Develop. 42 (1998) 117]
- Recent measurements has been one at sea level in northern hemisphere [Gordon et al, IEEE Trans. Nucl. Sci. 51 (6) (2004) 3427]
- Recent measured neutron flux is smaller at energies below 50MeV and larger between 50MeV and 1GeV



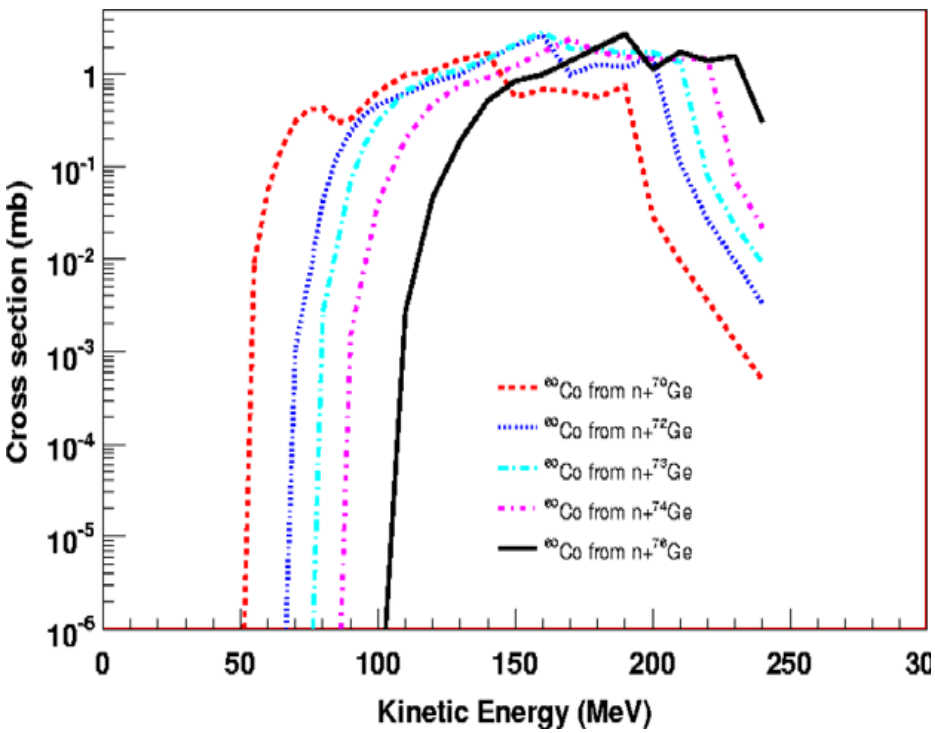
Gordon et al, IEEE Trans. Nucl. Sci. 51 (6) (2004) 3427

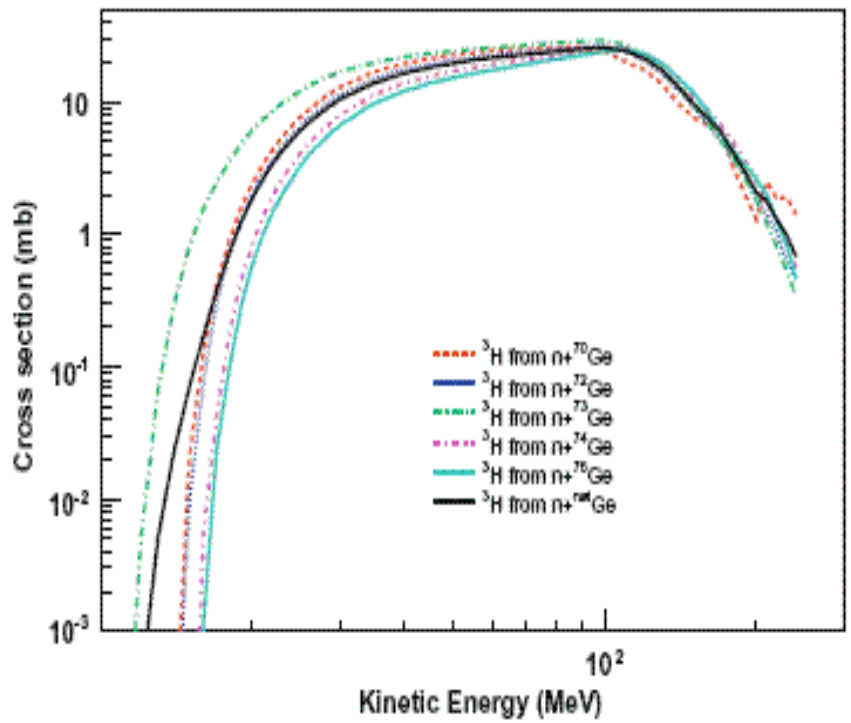
Excitation Function

TALYS 1.0 (A. J. Koning, S. Hilaire and M. C. Duijvestijn) is used to generate the excitation functions

- Provides a complete description of all reaction channels and observables
- Tested both formally, to check the computational robustness, and by comparison of calculated results with experimental data
- Enables to evaluate nuclear reactions from the unresolved-resonance region up to intermediate energies
- A versatile tool to analyze basic microscopic experiments and to generate nuclear data for applications

Excitation Function





D.-M. Mei, Z.-B. Yin, S. R. Elliott, Astroparticle Physics 31 (2009) 417–420

Production rates

	Natural Germanium (atoms/kg/day)				Enriched Germanium (atoms/kg/day)		
Cosmogenic isotopes	Lal Model [1]	Hess Model [2]	Mei et al. [3]	Experiment [1]	Lal Model [1]	Hess Model [2]	Mei et al. [3]
^{3}T	~178	~210	27.7	-	113	140	24
^{54}Mn	0.93	2.7	2.7	3.3 ± 0.8	0.37	1.4	0.87
^{60}Co	-	-	2.0	-	-	-	1.6
^{65}Zn	24.6	34.4	37.1	38 ± 6	3.12	6.4	20.0
^{68}Ge	22.9	29.6	41.3	30 ± 7	0.54	0.94	7.2

[1] - D. Lal, B. Peters, Cosmic Ray Produced Radioactivity on the Earth, Springer, Serlin/Heidelberg, 1967
[2] - W.N. Hess, H.W. Patterson, R. Wallace, Phys. Rev. 116 (1959) 449
[3] - D.-M. Mei et al., the submitted proposal to DOE 2009

- **^{68}Ge & ^{60}Co – produce signals around the energy of the neutrinoless double beta decay**
- **^{3}T – its beta spectrum is right in the region of interest for the detection of WIMPs**

Background Events in the ROI

Calculated cosmogenic background – one month exposure on the surface

	Natural Germanium		Enriched Germanium	
Cosmogenic isotopes	0νββ (2037 keV -2041 keV)	Dark Matter (1-30 keV)	0νββ (2037 keV -2041 keV)	Dark Matter (1-30 keV)
^{3}T	-	46700/ton/y	-	4048/ton/y
^{54}Mn	-	1429/ton/y	-	461/ton/y
^{60}Co	9/ton/y	84/ton/y	7/ton/y	67/ton/y
^{65}Zn	-	25575/ton/y	-	15044/ton/y
^{68}Ge	1566/ton/y	11885/ton/y	275/ton/y	2085/ton/y

- Since the production rates are substantial the reduction of the exposure of the target to cosmic rays is crucial
- The best way to avoid the cosmogenic production is to produce crystals underground
- The depth needed is on the order of 10 – 100 mwe – depending on the desired reduction factor

Underground Crystal Growth Lab

- **We have presented the cosmogenic production of various isotopes in several target or source materials pertinent for dark matter and double-beta decay experiments with improved measurement of the cosmic neutron flux.**

- **The tritium production in these materials due to cosmic-ray neutrons is substantial and steps must be taken to either reduce exposure of the target to cosmic rays, reduce the resultant ^{3}H within the target after exposure, or develop an event-by-event analysis to remove ^{3}H decay events from the data stream.**

Underground Crystal Growth Lab (cont)

- Neutrinoless double-beta decay experiments
  - Single crystal Germanium detectors
- Dark matter searches
  - NaI/CsI crystals
- Surface produced ^{76}Ge contains cosmogenic isotopes ^{68}Ge & ^{60}Co limiting the sensitivity if crystals that reside on the surface for ~ 1 week thereby constraining the production and transportation time
- Demand for grown crystals exceeds current production limits

Ultra-Low Background Counting Facility

- Contamination of the materials in the ultra-low background detectors at the level of 1-10 parts per trillion for ^{238}U and ^{232}Th (typical level of the order of 0.1-1 part per million)

- Screening measurements of such low counting rates accomplished by large (~3.3kg) high purity Germanium (HPG) detectors placed underground:
  - Extremely high purity
  - Outstanding energy resolution
  - High detection efficiency

- Detection of double-beta decay to excited states

- Ultra-sensitive screening detectors to be used in geology, microbiology, environmental science, national security

Ultra-Low Background Counting Facility - cont

- Two low background gamma-ray detectors made by Canberra
- Clover-leaf configuration
- Four high purity Germanium detectors each
- Multilayer shielding
- Additional detectors for Radon level monitoring in the lab air and water systems
- Possible location –> 4850-ft level underground
- Additional components: clean room (class 10,000) 3.5m by 4m, air ventilation, radon removal, power supply, nitrogen supply

Underground Copper Electroforming

- Purity of the commercially pure cooper is several orders of magnitude lower than that needed for the cryostat design
- Ultra-pure cooper produced on the surface experiences the contamination due to natural cosmic radiation
- Solution -> development of underground electroforming Copper facility at DUSEL

Purification/Depletion of Noble Gases

- Detectors for dark matter experiments based on noble liquids:
  - Argon
  - Xenon
- Presence of $^{39}\mathrm{Ar}$ in natural Argon as a source of radioactive background
- Depletion of Argon will allow a 10keV electronic recoil energy threshold for direct dark matter search with sensitivity of $10^{-46} cm^2$ or better

Purification/Depletion of Noble Gases (cont)

- Argon depletion
  - Purification via thermal diffusion columns
  - Extraction from underground gas wells (ex. natural Helium gas wells) and water reservoirs from geologically old rock formation
- Production of depleted Argon at a rate of 1ton/year
- Purification to achieve the purity level of 99.9999999% (contamination of Oxygen, Nitrogen, water vapor)
- Construction of depleted Argon detector at Sanford Lab

CUBED Impact

- Increases in the number of faculty and postdoctoral researchers
- Enhancement of facilities and equipment
- Continuation and development of partnerships
- Graduate education and STEM workforce development
- Education and outreach
- Economic impact

Conclusions

- DUSEL & Sanford Lab provide a unique opportunity for the growth of physics and cross filed research programs in South Dakota.
- Research Center will provide needed infrastructure and position South Dakota as a major contributor to DUSEL experiments.
- Proposed underground crystal growth facility provides a opportunity for commercialization and economic development for South Dakota.

Sanford Lab at Homestake Mine

Multilayer shielding

- Inner shielding – 10cm of oxygen free high conductivity (OFHC) cooper with 99.99% purity (used in cryostats for the low background detectors)
- Outside the copper shielding, a 5 cm layer of 30% borated polyethylene is used to absorb the low-energy neutrons produced in the lead by muons
- After the borated polyethylene layer, a 30 cm layer of lead is utilized to stop environmental gamma rays from entering the detector
- The outermost shielding is a 50 cm layer of pure polyethylene bricks to stop the neutrons produced from the surrounding rock.
- Muon veto detectors are placed outside the outer shielding, providing coverage of 4π.