Solar Neutrino Research and XAX

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CURRENT DARK MATTER EXPERIMENTS−XENON

At this time, a number of collaborations have designed and deployed a first round of dark matter detectors. Though the experimental limits set by these detectors have not yet reached the thresholds predicted by theory, the next round of detectors−barring any practical difficulties−is expected to do so. Figure 1 shows these limits and the probability densities for the WIMP (Weakly Interacting Massive Particles) cross-sections predicted by theory.

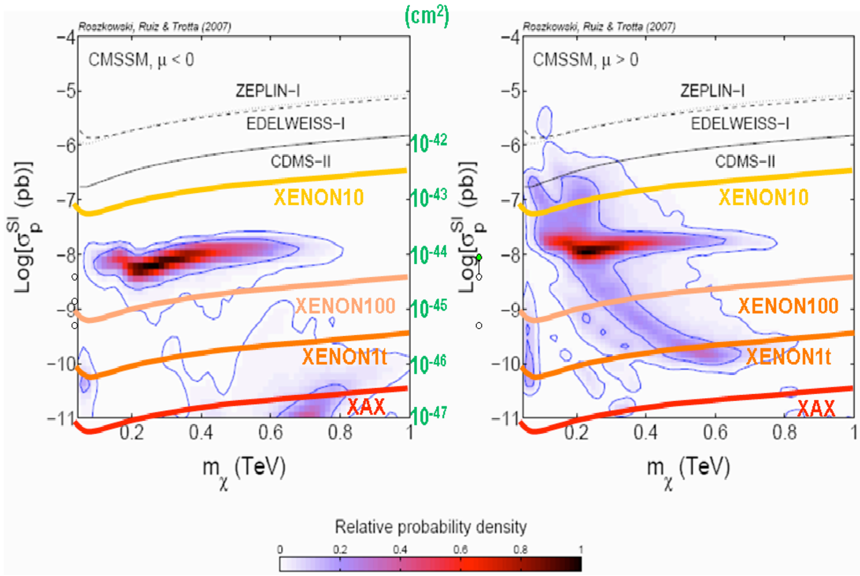

Figure 1: current and future cross-section thresholds for various experiments.

The UCLA group, which is led by Dr. Katsushi Arisaka and Dr. Hanguo Wang, is a member of the XENON dark matter collaboration. As Figure 1 shows, the XENON100 detector, which is currently in the Gran Sasso National Laboratory (LNGS) in Italy, is expected to have the sensitivity required in order to detect WIMPs. The XENON100 detector is comprised of a total 170 kg of liquid xenon with a 50 kg fiducial mass after shielding cuts. In general, liquid noble gases are good materials for experiments of this sort; they have high scintillation yields, they are easily purified, and, depending on the particular liquid, one can drift ionized electrons to allow for a secondary signal, as in XENON100. The detector uses a double-phase TPC (Time Projection Chamber) concept to detect the elastic scattering of WIMPs with Xe nuclei. The first phase is the so-called prompt light signal, due to the scintillation resulting from the collision. Then, an electric field is uniformly applied throughout the detector so that electrons ionized in the collision are drifted upwards toward a portion of the detector containing Xe gas. When the drifted electrons enter the gas phase, they cause a second scintillation, which is then detected as so-called proportional light. A picture of the process is shown in Figure 2. An advantage of the double-phase feature is that it allows for much better discrimination against gammas and other unwanted events, since the ratio $S2/S1$ of the second signal to the first signal is much greater for gammas than for WIMPs.

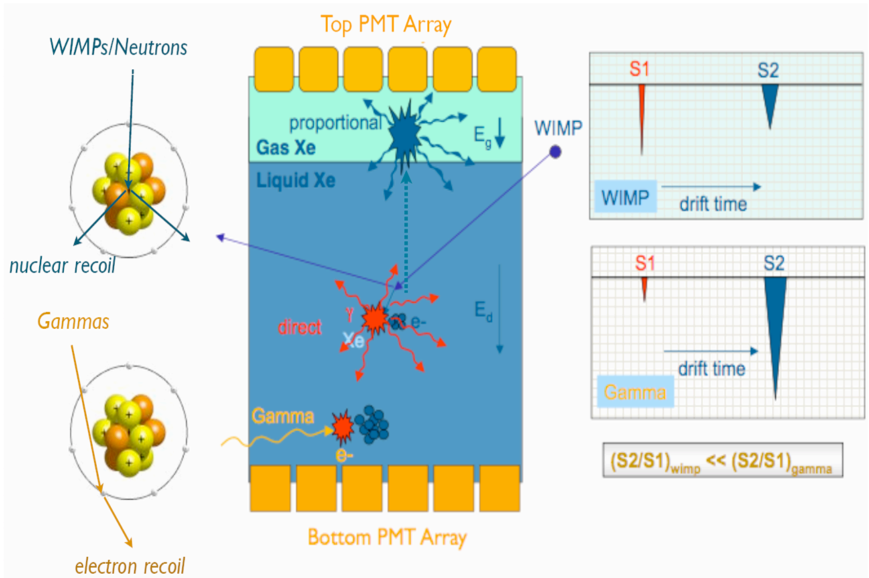

Figure 2: Principle of double-phase scintillation detection

Future detectors in the XENON collaboration will include a one ton LXe detector, and eventually a ten ton detector known as XAX (Xenon-Argon-Xenon). We shall say more about this detector and the principles of double-phase detection later on. It turns out that XAX will have sensitivity not only to WIMPs, but also to solar neutrinos from the *p*-*p* chain. We shall therefore pause to discuss solar neutrinos and a brief history of their detection.

SOLAR NEUTRINOS AND THE SOLAR NEUTRINO PROBLEM

Neutrinos are produced as byproducts of the nuclear fusion reactions in the sun. The primary neutrino-producing chain reaction in this process is known as the $p - p$ chain (proton-proton), which consists of the following five neutrino-producing reactions [1] (the flux at Earth in $s^{-1}cm^{-2}$, as well as the energy threshold of the released neutrinos, is given in parentheses [2]):

- pp: $p + p \rightarrow^2 H + e^+ + \nu_e$ $(5.95 \times 10^{10}; \leq 0.42\text{MeV})$
- pep: $p + e^- + p \rightarrow^2 H + \nu_e$ $(1.40 \times 10^8; 1.44\text{MeV})$
- hep: $^3He + p \rightarrow^4 He + e^+ + \nu_e$ $(9.3 \times 10^3; \leq 18.77\text{ MeV})$
- ^{7}Be: $^7Be + e^- \rightarrow^7 Li + \nu_e$ $(4.77 \times 10^9; 0.861\text{ MeV})$
- ^{8}B: $^8B \rightarrow^8 Be^\star + e^+ + \nu_e$ $(5.05 \times 10^6; \leq 14.06\text{MeV})$

A plot of energy vs. flux for these reactions is given in Figure 3 below [3]:

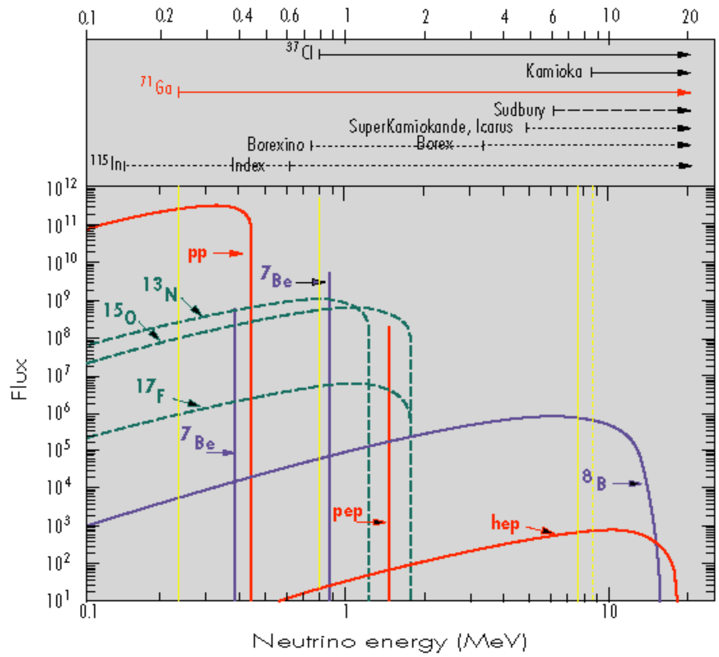

Figure 3: Solar neutrino energy spectra and experimental sensitivities.

Another chain, known as the CNO (Carbon Nitrogen Oxygen) cycle, is also responsible for the production of neutrinos in the sun, but comprises only about 1.5% of the total flux [2].

The study of solar neutrinos affords one of the most accessible ways of studying fusion processes in the sun, which can otherwise be very difficult considering the impracticality of recreating such conditions in the laboratory, as well as given the amount of time that it takes (~10,000 years) for a photon to travel from the core of the sun to its surface [1].

Predictions of the electron neutrino (ν_e) flux were made primarily by John Bahcall beginning in the 1960s. However, as experiments were designed that became capable of detecting solar neutrinos, it was realized that the recorded fluxes were significantly less than those predicted. In fact, until the year 2000, all detected neutrino fluxes (using the chlorine, gallium, and Kamiokande experiments that we shall describe in the next section) fell well short of the best predictions [2], a situation that came to be known as the "solar neutrino problem." It was hitherto thought that neutrinos were massless, but if it was allowed that neutrinos had mass, then it would be possible for them to undergo oscillations from one flavor to another [2]. This turned out to be the most compelling solution to the solar neutrino problem: electron neutrinos change to muon neutrinos (ν_μ) and tau neutrinos (ν_τ) en route from the sun to Earth. This was experimentally confirmed by the Super-Kamiokande and SNO collaborations [4], which we describe next.

PAST SOLAR NEUTRINO EXPERIMENTS

THE DAVIS CHLORINE EXPERIMENTS

Ray Davis pioneered the first experiments capable of detecting solar neutrinos in the mid-1960s [1]. He designed an experiment which relied on the principle of radiochemical detection, whereby radioactive isotopes created in neutrino interactions are counted after a certain data-taking period. This became known as the Homestake Experiment, for the Homestake Mine in South Dakota where they were performed. The concept for this experiment was developed originally by Bruno Pontecorvo in 1946, and its underlying principle is the reaction [1]:

$$\nu_e +^{37} Cl \rightarrow e^- +^{37} Ar$$

which has energy threshold 0.814 MeV. The argon atoms decay back to chlorine with a half-life of 35 days; at the end of a month or so of data-taking, only two to three argon atoms would typically be found [1]. The first results of the Homestake Experiment were released in 1968; the capture rate that Davis measured was $2.56 \pm 0.16 \pm 0.16$ SNU (Solar Neutrino Unit; 1 SNU= 10^{-36}captures per target atom per second), whereas the most up-to-date theoretical calculations during that period predicted a rate of about $7.6^{+1.3}_{-1.1}$ SNU for neutrinos above the given energy threshold [4]. This was the first sign that there was a problem with models of neutrino physics.

THE GALLIUM EXPERIMENTS (GALLEX/GNO AND SAGE)

The gallium experiments GALLEX/GNO and SAGE constituted another set of radiochemical solar neutrino detectors. They looked for the reaction

$$\nu_e +^{71} Ga \rightarrow e^- +^{71} Ge$$

and counted the Ge atoms produced. One of the primary advantages of this experiment over the chlorine experiments was that the energy threshold for the gallium experiments was a much lower 0.233 MeV [1], and so one sees from Figure 3 that the gallium experiments were sensitive to to neutrinos from chain reactions other than the ^8B and *hep* chains (though the flux from the *hep* chain is comparatively negligible), and therefore counted a higher overall flux. Once again, however, the flux predicted for these experiments was 129^{+9}_{-7} SNU, whereas the observed fluxes were all between 60 and 80 SNU [1].

KAMIOKANDE AND SUPER-KAMIOKANDE

The Kamiokande water Čerenkov detector, housed in the Kamiokande mine in Japan, used 2,140 tons of water observed by 948 PMTs. It once again observed a deficit in the predicted flux in 1987 [1]. Čerenkov detectors are designed to detect the Čerenkov radiation produced in neutrino reactions. When a neutrino strikes one of the electrons of a water atom ($\nu_x + e^- \rightarrow \nu_x + e^-$), the recoiling electron can move faster than the speed of light in water, emitting Čerenkov radiation, which can be thought of as analogous to a sonic boom. The follow-up to Kamiokande was SuperKamiokande, a detector comprised of 50,000 tons of light, ultra-pure water with over 11,000 PMTs monitoring the inner fiducial volume. While these experiments had relatively high energy thresholds (above about 5 MeV), they were sensitive to all flavors of neutrino, albeit with suppressed fluxes for $\nu_\mu$and ν_τ neutrinos (the cross-sections for $\nu_{\mu\tau} + e^- \rightarrow \nu_{\mu\tau} + e^-$events are ~ 0.15 times that for $\nu_e + e^-$events [1]). Nevertheless, the total recorded flux was $(2.35 \pm 0.02 \pm 0.08) \times 10^6 cm^{-2} s^{-1}$, about 46.5%of what theory predicted for the experiment [1].

SNO

SNO refers to the Sudbury Neutrino Observatory, a heavy water Čerenkov detector located in the Creighton Mine in Sudbury, Ontario. It used 1,000 tons of deuterium-enriched water, housed in a 12 m diameter acrylic vessel supported inside an 18 m geodesic structure, and monitored by 9,456 PMTs. An advantage of the SNO detector is that it was sensitive to all flavors of neutrino via three reactions [5], with measured fluxes for each reaction in parentheses [1]:

- Electron Scattering (ES): $\nu_x + e^- \rightarrow \nu_x + e^- (\Phi_{ES} = 2.39^{+0.24+0.12}_{-0.23-0.12} \times 10^6 cm^{-2} s^{-1})$
- Charged Current (CC): $\nu_e + d \rightarrow e^- + p + p$ ($\Phi_{CC} = 1.76^{+0.06+0.09}_{-0.05-0.09} \times 10^6 cm^{-2} s^{-1}$)
- Neutral Current (NC): $\nu_x + d \rightarrow \nu_x + n + p$ ($\Phi_{NC} = 5.09^{+0.44+0.46}_{-0.43-0.43} \times 10^6 cm^{-2} s^{-1}$)

The dominance of the Neutral Current flux provided the most direct evidence to date of neutrino flavor oscillation en route from the sun.

FUTURE EXPERIMENTS AND *P-P* CHAIN NEUTRINOS

Thus, the Solar Neutrino Problem was essentially solved by the turn of the century, and the neutrino oscillation picture was firmly established. There remains much to be determined, however, especially including the details of neutrino oscillation models. The most precise flux measurements have been made for ^8B neutrinos, which are also the only neutrinos for which energy measurements have been made. And yet, they comprise less than 10^{-4} of the total solar neutrino flux [6]. Future experiments, then, will focus on detecting solar neutrinos from the *p-p* chain, which comprise about 91% of the total flux. Though the gallium experiments that we have reviewed were sensitive to the *p-p* chain, they were not sensitive to its entire spectrum; their threshold was above about 0.233 MeV. Furthermore, they were not capable of making measurements in real-time with energy data. The importance of experiments capable of direct detection of neutrinos from *p-p* chain is expressed by John Bahcall as follows [6]:

The most urgent need for solar neutrino research is to develop a practical experiment to measure directly the p-p *neutrino flux and the energy spectrum of electrons produced by weak interactions with* p-p *neutrinos. Such an experiment can be used to test the precise and fundamental standard solar model prediction of the* p-p *neutrino flux. Moreover, the currently favored neutrino oscillation solutions all predict a strong influence of oscillations on the low-energy flux of* ν_e.

Several experiments with this capability are being developed. On average, it is expected that noble liquid scintillation detectors should be able to achieve about 1 *p-p* event per day per ton of scintillator with a 50 keV neutrino-electron recoil threshold [7]. Notable experiments include the CLEAN, HERON, XMASS, and LENS collaborations. The first three involve noble liquid scintillation detectors, while LENS uses indium-loaded liquid scintillator. We summarize each briefly:

- **CLEAN** (Cryogenic Low Energy Astrophysics with Noble Gases) will use a 135 ton liquid neon scintillation detector (10 ton fiducial) and will be sensitive to all flavors of neutrino via electron scattering interactions, as well as the $\nu_e +^{20} Ne \rightarrow \nu_e +^{20} Ne$ interaction. CLEAN expects to reach an energy threshold of as low as 20 keV [8]. About 2,900 *p-p* events are expected per year. The boiling temperature of liquid neon is 27°K, which presents a great difficulty for the operation of PMTs. The CLEAN collaboration has reported, however, that it has successfully operated certain PMTs at this temperature [9].

- **HERON** (HElium Roton Observation of Neutrinos) is a planned scintillation detector that will use 20 tons of liquid helium at 50 mK to achieve an expected 45 keV threshold to detect mainly $\nu_e$via electron scattering interactions. The collaborators expect to be able to detect 2.5 *p-p* events/day/ton [10]. Rather than PMTs, rotons (excitations in superfluid helium due to the energy of helium atoms imparted by recoiling electrons) and scintillation photons will be detected using thin arrays of sapphire or silicon calorimeters [11].

- **XMASS** (Xenon detector for weakly interacting MASSive particles) is a liquid xenon experiment whose ultimate physics goals include searching not only for low-energy solar neutrinos, but also for dark matter. An 800 kg detector is being constructed for deployment in the Kamioka mine in Japan, and will look primarily for dark matter. The collaboration has expressed the intent to eventually construct a 10 ton detector capable of detecting solar neutrinos from the *p-p* chain with a 50 keV threshold [12].

- **LENS** (Low Energy Neutrino Spectroscopy) is a planned indium-loaded liquid scintillation detector for use at LNGS, which will emply about 60 tons of ^{115}In with energy threshold 120 keV in 3000 tons of indium-free liquid scintillator. LENS looks for the interactions

  $$\nu_e +^{115} In \rightarrow^{115} Sn + e^- + 2\gamma$$

  to detect solar electron neutrinos [13].

XAX ($^{129/131}$XENON-ARGON-^{136}XENON)

Like XMASS, XAX is a planned multi-target detector which will use liquid xenon at the multi-ton scale. However, it will have of a variety of advantages which make it superior to all the planned detectors. We shall attempt to outline its main features here. What follows can be found in much greater detail in [14].

The basic detector structure is shown in Figure 4 below, and Figure 5 gives a more detailed look at one of the individual detector targets:

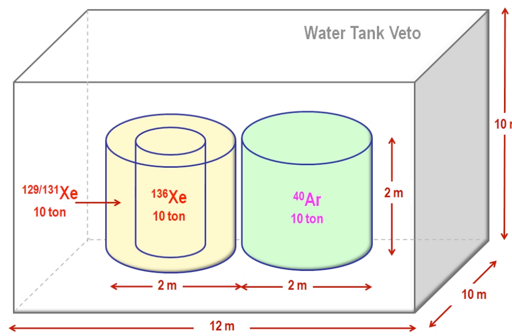

Figure 4: XAX—possible overall structure.

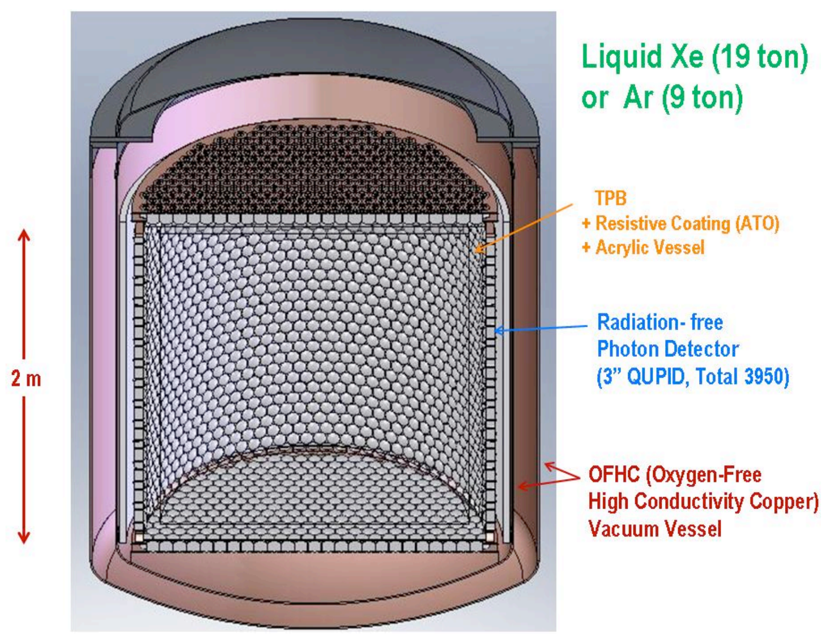

Figure 5: One of the individual target detectors in XAX.

The xenon targets are concentric and each is comprised of 10 tons of liquid xenon. Both the xenon and argon targets are two-phase scintillation/ionization TPC detectors with 4π steradian PMT coverage. The PMTs are Quartz Photon Intensifying Detectors (QUPIDs), specially designed in collaboration between UCLA and Hamamatsu Photonics. These superior PMTs will be the cleanest yet, with backgrounds below 10-100 emitted gammas and 0.01-0.1 emitted neutrons per year per QUPID. XAX will be able to accomplish a number of physics goals owing to its versatility as a low-background, multi-target system. These goals are as follows:

1. The $^{129/131}Xe$-enriched (^{136}Xe-depleted) target will examine how dark matter interacts with nuclei of non-zero spin.
2. It will also look for elastic scattering interactions of electron neutrinos ν_e from the $p-p$ chain.
3. The ^{136}Xe-enriched target will study how dark matter interacts with zero-spin nuclei.
4. The ^{136}Xe-enriched target will also look for neutrinoless double beta decay.
5. The ^{39}Ar-depleted liquid argon target will provide a test of the A^2-dependence of a coherent cross section, where A is atomic number.
6. Optionally, liquid neon may be used in place of argon, in which case it will provide an alternate target for $p-p$ chain solar neutrinos.

One of the most serious problems afflicting experiments of this sort is achieving the necessary reduction of gamma and neutron backgrounds from the PMT array. It is shown in [14], however, that XAX can be constructed with sufficiently low backgrounds to observe dark matter events at a rate of about 100 events/year for cross-sections 10^{-10}pb. The combination of ultra-clean QUPID photodetectors, the discrimination using $S2/S1$ allowed by the double phase, and the various scattering and shielding cuts that can be made make XAX completely unique among the experiments being proposed.

A POSITION RESOLUTION STUDY

The figures below shows a more detailed depiction of the double-phase scintillation detection process in the XAX geometry.

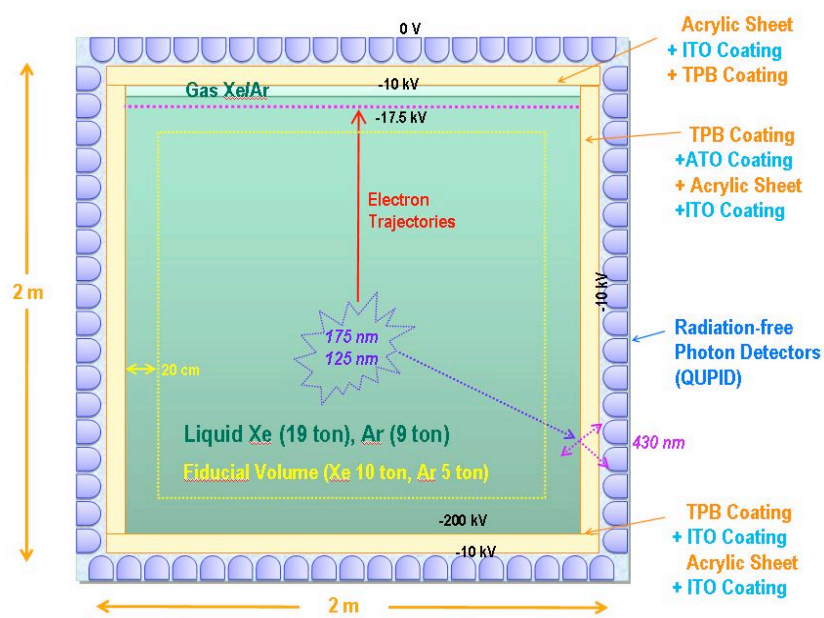

Figure 6: Double-phase scintillation detection in XAX.

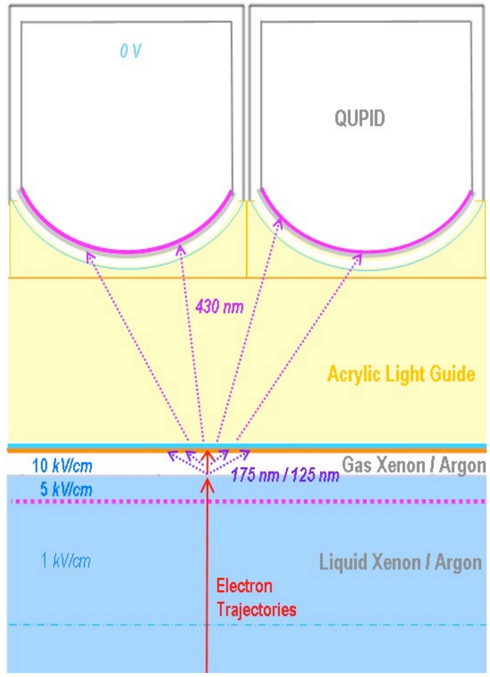

Figure 7: The $S2$ phase.

The QUPIDs which will cover the walls of the XAX detector each have a diameter of 3 inches. Of course, one would like to be able to reconstruct the (x, y) location of $S2$ events to greater precision than this, and it is of interest to know how well one should in principle be able to do this. In particular, one would like to know the value of the width of the gas phase of the detector—a controllable parameter—which best optimizes (x, y) position resolution.

One of the things that I spent time on this summer was studying a very basic algorithm for how this sort of task might be accomplished. Consider a hypothetical 5×5 grid of PMTs, and a certain distribution of recorded hits of $S2$ scintillation photons for a single detection event. Histogram the hits by column, and call the number of hits recorded in the column immediately to the right of center R, and the number of hits recorded in the column immediately to the left of the center L. For each event, we can then calculate a parameter $(R - L)/(R + L)$. The idea is summarized in the following figure:

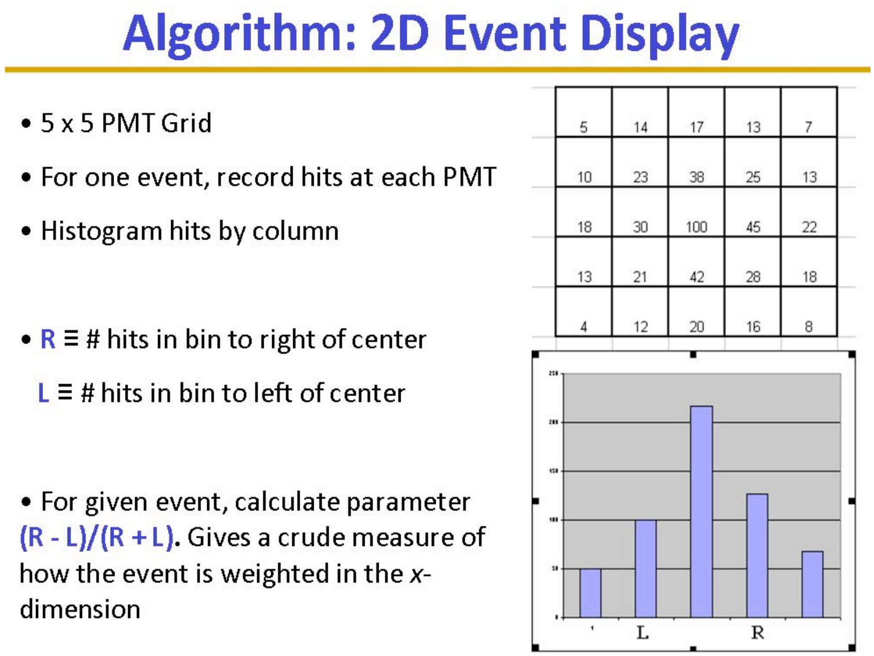

Figure 8: Data is recorded for a sample 5×5 grid of PMTs, and histogrammed by column.

We used GEANT4 for simulations, assuming a 5×5 grid of 2.5×2.5 inch PMTs. We simulated 50 events centered at a given x-location, and computed the average value of the $(R-L)/(R+L)$ parameter for the set of 50 events. We then repeated the process, incrementing $1mm$ in x for successive simulations. All events were simulated at a certain energy and with a certain gas phase width. For each energy and gas phase width, we would then have a set of $(R-L)/(R+L)$ values that we could plot versus position relative to the center of the PMT. An example of such a plot is shown in the next figure:

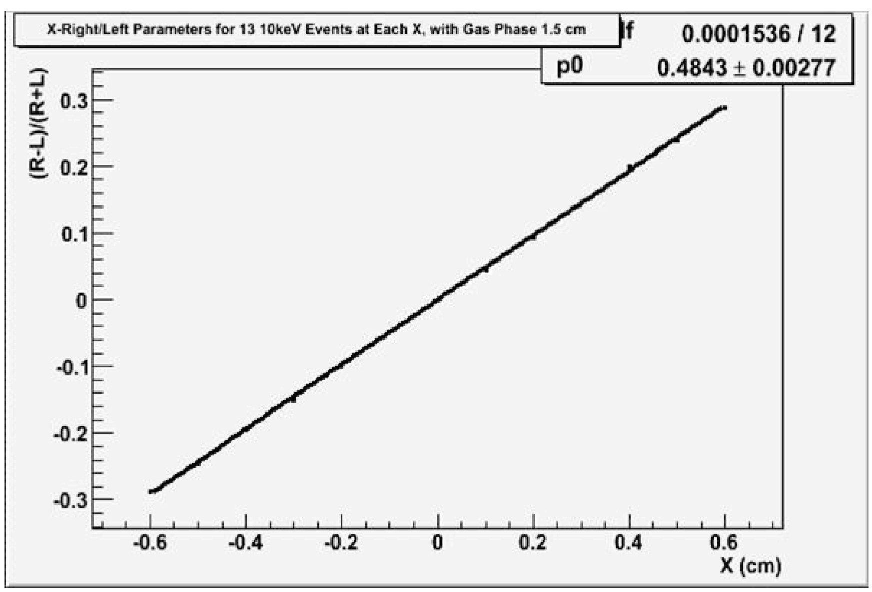

Figure 9: Each point represents the average value of $(R-L)/(R+L)$ for 50 events generated at the corresponding x-location relative to the center of the PMT.

We then obtain a fit line through the points. Next, we generate a large number of events for the same energy and gas phase width, all centered at the same x. Imagining these as horizontal lines through the $(R-L)/(R+L)$ axis, we can determine where each point would intercept the fit line, and then histogram these intercepts. Fitting a Gaussian to the result, the root-mean-square (RMS) should give a rough measure of the 2D position resolution.

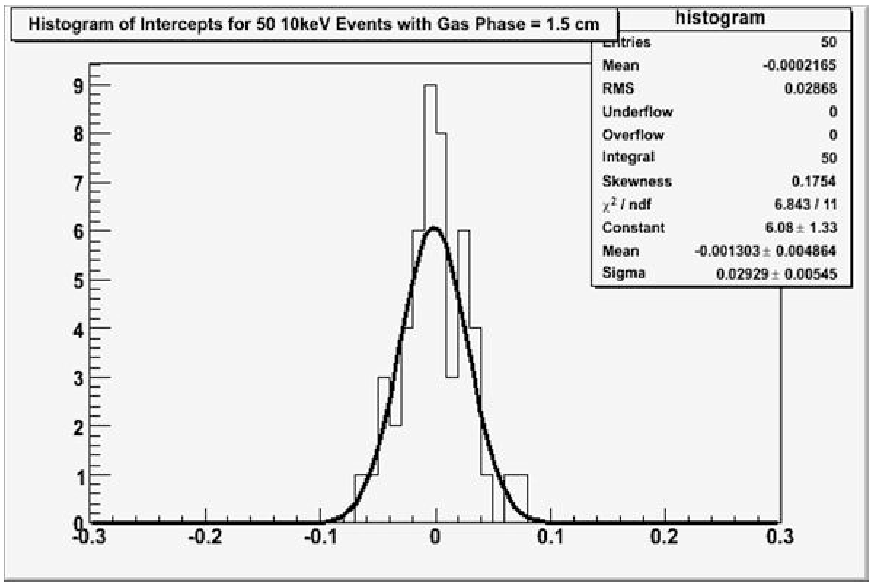

Figure 10: A histogram of the intercepts of $(R-L)/(R+L)$ values for 50 events with the fit line above in Figure 9.

The next step is to repeat this process for different gas phase widths, holding other variables constant. One then plots the RMS as a function of gas phase width and looks for the minimum. This may be repeated by varying other parameters and holding everything else constant, such as the energy of events, in order to determine the dependence of position resolution on a variety of experimental factors.

The problem with what we have done here is that, according to Figure 10, we are getting position resolutions on the order of $0.1mm$, where we would actually expect to be able to do no better than mm order (~1/10 the size of the PMT). We concluded that our GEANT4 simulations were just too rudimentary, and too full of simplifications to be very accurate. However, our resolution algorithm is, in principle, a very basic example of the procedure that one might carry out in a study of this kind.

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