eBubble Research and Development Program
Nevis Laboratories, Columbia University
August 2003

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Introduction and Motivation
Today as physicists try to unearth the secrets of the universe they take a constructionists view. By trying to determine the properties of the smallest particles they try to piece together the macroscopic worldview. This experiment, known as eBubble, is designed to study neutrino physics and when implemented will provide information about neutrino magnetic moments, which could be parameters in the Standard Model.

The neutrino was first predicted by Wolfgang Pauli to maintain conservation of energy and momentum in nuclear beta decay. They were later named by Enrico Fermi, and their names mean “little neutral one.”¹ They come in three different flavors that correspond to the three charged lepton counterparts, electron, muon, and tau. They are fermions with spin ½ and they permeate space in gigantic numbers. However, they are weakly interacting and therefore even though there are billions of them speeding through the earth every second they pass through intact. Most interestingly, they are described by the Standard Model to be massless, but recently physicists have shown otherwise². They are now expected to have a very small mass and this allows them the ability to oscillate between the flavors by quantum mechanical mixing. If the Standard Model predicts this incorrectly then where could other discrepancies lie?

One way that neutrinos can interact is through the weak force. They are a result of nuclear beta decay and are also produced in fusion reactions like in the sun. The potential problem that is more interesting for this experiment is a possible electromagnetic interaction via magnetic moment. Neutrinos do not interact electrically because they are neutral, but if they have even a small magnetic interaction it could have big ramifications because there are astronomical numbers of them everywhere.

The job of the eBubble experiment is to try to reduce the current upper limit for the tau neutrino magnetic moment. We feel that we can improve on the existing upper limit by getting better spatial resolution and detecting lower energy electrons from the scatters. Looking for lower energy electrons improves the cross-section, which makes the probability for seeing an event higher. Another thing that contributes to raising this cross-section is having higher energy neutrinos. The place to get those is the LHC in Geneva Switzerland.

The beam at the Large Hadron Collider when it comes online in 2008 will have the highest energy and the highest luminosity in the world. It will be a proton to proton collider with $10^{14}$ protons filled every 8 hours that have 7 TeV of energy per proton. To keep the luminosity high about every 8 hours they have to dump the beam and start over. Those protons have a huge energy so when they dump the beam it has to go somewhere that can absorb the energy without exploding. The beamdump is made of carbon stops surrounded by iron. When the protons interact with the stops they produce a shower of particles including tau neutrinos. The detector can be situated behind the beamdump for a virtually free neutrino beam.³

The detector itself is just as clever. Liquid helium will be the detection medium. This has many advantages: purity, temperature, density, and electron bubbles. First of all, Liquid Helium is self-purifying because of its low temperature. All other materials change to solid phase and precipitate out. This is one advantage Helium has over liquid Xenon or any other noble liquid; it is inexpensive to purify. It also has a low temperature, below 4 K. This
helps with the purification as well as the diffusion rate, which depends on temperature. The density is small enough to be able to see the tracks of low energy electrons and large enough to have a reasonable volume for the size of mass necessary to see interactions.

The most important property of liquid Helium for this experiment is the electron bubble. When a free electron is introduced into a volume of liquid helium a bubble forms around it from which the helium is excluded. This bubble has a negative charge and mass. It is typically about 16-18 Angstroms in size. The bubbles have a slow drift velocity, which we will use for an innovative detection scheme. This is the mechanism we intend to use to extract spatial resolution of neutrino scatter events.

Cross Section
The thing that determines the rate at which particles interact with each other is called a cross-section. This is determined by the force carrier of the interaction so each force has a different cross-section associated with it. For the purpose of this experiment the differential cross-section needs to be maximized. Here is the equation for the neutrino electromagnetic cross-section due to magnetic moment.4

\[
\frac{d\sigma}{dT} = \frac{\pi \alpha^2 \mu_e^2}{m_e^2 \mu_B^2} \left[ \frac{1}{T_e} - \frac{1}{E_\nu} \right]
\]

The parameters available are \(T_e\) the kinetic energy of the scattered electron, and \(E_\nu\) which is the energy of the incoming neutrino. The high value for \(E_\nu\) is taken care of by the high energy protons from the LHC beam. To get a better limit on neutrino magnetic moment the detector must be able to see low energy electrons from these scatters. The way to lower \(T_e\) is to have better spatial resolution in order to be better able to identify background events. The current limits are in Table 1. We believe that they can improve the \(T_{\text{min}}\) limit for the tau neutrino by 5 orders of magnitude.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Limit on (\mu_\nu)</td>
</tr>
<tr>
<td>(\mu_{\nu e}) &lt; 1.3 x 10^-10 (\mu_B)</td>
</tr>
<tr>
<td>(\mu_{\nu \mu}) &lt; 6.8 x 10^-10 (\mu_B)</td>
</tr>
<tr>
<td>(\mu_{\nu \tau}) &lt; 3.9 x 10^-7 (\mu_B)</td>
</tr>
</tbody>
</table>

Background
There are several types of background that need to be considered during this experiment, some due the nuclear scatters and some due to Compton scattering. The first kind of scattering is neutrino- nucleus weak interaction scattering:

\[
\bar{\nu} + \text{He}^+ \rightarrow e^+ + H^3 + n \quad \nu + \text{He}^+ \rightarrow e^- + \text{He}^3 + p
\]

These can be differentiated from an interesting event by the track angle which can be resolved by the high spatial sensitivity of the machine. It obeys the equation
Another thing in favor of the eBubble detector is that it can reach 1 keV as its minimum scattered electron energy. At this energy the nuclear scatters tend to be less probable. Figure 1 depicts a black shaded area that represents the cross-section of these nuclear scattering events as well as the ranges available to the different experiments for scattered electron kinetic energy. The Compton scattering can be found by looking for characteristic clusters. When a photon enters the volume of helium it scatters an electron

\[ \theta_e < \frac{2m_e}{T_e} \]

which the detector sees. But also a less energetic photon is emitted. This scatters again and so on until the detector sees a small cluster of tracks looking like the picture in figure 2. These would be easy to distinguish from a regular neutrino event because of the clusters, but the detector must be a large volume so that the scattered photons cannot escape before they interact enough to make a clear cluster.

\[ \nu + e \rightarrow \nu + e \]
Figure 3 is a graph of attenuation coefficients and it is important to note that the energy of photons that interact in this case are usually well below an MeV. This means that a meter in any direction is enough to see most Compton scattering clusters and exclude them from the data as such. Another feature of helium is that it is self-shielding from most background radiation. Also the experiment will be underground to shield from cosmic ray background.

**Description of Entire Detector**

At the center of this setup is a plexiglass box with no top, whose sides are 1 cm thick. It is filled with helium at 2 K such that the liquid helium is 1.15 m deep, and the space above it is helium gas. 15 cm from the sides and bottom of the box is the 1 m x 2 m x 1 m detection volume. Around the detection volume are 12 copper rings that create an electric field on the order of 50 V/cm in the volume from potential difference between them. 1 cm above the liquid-gas interface is the GEM, which covers the entire 1 m x 2 m area above the detection volume, and 1 cm above the GEM is a series of detection wires, spaced every 250 µm, 2 m long each. Above the wires is, naturally, the electronic equipment to control them. Surrounding the plexiglass box is a copper box, with 5-cm thick sides and two chambers. The lower one contains solid helium at 2 K; the upper one at 20 K. The barrier between them (also copper) provides the top for the plexiglass box. Outside the copper box is a box of stainless steel, 2 cm thick. Between the copper and steel is a vacuum chamber to insulate the detector. A single tube, composed of stainless steel above and copper closer to the detection chamber, passes down into the detector to allow wires to drop down into the chamber. To stem heat loss, it will need several bulkheads and at least one area of vacuum.

**Figure 4** Perspective Drawing of Detector
Figure 5 Front-End View of Detector (dimensions in mm)
Figure 6 Side View of Detector (dimensions in \textit{mm})
Detecting a Neutrino

Given our experimental requirements, we propose to build a detector with a 2 cubic meter detection volume of helium, and a mass of 250 kg. A neutrino will enter the detection volume with high energy. It will scatter off either an electron or the nucleus of a helium atom emitting a high-energy electron. This electron will travel through the liquid, losing energy as it knocks other electrons out of their respective helium atoms. A track of ionized electrons will form in the liquid. The angle and length of the track will be detected and used to reconstruct the event that caused the track.

The process of converting the track of electrons in liquid helium into electric signals has three steps: drift to the helium surface, release from the surface by acoustic pulsing, and amplification and detection. Drift to the surface occurs because of the electric field present in the chamber. Since the bubbles drift at a constant velocity, one dimension of the bubble’s position can be determined by the time of arrival of the electron on the detector element. The bubble around the electron limits the drift velocity and allow for good resolution of the electron’s position. Once the bubble gets to the surface, it is trapped by the electrical image charge that it induces on the surface. It stays on the surface for a finite amount of time. An ultrasonic pulse will then scan the surface at regular intervals to excite the bubbles and eject them from the surface into a gaseous amplification region and then to detection wires. The ultrasonic pulse will provide another dimension of the electron’s initial position. Since it travels through the liquid at a constant velocity, the interval between the time the pulse was emitted and the time an electron is ejected and detected will indicate the electron’s distance from the transducer. Above the surface of liquid helium is gaseous helium containing a gas electron multiplier (GEM). GEMs work by accelerating electrons and causing them to ionize other helium atoms, causing more free electrons to be present in the signal. This process, called avalanche gain, can amplify the signal by a factor of up to $10^5$. GEMs were tested in gaseous helium, and such gains were observed.

Figure 7 Schematic of a GEM

![Schematic of a GEM](image)
Specifics of Neutrino Detection Scheme
The process described above for detecting a neutrino requires some fine-tuning of the parameters of the liquid detection volume such as the strength of the electric field, and the temperature of the liquid. Also the acoustic pulse needs to be engineered to release the electrons from their surface trap. A discussion of these parameters follows.

Readout Scheme Parameters
From the geometry of the detection volume, we must have an acoustic pulse that travels for 1 meter:

**Scan Length:** \( l_{\text{scan}} = 1m \)

Since the speed of sound in helium is \(220m/s\), it takes \(5 ms\) to scan the surface. Scanning can occur once every \(5 ms\), and not more often, since each pulse represents an individual bin in the depth dimension of the liquid.

**Scan Time:** \( t_{\text{scan}} = 5 ms \)

From the resolution goal of \(250\mu m\), the maximum drift velocity is the resolution divided by the scan time.

**Maximum Drift Velocity:** \( v_d <= 5 cm/s \)

Also, the electron must remain on the surface for at least as long as \( t_{\text{scan}} \). The lifetime on the surface must be greater than \(3 * t_{\text{scan}} \).

**Surface Lifetime:** \( \tau_{\text{surf}} >= 15 ms \)

Diffusion over the 1cm drift distance must be less than the resolution of the detector, \(250\mu m\).

**Diffusion Distance:** \( \sigma <= 250\mu m \)

The above constraints must be satisfied by the parameters that we control, temperature, \(T\) and drift field strength, \(E\). Drift velocity is determined by the following property of helium. \( v_d = \mu_e E \) with electron mobility, \(\mu_e\). (Figure 3) There is a critical point where
the mobility goes up drastically due to helium’s superfluid properties. The liquid must stay above this temperature because it would cause us to violate the maximum drift velocity constraint.

Figure 9 Electron Mobility of Liquid Helium\(^8\)

![Electron Mobility of Liquid Helium](image)

Diffusion distance depends on temperature, field strength, and drift distance. It is calculated with the Einstein-Nerst formula where \(\sigma\) is the diffusion distance, \(k\) is Boltzmann constant, \(E\) is the electric field strength, \(e\) is the electron charge, and \(\text{dist}\) is the drift distance, 1 meter:

\[
\sigma = \sqrt{\frac{2k \cdot \text{Temp}}{eE} \cdot \text{dist}}
\]

The relationship between field strength and temperature and surface lifetime is shown on the plot of Shoepe and Rayfield’s experimental results.\(^4\) (Fig. 4)

The three lines show electric field strength where the lifetime, temperature, drift velocity, and diffusion are all in the range that satisfy our parameters. We have extrapolated their results and intend to reproduce their experiments in the interesting range of parameters. If the field is stronger than \(\sim 100 \, V/cm\), the drift velocity increases above \(5 \, cm/s\). If the field is any weaker than \(\sim 50 \, V/cm\), then diffusion will be greater than the resolution required by the experiment. Table 2 shows an interesting range of parameters which brackets our constraints.

| Table 2 |
|---|---|---|
| **Electric Field Strength** | 48.6 \(V/cm\) | 115 \(V/cm\) | 152 \(V/cm\) |
| **Temperature** | 2.2 \(K\) | 1.95 \(K\) | 1.85 \(K\) |
| \(\mu_e\) (electron mobility) | \(0.0326 \, cm^2/Vs\) | \(0.07 \, cm^2/Vs\) | \(0.09 \, cm^2/Vs\) |
| \(v\) (Drift Velocity) | 1.6 \(cm/s\) | 8.05 \(cm/s\) | 13.68 \(cm/s\) |
| \(\sigma\) (Diffusion Distance over 1m) | 275 \(\mu m\) | 170 \(\mu m\) | 145 \(\mu m\) |
Figure 10 Lifetime of Trapped Electrons on Helium Surface in Presence of Drift Field.
Ultrasonic Pulse Considerations
In order to create an acoustic pulse that scans across the surface and releases the electrons that are trapped just below the surface, the amplitude of the pulse needs to be just enough to expand the electron bubbles until the electrons are emitted. The depth of the resting position of the electron while it is trapped below the surface is important. To calculate this depth, the electron’s potential function is plotted. The two dominant terms in its potential energy are the image charge potential and the drift field potential. The first term is the image charge and the second term is the drift field potential: (\(z\) is the depth; \(\varepsilon\) is the dielectric constant of helium; \(E\) is the field strength; \(e\) is the electron charge.)

\[
V = \frac{e^2}{4\pi\varepsilon_0} \left( \frac{\varepsilon - 1}{4\varepsilon(\varepsilon + 1)} \right) + eEz \quad 10,11
\]

The minimum of the potential function is where the electron is most likely to rest. This is the depth of the electron while it is trapped below the surface, shown with the arrows for the three values of electric field strength that satisfy all necessary parameters.

**Figure 11**
The electron will come to rest approximately 30 nm below the surface of helium. Since the transducers are a few nanometers wide, (say 5 mm), the electrons that are drifting towards the surface must be left undisturbed by the pulse and only the surface electrons ejected. Experiments will be necessary to determine the exact amplitude of a wave pulse that will just cause the electron bubbles right below the surface to emit their electrons into the gas. Figure 5 shows two pulses passing a track of electrons that is drifting towards the surface. The first pulse only causes the top electron to be emitted into the gas, but the second pulse causes a cluster of electrons that have collected at the equilibrium distance to be emitted.

**Figure 12**

![Diagram showing pulse effects on electron tracks](image-url)
The beam must be focused so that it is 5 mm deep when it has traveled the entire 1 m scan length. The following relationship for diffraction describes the width of a pulse at a given distance from its source.

\[ \text{width} = \frac{\lambda}{L} \times D \]

\( \lambda = 0.22 \text{ mm} \), the wavelength of the pulse. So for \( L = 1 \text{ mm} \), \( D \), the width of the transducer, equals 5 mm.

The transducer will need to be aimed at the surface so that each part of the surface receives a pulse of equal power (ignoring attenuation, which is small).

**Figure 13**

\[ \text{Figure 13} \]

\[ \text{D} \]

\[ \lambda \]

\[ L \]

\[ \text{width} \]

\[ \text{D} \]

\[ \lambda = \frac{\text{width}}{L} \times \text{D} \]

\( \lambda = 0.22 \text{ mm} \), the wavelength of the pulse. So for \( L = 1 \text{ mm} \), \( D \), the width of the transducer, equals 5 mm.

The transducer will need to be aimed at the surface so that each part of the surface receives a pulse of equal power (ignoring attenuation, which is small).

**Figure 14** Cartoon of Transducer Sending an Equal Amount of Energy to Entire Surface

**Acoustic Power Considerations**

This section shows an estimate of how much power the ultrasonic transducers will need to deliver to the liquid in order to eject the top layer of electrons. According to experiments conducted by Maris and others, electron bubbles tend to grow without limit in the presence of a pressure wave of –2 bars.\(^{12,13,14}\) If these bubbles are near the surface, the electrons will be ejected with an even weaker pulse than –2 bars. –1 bar will be used as the max pressure needed in a power estimate for the acoustics. Given the formula for acoustic intensity (power per unit area),

\[ I = \frac{\Delta P_{\text{max}}^2}{2 \rho v} \]

with density \( \rho = 0.125 \text{ g/cm}^3 \), and velocity of sound \( v = 200 \text{ m/s} \), we obtain acoustic intensity \( I = 10^5 \text{ W/m}^2 \). To find the energy density of one pulse, the intensity is multiplied by the duration of the pulse, which is on the order of 1 µs. The energy density multiplied by the area over which the pulse travels, which is 5mm, the depth of a transducer, multiplied by 2 m, the length of the container. The energy per pulse is 1 millijoule, and since the pulse occurs every 5 ms, the total sustained power is 0.2 Watts.

Acoustic attenuation should also be mentioned, since the pulse must not die out before it passes the entire length of the surface. Acoustic pulses die out with a characteristic exponential constant, \( \alpha \), which is proportional to the squared frequency of the pulse. For liquid helium at 2 K, \( \alpha = 17 \times 10^{-15} \text{ s}^2/\text{m} \times f^2 \). For a frequency of 1 Mhz, this corresponds with a decay length of 14 meters, so the pulse would not be significantly decayed after it has traveled the required length of 1 meter.\(^{15}\)
**Surface Atomization**

In many industrial applications, ultrasound is used to atomize liquid surfaces and generate sprays. It is expected that in our experiment the acoustic pulse may be strong enough to disturb the surface enough to cause droplet formation. Many experimental and simulated studies have been conducted in water and other substances to investigate surface atomization. These studies have shown that the diameter of formed droplets is approximately .36 times the wavelength of the pulse. For a 1 Mhz pulse in helium, this corresponds with a drop diameter of approximately 100 µm. The drop is much larger than the distance from the surface to the electron that rests below it (30 nm), but we expect that the surface will be sufficiently perturbed in droplet formation that the electron will be ejected.

**Figure 15** Photographs and Simulated Mesh of Droplet Formation

Surface atomization is a process where instabilities on the surface are grown exponentially until shapes like droplets form. When an electron is trapped below the surface, a small bump forms above the electron to balance the image charge force with surface tension and gravitational forces of the risen liquid. (Figure 8) It is important to know the height of the bump in order to determine if it make any difference to the droplet formation process. Here we outline the calculation of the bump height.

**Figure 16**

**Force Balance:**
\[ \Sigma F = 0 = F_{\text{Image Charge}} - F_{\text{Gravity}} - F_{\text{Surface Tension}} \]
Image Charge Force: (assuming flat charge distribution: $h << d$)

\[
F_i = \int \frac{e}{4\pi \varepsilon_0} \frac{\sigma(r)dA}{(d + h)^2} \quad dA = 2\pi rd\theta
\]

\[
\sigma(r) = -\frac{e(1-\varepsilon)}{2\pi \varepsilon(1+\varepsilon)} \frac{d}{(r^2 + d^2)^{3/2}}
\]

\[
F_i = -\frac{e^2}{4\pi \varepsilon_0} \frac{(1-\varepsilon)}{\varepsilon(1+\varepsilon)(d+h)^2}
\]

Surface Tension Force: \hspace{0.5cm} Assume small $\theta$, $\theta = \sin \theta = \tan \theta$

\[
F_T = 2\pi r T \sin \theta
\]

\[
F_T = 2\pi r T \left( \frac{4h}{3r} \right)
\]

\[
F_T = \frac{8}{3} \pi Th
\]

\[
\Rightarrow \frac{4s}{r} = \frac{r}{r/2} \Rightarrow h = 3s
\]

\[
\Rightarrow \sin \theta = \frac{4h}{3r}
\]

**Figure 17**
Gravity is assumed to be small compared to tension, so we solve:

\[ \Sigma F = 0 \Rightarrow F_{\text{Image Charge}} = F_{\text{Surface Tension}} \]

\[
\frac{8}{3} \pi r h = \frac{-e^2}{4\pi \varepsilon_0} \left(1 - \varepsilon\right) \frac{1}{\varepsilon(1 + \varepsilon)(d + h)^2}
\]

Solve using values:
\[ \varepsilon = 1.057 \]
\[ d = 30\,\text{nm} \]
\[ T = 0.355 \times 10^{-3} \,\text{N/m} \]
\[ r = 30\,\text{nm} \]
\[ h = 0.226 \times 10^{-11} \,\text{meters} \]

Confirm approximations were appropriate:

- Small \( \theta \)
  \[ \sin \theta = \frac{4h}{3r} \]
  \[ \theta = 0.001 \]
- Weak gravity
- Tension is \( 10^{16} \) times stronger

\[ F_{\text{Gravity}} = \rho V g = \frac{2}{3} \pi h^3 \rho g = 5.6 \times 10^{-31} \]
\[ F_{\text{Tension}} = \frac{8}{3} \pi h T = 6.7 \times 10^{-15} \]

The height of the hill is very small so it will likely not affect the atomization position. It may still be large enough to cause more atomization directly above the trapped bubble than elsewhere in the liquid. This is something to be determined by experiment in liquid helium.

**Prototype Setups For eBubble Detector**

Test chambers have been built to investigate all the important factors of this idea for acoustic gating in liquid helium. At Brookhaven National Lab, a 1.5 liter liquid helium chamber has been constructed, with a liquid helium and liquid nitrogen cryostat for cooling. The test chamber has 5 optical windows, a field cage, and the following sources of test particles:

- Visible light beam from a flash lamp, to give a variable number of single electrons
- Radioactive source of low energy electros, to give a point source of lightly ionizing particle
- Alpha or Beta particles, to give a point of energetic, heavily ionizing particle
- Energetic photon from a beam at an accelerator

**Figure 18** Photo of Liquid Helium eBubble Chamber
At Nevis Labs, a test container for testing surface ultrasonics is being constructed. It will allow testing of the pulse with varying angle between the transducer and the surface. It consists of a plexi-glass cylinder, capped at both ends. It will be partially filled with water and a transducer will be mounted to the cylinder to send a pulse through the water.

**Figure 19** Drawing of Test Container for Water Acoustics Experiments
The transducers used can be controlled with software and a computer card. A readout of the voltage on the transducers, corresponding to a force delivered to or received from the liquid, will be shown on the screen. The characteristics will be able to be measured with the transducers, with phototubes detecting a bright light which scatters off the atomized surface, or with a cold finger which freezes the water which spray up from the pulse.

**Conclusion**

We think that we can use these techniques to improve the current limits for neutrino magnetic moment. Table 3 shows what improvement values are feasible. This value is bigger for electron neutrinos, but it would be difficult to get as close to a reactor as the TEXONO collaboration did in Taiwan. Since there is a significant gain available from using the LHC beamdump as a source that is what we have decided to concentrate on. We feel that the eBubble experiment could lower the limit on tau neutrino magnetic moment by a factor of 7 and we think it’s worth it to try.

**Table 3**

<table>
<thead>
<tr>
<th>Neutrino (collaboration)</th>
<th>Mass ratio</th>
<th>$\ln \left( \frac{T_{\text{max}}}{T_{\text{min}}} \right)$</th>
<th>Flux ratio</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ (TEXONO)</td>
<td>250</td>
<td>1.4</td>
<td>1</td>
<td>~20</td>
</tr>
<tr>
<td>$\nu_\tau$ (DONUT)</td>
<td>$\frac{1}{2}$</td>
<td>4.5</td>
<td>20</td>
<td>~7</td>
</tr>
</tbody>
</table>
Acknowledgements
This paper is a final report for a summer Research Experience for Undergraduates program at Columbia University’s Nevis Labs. We would like to thank Professor Bill Willis, Dr. Jeremy Dodd, and Dr. Yonglin Ju for spending time with us and for allowing us to participate in the planning of this project. We would also like to thank Professor John Parsons and the staff at Nevis for their hospitality and support this summer.

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9 Extrapolation From:
15 URL: http://www.ondacorp.com/tables/Liquids.pdf
16 URL: http://www.term.ucl.ac.be/recherche/ultrasonique/art0197.pdf
17 URL: http://www.me.umist.ac.uk/asrgpage/Publications/ILASS99_Orderly.pdf
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