The background in the 2π region was estimated from similar data taken at 290 MeV bombarding energy, which is just below the (p,2π) threshold. This showed that most of the events in the (p,$\pi^+\pi^0$) region at 330 MeV probably are background, and thus we have been able, so far, to place only an upper limit on the (p,$\pi^+\pi^0$) cross section of about 15 nb at 330 MeV bombarding energy.

PIONIUM PRODUCTION IN THE COOLER

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Experiment CE-49 is intended to evaluate the rate and cleanliness with which we can produce in the IUCF Cooler a tagged sample of "pionium," i.e., atomic bound states of a π^+ and a π^-. Such an atom has been predicted[1-4] to have a relatively long lifetime ($\tau \gtrsim 10^{-15}$ s) for a system with an allowed strong decay (from the S-states to $\pi^0\pi^0$). To date, there is only indirect experimental evidence for its existence, inferred[5] from the observed strength of $\pi^+\pi^-$ momentum correlations as a function of target thickness in 70 GeV p + Ta collisions. Pionium is worthy of fundamental study because it represents the lightest and, in some senses, simplest system of two interacting hadrons. More specifically, it allows study of the $\pi - \pi$ strong interaction at essentially zero relative energy, an interaction that would vanish in the limit of perfect chiral symmetry. Precise measurements of the interaction at zero energy provide probes of *dynamical* chiral symmetry breaking[6,7] (χSB), over and above the PCAC violation[8] that arises inescapably from the non-zero physical mass of the pion. The extent of such dynamical χSB is parametrized in Chiral Perturbation Theory, but should ultimately be predictable in a more fundamental theory (i.e., non-perturbative QCD solved in the confinement limit).

Our specific long-term interest is to use pionium decay to determine a linear combination ($|a_{T=0} - a_{T=2}|$) of the S-wave $\pi - \pi$ scattering lengths to a precision $\sim \pm 5\%$. This information can be extracted directly from a $\pm$ 10% measurement of the relative rates for the S-states of pionium to decay to 2γ *vs.* $2\pi^0$. For this purpose it is sufficient to measure the *absolute* 2γ branching ratio $B_{2\gamma}$. For pionium produced in a thin Cooler target (where there is negligible probability of ionization of the recoiling atom induced by collisions with electrons), all other decay branches (except $2\pi^0$) can be reliably predicted to be several orders of magnitude weaker than 2γ, so that the ratio of interest is, to excellent approximation, given by

$$W(2\gamma)/W(2\pi^0) = B_{2\gamma}/(1 - B_{2\gamma}). \tag{1}$$

Furthermore, it is not essential in an experiment to constrain the atomic states from which the decay occurs: *all* S-states give the *same* ratio in Eq. (1) because the atomic probability density within the interaction range, $|\Psi_{ns}(0)|^2$, cancels in the *relative* branching ratio; all $\ell > 0$ states should decay essentially exclusively by X-ray emission leading eventually to the S-states, since the $2\pi^0$ and 2γ branches are suppressed both by symmetry constraints (for odd-ℓ) and by the centrifugal barrier. This method for determining the scattering lengths avoids the model-dependence inherent in other approaches,[7,9] which rely on extrapolating down to threshold $\pi-\pi$ final-state interaction (FSI) information measured at higher relative energies.

The specific goal of CE-49 is to study the feasibility of producing pionium in pd collisions – pd $\to$ ^{3}He $(\pi^+\pi^-)_{atom}$ – at an energy very near the $\pi^+\pi^-$ production threshold (T_p^{thresh}=430.490 MeV), copying, for example, the successful use of the analogous pd $\to$ ^{3}He η to produce clean tagged η beams at Saturne.[10] Use of this reaction near threshold in the Cooler, with a pure windowless deuterium gas jet target, offers several important advantages: the recoil ^{3}He, focused in a small cone near $0°$, can be easily separated from the beam magnetically in the $6°$ magnet located in the Cooler T-section; they can be detected with 4π solid angle acceptance near threshold; background from reactions other than near-threshold two-pion production should be suppressed by the much smaller effective c.m. solid angle, and can be relatively easily eliminated by energy, angle, and timing measurements; production of *free* (as opposed to bound) charged pion pairs can be vetoed, because the low-energy pions themselves are also focused in a relatively small forward cone, and can be readily magnetically separated and detected. However, there are no reliable theoretical calculations of the pionium production cross section; the theoretical problem is significantly complicated near threshold by the Coulomb interactions among the three charged particles produced. We thus intend to measure (at least upper limits on) the production rate and signal/background ratio. A total production cross section $\gtrsim 1$ nb, ~ 1 MeV above threshold, is needed to make a decay experiment worth pursuing.

The CE-49 apparatus is indicated schematically in Fig. 1. ^{3}He products from proton beam interactions with a D_2 gas jet are collected and focused in a magnetic channel first assembled for CE-36 (Ref. 11). The channel comprises two $3°$ dipoles (following the $6°$ magnet in the T-section) and 3 large-aperture quadrupoles. The channel acceptance is expected to be just sufficient to enclose the full ^{3}He kinematic cone from pionium production 1 MeV above threshold. A thin (380 μm) plastic scintillator and a small drift chamber placed upstream of the first $3°$ dipole provide a start signal and entrance position information for the detected particles. At the end of the channel (roughly 5.3 m downstream of the start scintillator) we will place a 6-sector two-dimensional position-sensitive Si detector (500 μm thick), followed by a large-area intrinsic Ge detector (7 cm diameter by 1 cm thick), to measure the total energy, stopping power, stop time, and exit position of the ^{3}He's. We will eventually install a vacuum pipe through most of the length of the magnetic channel, with minimal entrance and exit window thicknesses, to limit multiple scattering and energy straggling of the ^{3}He's. We expect to achieve FWHM resolutions ~ 200 keV in energy and $\sim 0.1°$ in angle for the ^{3}He's, allowing us to reconstruct the missing mass with a resolution ~ 50 keV when the bombarding energy is ~ 1 MeV above the production threshold.
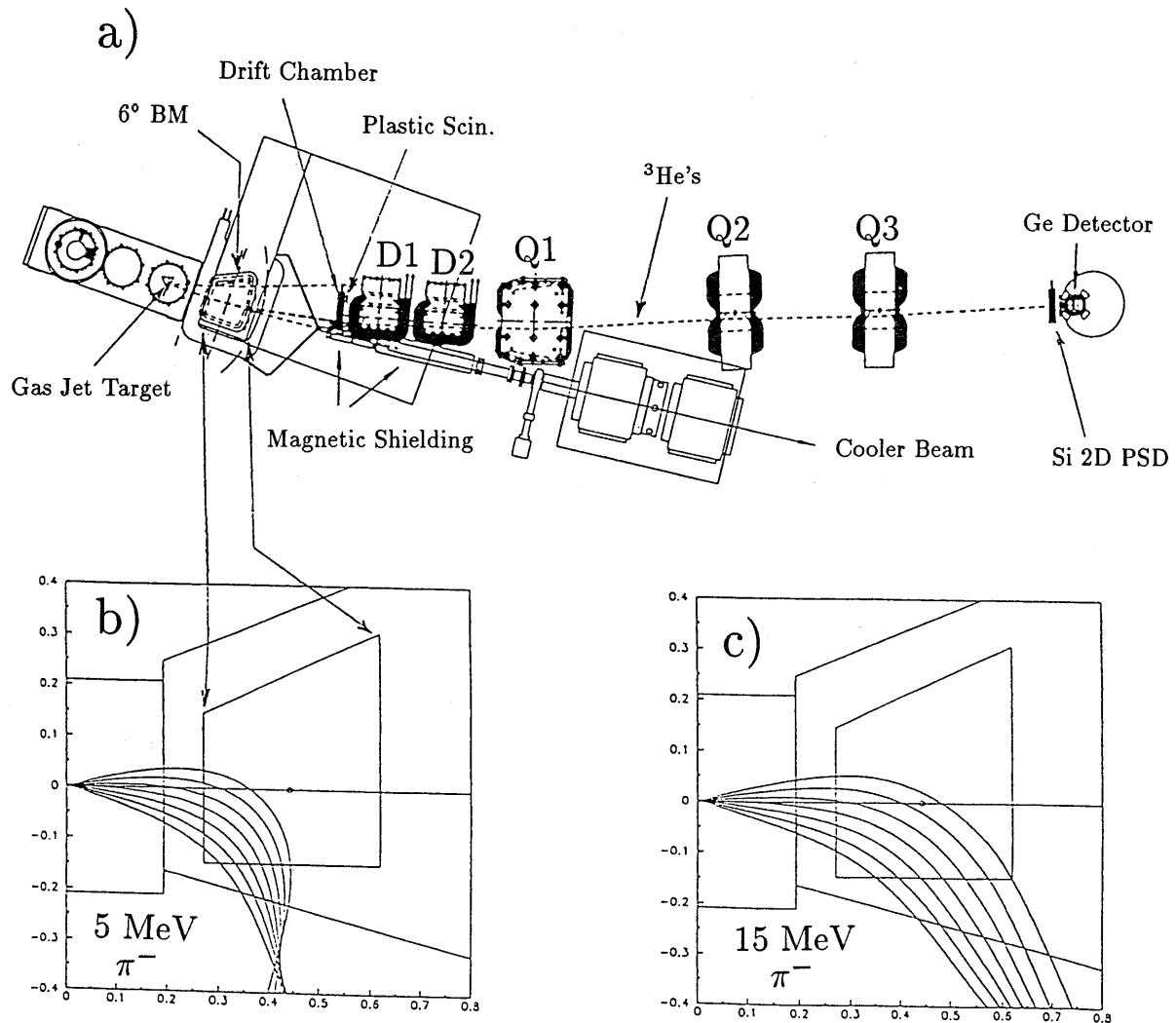
Figure 1. (a) Top view of the layout of the magnetic channel in the T-section of the Cooler. ^{3}He's traversing the channel are detected in a drift chamber and a thin plastic scintillator upstream of the first 3° dipole and in position-sensitive Si and large-area Ge detectors at the end of the channel. The bottom frames illustrate the trajectories that would be followed through the 6° magnet region by 5 MeV (b) and 15 MeV (c) π^- emitted from the gas jet target, over the entire angle range accessible to free $\pi^+\pi^-$ production 1 MeV above the threshold. These, and the symmetrically bent π^+, would be vetoed by plastic scintillators, to distinguish pionium production.

Good missing mass resolution is needed, above all, to distinguish a pionium peak above the expected broad continuum background from pd → ^{3}He $\pi^0\pi^0$. Since the bombarding energy will be ~16 MeV above the threshold for the latter reaction, the associated ^{3}He's will be spread over considerably greater ranges in lab energy and angle than those accompanying pionium production. Production of continuum $\pi^+\pi^-$ pairs (spread over a 1 MeV range in missing mass) that do not undergo capture into bound states will be vetoed with high efficiency by detecting the charged pions in plastic scintillators placed to the left and right of the 6° bending magnet, in which the pions of interest bend by ~ 70 − 120°.

We have recently taken the first data acquisition run for CE-49, in which we worked near the *single* π^0 production threshold: pd → ^{3}He π^0, $T_p^{thresh} = 198.6$ MeV. The aim was to understand the operation and acceptance of the magnetic channel, to test the cleanliness of ^{3}He identification and the level of backgrounds unassociated with pion production, as might arise, for example, from secondary reactions in pumping foils surrounding the gas jet or from accidental coincidences between the front and rear ^{3}He detectors. The single π^0 production reaction 1 MeV above its threshold provides a reasonable facsimile of the ^{3}He kinematics expected for pionium, but with a much larger, and previously measured,[12] cross section: $\sigma_{tot}(\Delta T_p = 1.0$ MeV$) \simeq 1.2$ μb. For the purposes of this run, it was sufficient to replace the rear solid-state detectors with a thin (1.0 mm) plastic scintillator of sufficient area (12.7 cm square) to enclose the entire expected ^{3}He locus. Since the vacuum pipe for the channel was not yet ready, we filled most of the length of the channel with a thin-walled helium bag. The $\pi^\pm$ veto scintillators were not yet installed.

After the completion of CE-36, the elements of the magnetic channel were significantly realigned for CE-49 in an attempt to optimize the acceptance for the ^{3}He's of interest. We found during the run that the ray-tracing calculations that had been performed to predict ^{3}He trajectories and optimal magnet currents were not reliable. Thus, much of the run had to be devoted to searching for suitable currents and a suitable location of the rear scintillator. This search was eventually successful, as illustrated by the spectra obtained, shown in Figs. 2-4. Figure 2 shows the raw particle identification spectrum obtained by plotting the pulse height from the front (S$_1$) *vs.* that from the rear (S$_2$) scintillator (the ^{3}He's are transmitted through both). The ^{3}He group is clearly visible in Fig. 2 and well separated from protons, even with the crude resolution obtained with these scintillators (we have not here corrected for a factor ~2 light attenuation for particles impinging on S$_1$ at the end opposite its phototube).

Figure 3 shows the spectrum of time of flight through the channel (flight path = 5.23 m) at two bombarding energies, both with and without gates on the ^{3}He group in Fig. 2. The ungated spectra are dominated by a broad peak resulting from inelastic scattering and knockout of protons from deuterium, but the ^{3}He's from pd → ^{3}He π^0 are very clearly visible atop the weak proton tail. (No deuterons or tritons are expected to fall within the momentum acceptance of the channel.) The ^{3}He-gated time spectra are remarkably clean. The width of the peak observed reflects the energy distribution of ^{3}He's from pd → ^{3}He π^0; it grows as expected kinematically as we pass from 1 to 2 MeV above threshold. (No evidence of a peak was seen 1 MeV *below* threshold.) At ΔT_p=2.0 MeV, the asymmetry we observe between the peaks corresponding to minimal (63 MeV) and maximal (71 MeV)
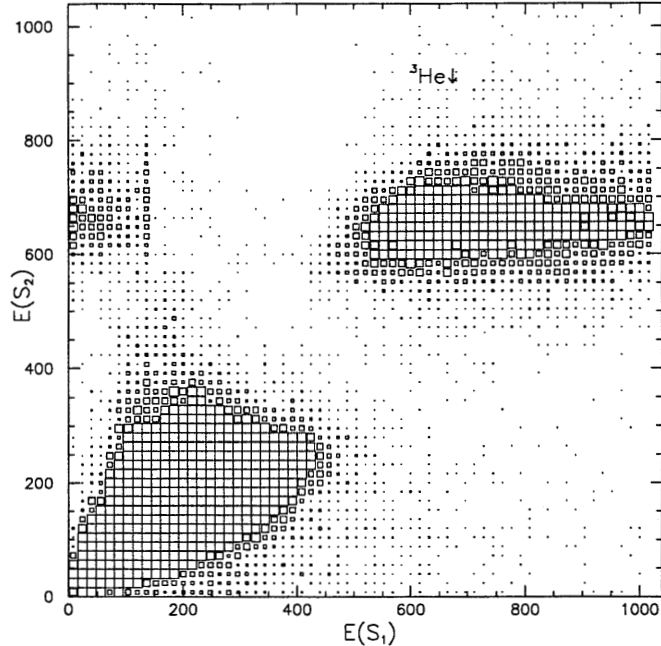
Figure 2. Raw particle identification spectrum obtained from scintillator pulse heights at the entrance *vs.* exit of the magnetic channel in CE-49 run A. The gate shown is used to select ^{3}He's, which are cleanly separated from the less heavily ionizing protons.

energy ^{3}He's is in excellent accord with the fore-aft π^0 asymmetry previously measured by Pickar *et al.*[12] The time resolution attained yields a ^{3}He energy resolution $\sim$1 MeV.

Despite the broad momentum acceptance of the channel, the yield of ^{3}He's (or apparent ^{3}He's) outside the kinematic region accessible to π^0 production is $\lesssim 0.1\%$ of the π^0 yield. (The small shoulder seen on the long time side of the ^{3}He peak at both energies in Fig. 3 presumably arises from ^{3}He's that are degraded by passing through some thicker material near the edges of the channel acceptance.) Since $\sigma_{tot}(\pi^0) \sim 1.0$ μb, we conclude that effective background cross sections are not worse than the 1 nb level, even without any additional cuts, e.g., on the energy-angle correlation. This augurs well for the pionium production search, which can be carried out with the same time-averaged luminosity ($\overline{\mathcal{L}} \simeq 3 \times 10^{30}$ cm^{-2}s^{-1}, attained with a beam current ~ 600 μA at the start of the flattop and a jet thickness $\simeq 3 \times 10^{15}$ cm^{-2}) as was used for the data in Figs. 2-4.

The absolute acceptance of the magnetic channel for the ^{3}He's can be assessed in two ways. One is to compare our measured cross section to earlier values. Normalizing to p-d elastic scattering[13] yields measured simultaneously in a luminosity monitor, comprising forward scintillators on beam right and a Si position-sensitive detector for the large-angle recoiling deuterons on beam left, we obtain $\sigma_{meas} \simeq 0.7$ μb at ΔT_p=1.0 MeV. If the beam energy was correct (which can be checked to high accuracy from the ^{3}He energy range observed), this suggests $\sim$60% acceptance in the channel. Alternatively, we can use ^{3}He position spectra from the drift chamber at the front of the channel to determine whether there were clear cutoffs in the geometrical acceptance. The relevant spectra for both ^{3}He and protons, at ΔT_p=1.0 MeV, are shown in Fig. 4. The protons fill the available aperture,
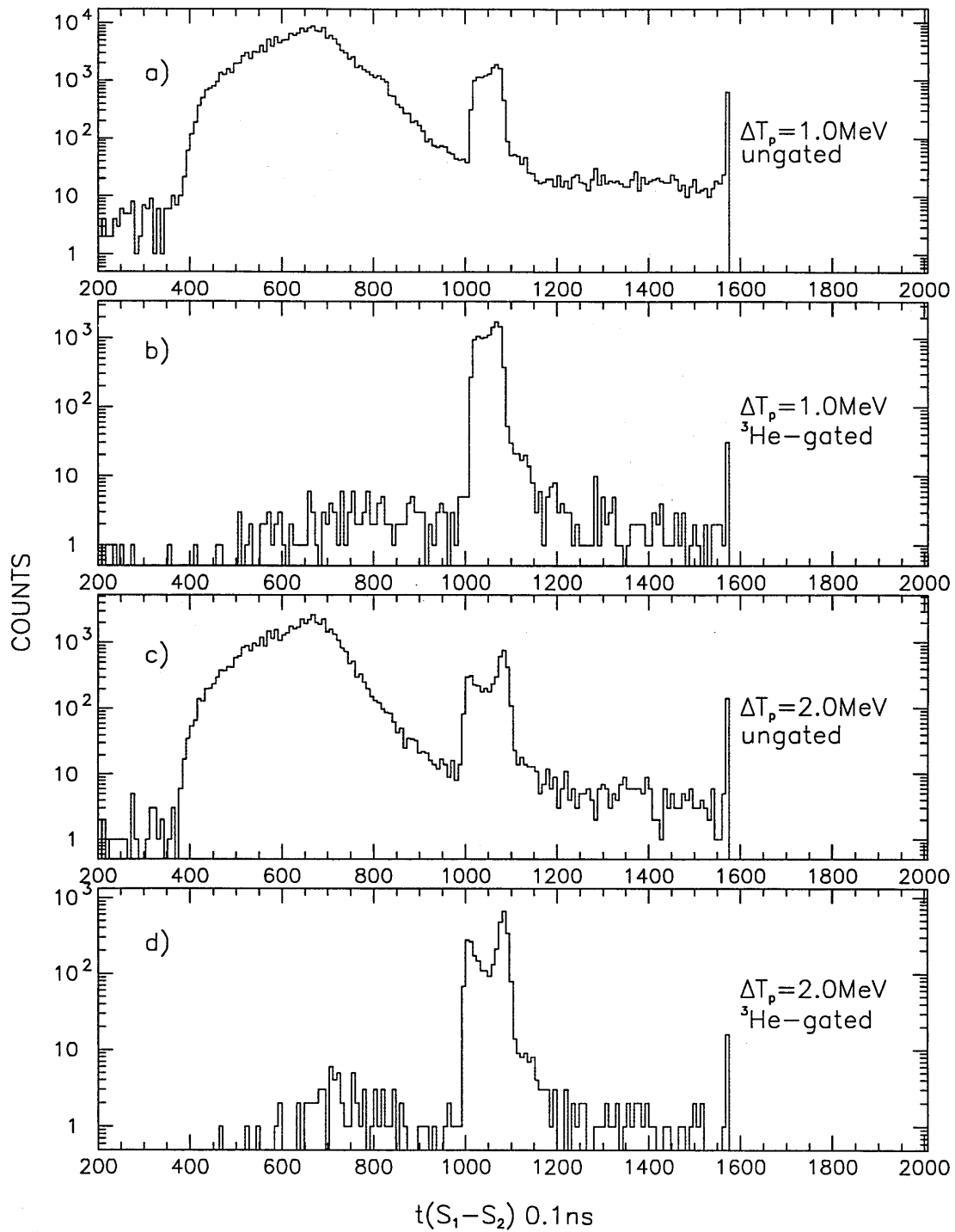
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Figure 3. Spectra of the time of flight of particles through the magnetic channel from front to rear scintillator, obtained during CE-49A at bombarding energies 1.0 MeV (a,b) and 2.0 MeV (c,d) above the pd $\rightarrow$ ^{3}He π^0 threshold. Spectra (a) and (c) are ungated, while (b) and (d) have been gated by the ^{3}He identification window in Fig. 2.

a) protons

ID		683
ENTRIES		26091
.000E+00	.000E+00	.000E+00
.000E+00	.26 E+05	.000E+00
.000E+00	.000E+00	.000E+00

Y (100=1.0cm) →

X (100=1.0cm) →

b) ^{3}He

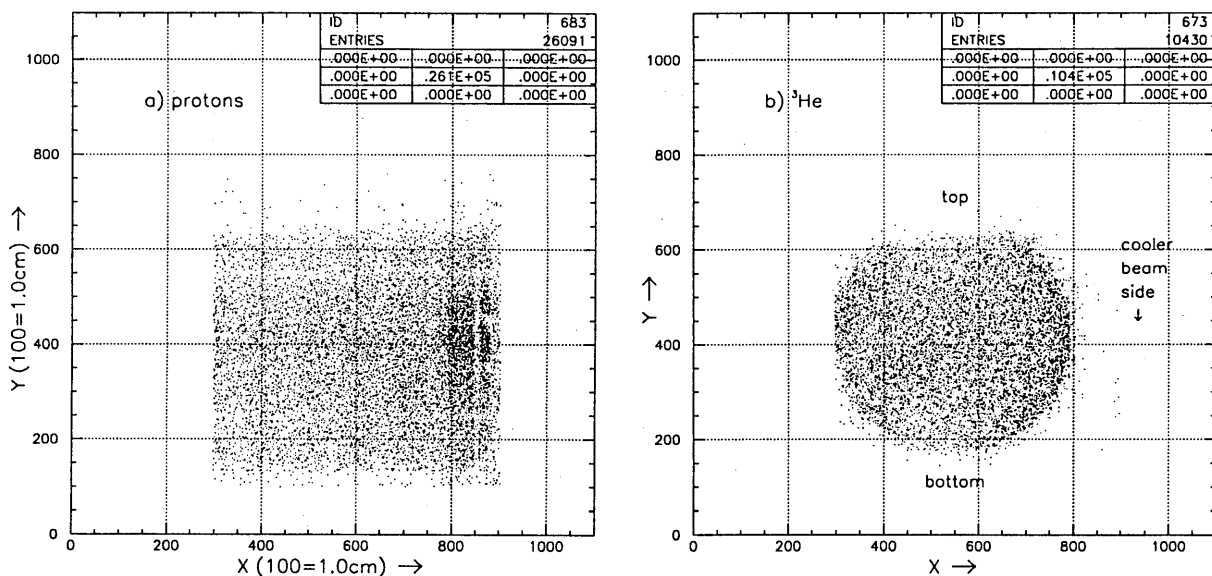| ID		673
ENTRIES		10430
.000E+00	.000E+00	.000E+00
.000E+00	.104E+05	.000E+00
.000E+00	.000E+00	.000E+00

top

cooler
beam
side
↓

Y →

bottom

X →

Figure 4. Two-dimensional drift chamber position spectrum measured at the entrance to the magnetic channel for (a) protons and (b) ^{3}He that gave front-rear scintillator coincidences at a bombarding energy 1.0 MeV above the pd $\rightarrow$ ^{3}He π^0 threshold. The approximately circular ^{3}He locus reflects the kinematic limits close to threshold, together with a vertical truncation imposed by the channel acceptance.

which is limited to ~5 cm extent vertically, presumably by the vertical gap between the poletips of the second 3° dipole. (The horizontal cutoff in Fig. 4, on the side away from the Cooler beam pipe, is artificial, resulting from timing problems for the last two wires on the drift chamber, rather than from the geometrical acceptance of the channel.) The ^{3}He region, confined to a cone by kinematics (although somewhat elongated horizontally by the dispersion in the 6° bending magnet), appears well-centered on the channel's acceptance horizontally, but is clearly truncated at the top. The truncation, which appears to reflect a small (correctable) vertical misalignment of the channel dipoles, eliminates perhaps 10% of the ^{3}He yield. Additional losses may have arisen from multiple scattering out of the acceptance along the length of the channel, but these will be reduced in future runs by the addition of the vacuum pipe. The results of this first run thus encourage us to expect nearly 100% acceptance in future runs at an energy 1 MeV above the pionium threshold, where the size of the ^{3}He kinematic cone is essentially identical to that for single π^0 production at 199.6 MeV, but the ^{3}He's have about twice as high a laboratory kinetic energy.

In a second CE-49 run, scheduled later in 1994, we will investigate backgrounds and channel acceptance, and make the first measurements of absolute production cross sections, near the $\pi^0\pi^0$, but below the $\pi^+\pi^-$, production threshold. This run will offer an opportunity to install the solid-state detectors at the end of the channel, and to measure the singles rates we will have to withstand in the $\pi^\pm$ veto scintillators around the 6° magnet. The actual search for pionium production will not occur until the third, as yet unscheduled, run.

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