A SEARCH FOR COHERENT PION PRODUCTION IN THE ^{12}C$(p, n\pi^+)$ REACTION AT 800 MEV*

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Planned high resolution measurements of pions at very small angles in coincidence with neutrons from the (p,n) reaction on ^{12}C at 800 MeV are discussed. The experiment is scheduled for the Neutron Time-of-flight Facility NTOF at LAMPF. It is based upon the results of recent coincidence measurements for (p, n) reactions in the Δ resonance region carried out at KEK by J. Chiba *et al.* The location of the Δ peak in the neutron spectrum was found to be dependent on the coincident particles, in qualitative agreement with a theoretical model which suggests that a significant component of the shift is related to spin-longitudinal $(\sigma \cdot q)$ correlations. In that model, coherent pions, pions which traverse the nucleus as in elastic/inelastic pion scattering, are the signature of the spin-longitudinal correlations. Some evidence for coherent pions can be found in the KEK coincidence data. The experiment scheduled for this summer at LAMPF is a measurement of the total energy of the $n + \pi^+$ with much higher resolution than the KEK experiment, so that the ground state of ^{12}C can be clearly separated from the low-lying excited states. A later measurement of the neutron polarization in coincidence with the pions is expected to determine whether the spin-longitudinal response is strongly enhanced.

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1. Introduction

The interpretation of the large shifts observed in the position of the Δ resonance excited by charge exchange reactions on nuclear targets compared

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to proton targets is still uncertain. The calculations of Udagawa and his coworkers [1], as well as those of the Lyon group [2], suggest that an important component of this shift is related to dynamical correlations introduced by the residual spin- longitudinal ($\sigma \cdot q$) delta-particle nucleon-hole interaction. Such 'pionic' collectivity may be closely related to the pionic enhancements predicted in the quasielastic region, and sought but not seen in both $(\vec{p}, \vec{p}\,')$ and $(\vec{p}, \vec{n}')$ reactions as described by McClelland *et al.* [3] Decay information should provide important tests of the theory as discussed at this Conference by Oltmanns. We will first review the existing decay data, and then tell you about the high resolution measurements of coherent π production planned for LAMPF.

2. Review of the KEK Experiment

The only investigation of the decay of nuclear Δ's excited in the (p, n) charge exchange reaction on a nucleus took place at KEK [4]. Similar results have recently been reported for the (^{3}He,t) reaction at Saturne [5]. The (p, n) experiment was carried out with a secondary beam of 822 MeV protons from the Proton Synchrotron. It ran for about six months under the leadership of J. Chiba. The Rütgers group joined toward the end of the run and played a significant role in the analysis and interpretation of the data. Neutrons scattered between 0° and 6° were detected in a 10x5 array of plastic scintillators at a distance of about 10 m. Surrounding veto scintillators rejected charged particles. Decay particles were detected in FANCY, a cylindrical spectrometer [6] composed of a solenoid with a 3 kG magnetic field, a cylindrical drift chamber and a cylindrical hodoscope. The efficiency of the FANCY detector was greater than 95% over the angular range from 12° to 141°. Table I lists important experimental parameters.

TABLE I

Experimental Parameters (KEK)

	Neutron Detection
Efficiency	5.5%
TOF Resolution	350 ps
Momentum Resolution	15 MeV/c at 1.0 GeV/c
	50 MeV/c at 1.5 GeV/c
	FANCY Spectrometer
Efficiency (12°-141°)	>95%
Momentum Thresholds	75 MeV/c (π)
	220 MeV/c (p)
Momentum Resolution	15 MeV/c at 1.0 GeV/c

	Proton Beam
Momentum	1.49 GeV/c
Momentum Spread	0.02 GeV/c

The targets were carbon and polyethylene (CH_2); H-target results were deduced by subtraction of the C from the CH_2 spectra. Comparison of the inclusive neutron spectra for C and H shows that the Δ resonance peak in the C neutron spectrum is clearly shifted to higher neutron momenta relative to the corresponding peak in the H spectrum, as previously observed.

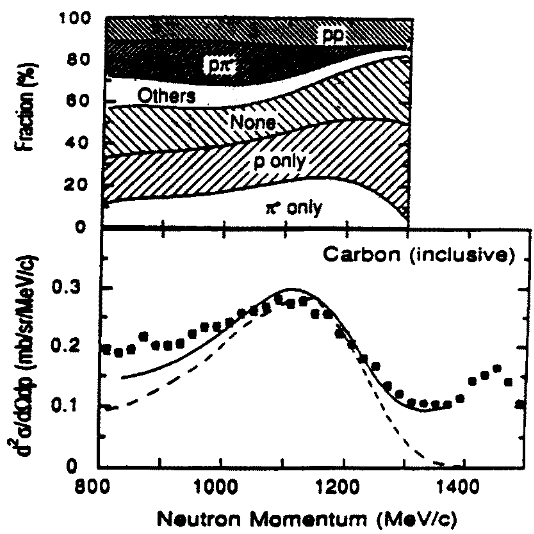

Fig. 1. The fraction of each event type in the inclusive spectrum from KEK.

The following two figures reprise the published results [4] concerning the decay in the nucleus of the Δ resonance created in the (p,n) reaction. The solid line drawn on the inclusive spectrum in Fig. 1 shows the cross sections (scaled by a factor of 0.85) for the same reaction at 800 MeV [7] at 4° with a shift of about 35 MeV/c to account for the difference in incident momentum. The dashed line corresponds to a calculation of quasi-free Δ production with a mass of 1207 MeV and a width of 190 MeV. The shaded bands at the top of the figure indicate the fraction of events in six categories. The event trigger consisted of a coincidence of a beam proton and a hit in any neutron detector and an anti-coincidence with the veto scintillators. The six event categories then correspond to the particles observed in FANCY in coincidence with the forward neutron. A 'π-only' event, for example, corresponds to the observation of a neutron and one π^+ in coincidence, and no other observed particle. 'Others' includes three-particle coincidences, unidentified particles, *etc.* A p and π^+ in coincidence, the two particles expected from the decay of the free Δ^{++}, constitute only a small fraction of the events at the high momentum end of the neutron spectrum. At least one charged particle was observed in about 80% of the events. The other 20%, with decay neutrals and/or charged particles lost to threshold and acceptance limits, are labeled 'None'.

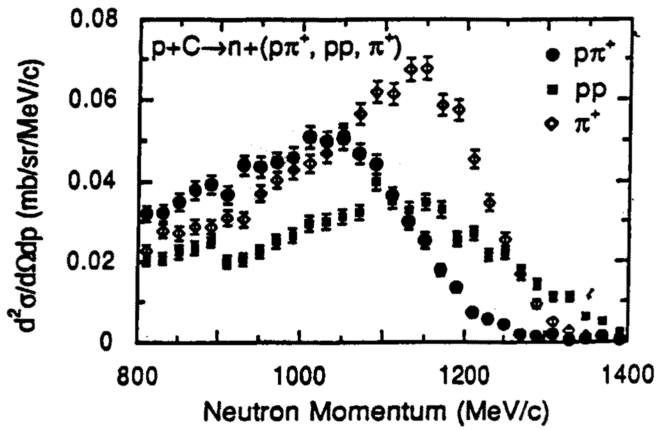

Fig. 2. Momentum spectra of forward neutrons for π, pp, and $p\pi$ events on C targets.

Fig. 2 shows the momentum spectra of forward neutrons for the various kinds of events on the carbon target. In contrast to the inclusive data, the neutrons from C corresponding to $p\pi^+$ events are shifted slightly to *lower* neutron momenta relative to H. The neutron spectra corresponding to pp and π-only events, on the other hand, are shifted in the same direction and roughly by the same magnitude as observed in the inclusive spectra. Some of this shift is purely kinematic in origin, due to the relative phase space available for the different decays or to limited acceptance and thresholds in the detectors. Indications are that these factors largely explain the pp spectrum. However, it is apparent that the pp and π-only shifts are in large measure responsible for the observed shift in the inclusive spectrum and that the apparent mass of the Δ depends on its decay mode. A definitive theoretical analysis should include the effects of experimental cuts. Nevertheless, it is useful to compare these results with preliminary calculations from Udagawa *et al.*, shown in Fig. 3. [8] The shift between the $p\pi^+$ results and the pp or π-only results is well reproduced. The normalization factors shown (0.25, 0.38, and 1.67) make up for losses due to distortions of the outgoing particles, acceptance cuts, neutrals, and the like. The fact that the normalization factor is greater than 1.0 for the single π events is interesting, and only partly explained by the fact that some of these events are actual $p\pi^+$ events in which the p was not detected. But it is also important to note that distortion corrections for theoretical π-only events are already included in the inclusive calculation, since pion propagation through the nucleus is an integral part of the calculation. It is these 'coherent' pions which are the theoretical signature of the dynamic pion collectivity and it is important to determine whether we are indeed seeing such pions.

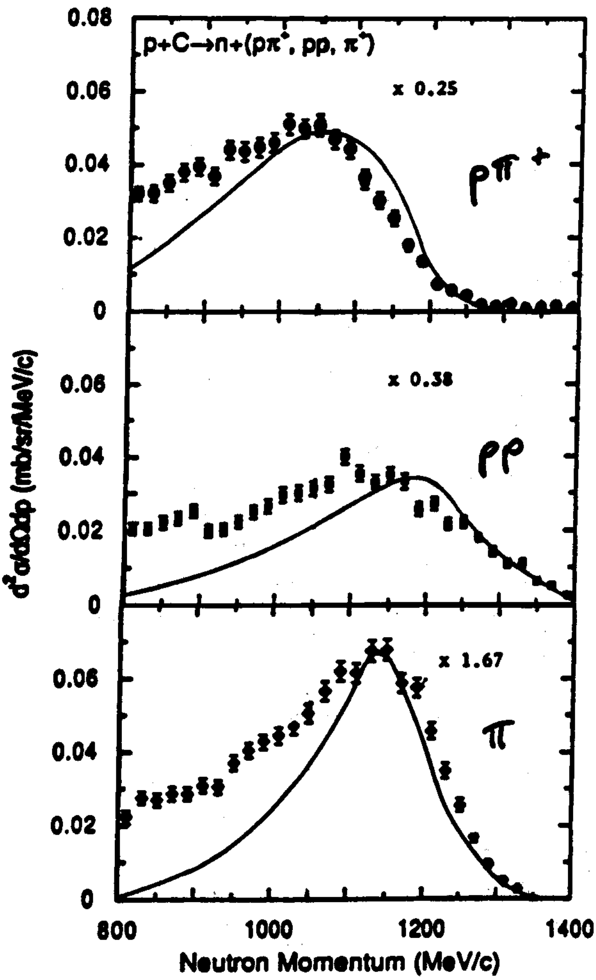

Fig. 3. Neutron spectra for the three types of events predicted by T. Udagawa *et al.* [8].

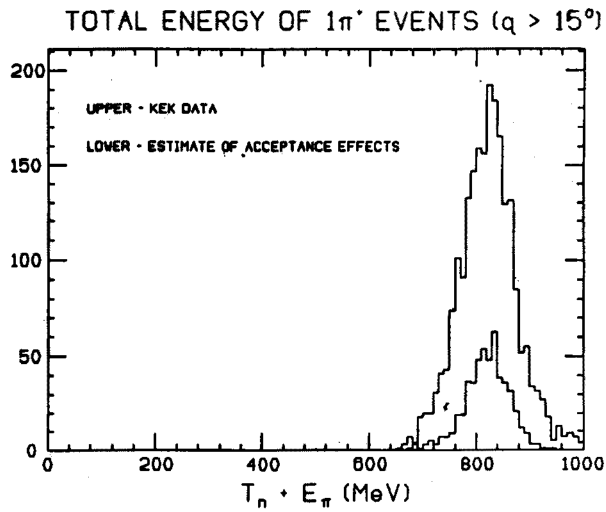

Fig. 4. Total energy observed in π events. The upper curve corresponds to the KEK data. The lower curve shows the results of a Monte Carlo calculation of expected events without coherent pions.

There are strong indications from consideration of the total observed energy of detected particles that coherent pions are being seen. The pp events presumably correspond mostly to $\Delta N \rightarrow pp$ reactions inside the nucleus, and they are related to the spreading potential of the Δ. The total observed energy for these events peaks within 60 MeV of the beam energy of 822 MeV, but it is clear that energy is typically lost, probably to nuclear decay particles. The corresponding spectrum for π-only events is shown in Fig. 4. When a cut on the momentum transfer is made, the resulting peak is essentially right at the beam energy, as expected for coherent pions. The width is large, consistent with the experimental energy resolution. The momentum transfer cut tends to eliminate background due to the acceptance hole in the KEK detector. The Monte Carlo estimate of apparent π-only events due to actual $n\pi^+$ events, *e.g.*, and other acceptance cuts are shown to be much smaller than the observed number.

The spin-longitudinal (ΔN^{-1}) interaction should lead to forward-going pions in the delta rest frame. The experimental angular distribution of pions relative to q is shown in Fig. 5 with a peak at small angles, close to the acceptance hole. Fig. 5 appears to be in qualitative accord with theoretical expectations for coherent pions [9, 10]. Monte Carlo estimations of the angular distribution of pions from $p\pi^+$ events where the proton is missed due to the spectrometer acceptance cuts cannot reproduce the strong

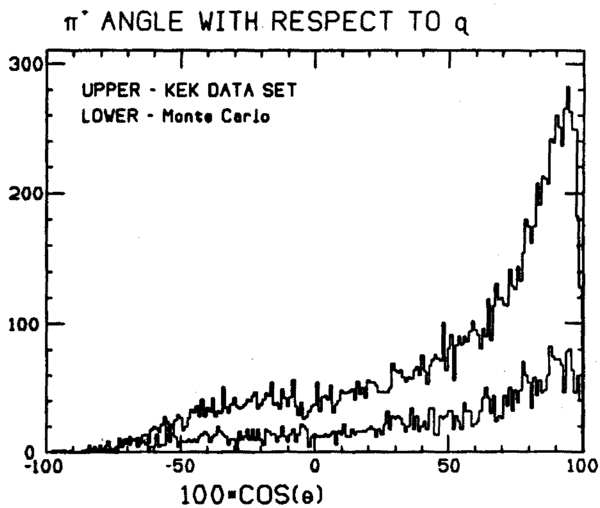

Fig. 5. Angle of observation of the π for π-only events, relative to the angle of the momentum transfer vector. The upper curve corresponds to the KEK data. The lower curve shows the results of a Monte Carlo calculation without coherent pions.

forward peaking of the observed spectrum. Furthermore, a widely discussed possible contamination reaction, the observed neutron originating in the decay of a Δ^+, does not have the correct angular distribution of pions either.

These data have been accepted by Oltmanns *et al.* [9] as evidence for coherent π production. Nevertheless, it is important to obtain the really definitive data which will be possible at LAMPF.

3. The measurements planned for lampf

At LAMPF, we expect to measure the cross section for coherent pion production from 0° to 10°–in the region of the acceptance hole in the KEK data, where the predicted cross section is very large– and we will do this with about 3 MeV total resolution, much better than was possible at KEK. With this resolution we will determine whether indeed the target nucleus is being left in its ground state (or other excited states) or whether the spectrum corresponds to a different process. Observation of the ^{12}C spectrum would be a very elegant result, independent of the prediction of Udagawa *et al.*, [8] since it would tie together two apparently very different reaction modes so neatly. But it would also be a beautiful confirmation of the theoretical predictions.

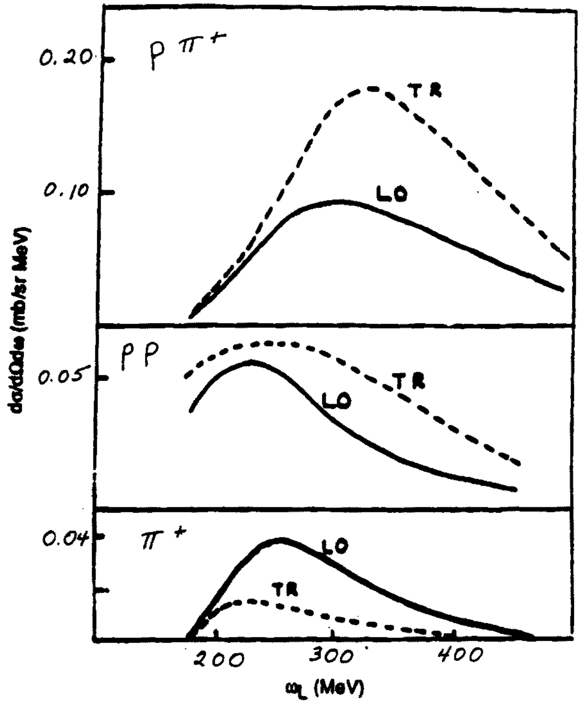

Fig. 6. Preliminary calculations by Udagawa *et al.* [8] of spin-longitudinal and spin-transverse contributions to the three types of events.

A measurement of polarization transfer observables can separate the spin-longitudinal and spin-transverse response in the delta region. Such measurements have been carried out for the inclusive reaction, and results are expected soon. But the clearest signature of a spin-longitudinal enhancement is predicted when the polarization transfer experiment is carried out with a forward pion in coincidence. The reason is illustrated in Fig. 6. These are Udagawa's (preliminary) calculations [8] of the spin longitudinal/spin-transverse contributions to the exclusive cross sections for the three types of events: $p\pi^+$ (quasi-free), pp (spreading), and coherent pions (π^+). The quasi-free events maintain essentially the free L/T ratio. The pp events show some enhancement of the L component. But the coherent pion events invert the free ratio, and thus should show an enormous spin-longitudinal enhancement in the polarization transfer experiment. These are the events which give essentially all the signal expected in the inclusive reaction where it is only masked by the other decay modes. Our measurement of the polarization transfer has been approved for LAMPF with the same high priority as the cross section measurements, but the experiment cannot run this year because of the short running schedule. Whether it runs in 1994 depends on the success of the cross section measurements and the funding of nuclear physics (and NTOF in particular) at LAMPF next year.

4. Experimental setup

A schematic description of our set-up is shown in Fig. 7. A proton beam is incident on a target in the target chamber. Neutrons created in the charge exchange reaction at 0° follow the dashed line straight through several magnets toward the NTOF detector 170 m away. The incident beam is diverted into the beam dump by a sweeping magnet BM-05. Serendipity has provided that just the same field in the sweeping magnet that bends the protons into the beam dump also bends charged pions of the momenta we want to observe into detectors at the side of the magnet. A multi-wire drift chamber will be placed inside the yoke of the sweeping magnet but just outside of the magnet polefaces and parallel to the line connecting the target to the beam dump. It will be a straw chamber, a small version of the chambers being built at Rutgers and William & Mary for the CEBAF polarimeter. It will be about 80 cm long and 15 cm high and will contain four planes with 80 individually instrumented vertical wires each and three planes of horizontal wires. Particle position will be measured to about 200 μm and angular information will obtained to better than .02 rad. Two scintillators placed behind the second chamber will provide timing pulses for the neutron coincidence permitting identification of the beam burst in which true events originate. These scintillators will also permit us to distinguish between protons and pions of equal momentum since these are separated (over a 3 m path length) by at least several ns and generally more than 10ns in the region of interest.

Calculations which include the effects of beam spot size of about 1 cm diameter indicate that the exit position and angle measured in this way will define the track momentum to within 1.5 MeV/c. This figure (which corresponds to between 1.0 and 1.5 MeV depending on pion energy) will combine with a similar energy resolution for the neutron arm for a total energy resolution of about 3 MeV. This will permit us to clearly identify the ground state and possible low lying excited states of ^{12}C. Fig. 8 illustrates some sample tracks through the sweeping magnet to the wire chambers. Calibration of the spectrometer will be done by measuring the angular distribution of pions from the $p(p,\pi^+)d$ and $p(d,\pi^+)t$ reactions at 360 and 500 MeV. Since there are only two particles in the final state, kinematics defines the energy to angle relationship precisely.

With this system, we will be able to measure the pion spectrum from about 150 to 400 MeV/c. Even more importantly, we will be able to measure the angular distribution from 10° all the way in to 0° and test the

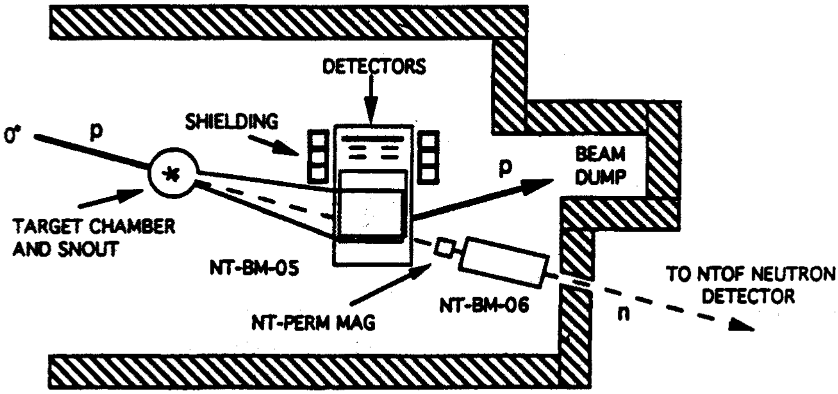

Fig. 7. A schematic diagram of the NTOF facility at LAMPF. The straw chamber and trigger scintillators are placed inside the yoke of the sweeping magnet BM-05.

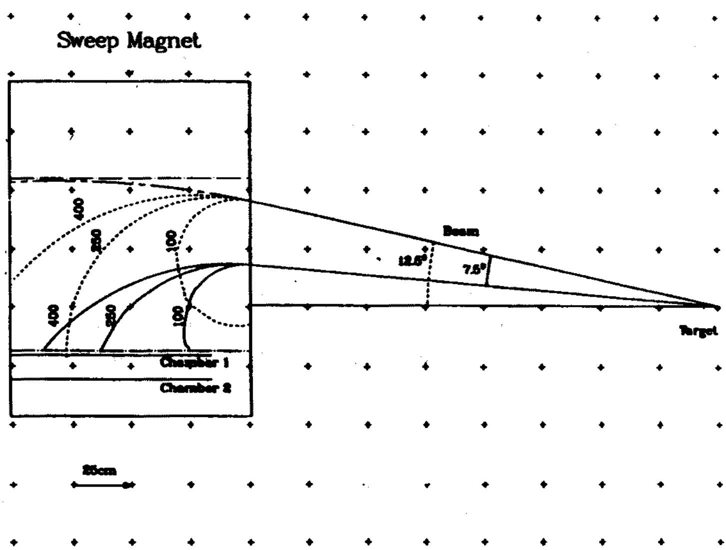

Fig. 8. Sample tracks of particles with momenta (MeV/c) specified at 0° and 7.5° in the field of the sweeping magnet.

theoretical predictions [9,10] which show a very strong increase in cross section at forward angles. The practical advantage of this system will be the low background due to the insensitivity of the detectors to neutrons and the small angular cross section shown to the target. Shielding material stacked between the detectors and the target, and between the detectors and the beam dump, will further reduce unwanted hits.

Simulations show that the data taking rate will be limited by the proton rates on the wire chambers, and by the rate of accidental $n\pi^+$ coincidences. The first of these rates will be mostly determined by the flux of protons from the $^{12}C(p,p')X$ reaction at the target, with a 10% contribution from π^+s from Δ^{++} production and Δ^+ production. To reduce this flux, we will block off all angles greater than 10° from the 0° line. For 8 nA of proton beam on a 0.25 cm CH_2 target, the maximum instantaneous hit-rate on any individual wire will be approximately 30000/sec/wire, about twice the average rate. 'Accidental' coincidences, events where a pion and neutron are seen from two separate events in the same beam burst, will be significantly less than the rate of good events in the energy regime where the two particles add up to the beam energy.

Time estimates for this experiment required the extraction from the KEK data of the total expected flux of neutrons at low angles and the expected flux of pions from delta decay and coherent pion production. In order to extract these quantities from the data, Monte Carlo (MC) simulations of the experiment were run in order to correct for the acceptance of the CDC and neutron hodoscope. These simulations were successful in describing both the hydrogen-target and carbon-target angle and momentum distributions for protons and pions, failing only to predict the number of single-π^+ events for carbon (which we will investigate in this experiment) and the precise shape of the pion momentum distribution from Δ^{++} decay (which is strongly affected by rescattering). A separate simulation was done to estimate the efficiency of the KEK neutron detector, the result of which was 5.5% independent of neutron energy and angle over the whole of the Δ region.

The following run parameters are envisioned:

$$\text{beam current} = 8\ \text{nA}$$

$$\text{target thickness} = 0.22\ \frac{\text{gm}}{\text{cm}^2}$$

$$\text{NTOF detector efficiency} = 20.0\%$$

$$\text{NTOF detector solid angle} = .0245\text{msr}.$$

These parameters should yield the following rates:

$$\text{event rate of coherent } n\pi^+ = 440/\text{hr}$$

$$\text{accidental coincidence rate} = 46/\text{hr}/\text{MeV}$$

If these estimates are accurate, we should get a spectrum with high statistics in 1 week of running time, good enough to identify the features of the ^{12}C spectrum and to bin the data in 1° bins. This work should provide a firm basis for proceeding to the polarization transfer measurement in the following year.

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