Communications

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Comparison of activation and direct measurement yields for the $^{13}C(p,n)^{13}N$(g.s.) reaction*

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A measurement was made of the angular distribution of neutrons from the $^{13}C(p,n)^{13}N$(g.s.) from which the total cross section leading to the ground state of ^{13}N was determined. At the same time, the determination of the ^{13}N activity was made. The ratio of the reaction cross sections at 22.8 MeV determined from ^{13}N activation to the yield of the ground state neutron group is 1.06 ± 0.07. Thus there is no significant competition in the decay of excited states by γ emission with particle emission. This result implies that the reaction can be used as a convenient fast neutron calibration source.

[NUCLEAR REACTIONS $d\sigma/d\Omega$ $^{13}C(p,n)^{13}N$(g.s.), $E = 16.3$, 22.8 MeV. Comparison of neutron yield and ^{13}N activity.]

In a talk for the 1973 Pion Physics Summer School at LAMPF, Rost[1] cited activation measurements of the $^{13}C(\pi^+,\pi^0)^{13}N$ reaction by Chivers *et al.*[2] and Zaider *et al.*[3] that are in serious disagreement with generalized optical model calculations of Koren[4] or Gibbs, Jackson, and Kaufman[5] and a coupled channel calculation of Miller.[6] The observed cross section was much larger at 180 MeV than could be achieved by any reasonable calculation in the vicinity of the (π,n) 3, 3 resonance. A suggestion was made that although only the ground state of ^{13}N is particle bound, γ decay from excited states feeds that state sufficiently to cause the discrepancy. All such (π^+,π^0) single charge exchange reactions have been identified to date only by radioactivity or particle decay of the daughter state.

This investigation bears in another way on the anomaly. Rost, Kraushaar, Sparrow, and Anderson[7] have looked at the contribution of sequential reactions of the type $^{13}C(\pi^+,p)^{12}C$ followed by $^{13}C(p,n)^{13}N$ in the rather large samples used by investigators. The effects may be considerable for this and many other reactions initiated by pions. Therefore a knowledge of the total (p,n) cross section as a function of energy is needed.

A measurement of the $^{13}C(p,n)^{13}N$ reaction cross section by observation of neutron groups and by the ^{13}N activity generated simultaneously was undertaken. A target of 5.41 mg/cm^2 carbon enriched to 80 atomic percent in ^{13}C was prepared on an 0.8 mg/cm^2 ^{58}Ni backing.[8] Angular distributions at 16.3 and 22.8 MeV were made over 10° to 145° laboratory angle for neutron groups leading to the ground state and states at 2.366 MeV and 3.51 + 3.55 MeV. The time-of-flight spectrum of neutrons is shown in Fig. 1. The states of ^{13}N above 6.38 MeV result in a broad distribution which was not resolved. The resultant angular distributions for the several low-lying states only are shown in Fig. 2.

The measurement of ^{13}N activity was made with the same target under identical bombardment conditions using, as with the neutron measurements, a proton detector set at 55° to normalize the yields from the target. The carbon targets were inserted into a graphite sandwich 1 cm thick to stop the positrons. A ^{22}Na calibration source was inserted in the same sandwich; the difference in range of ^{22}Na and ^{13}N positrons is sufficiently small to introduce negligible error in the effective source detector distance. The calibration of the Ge(Li)

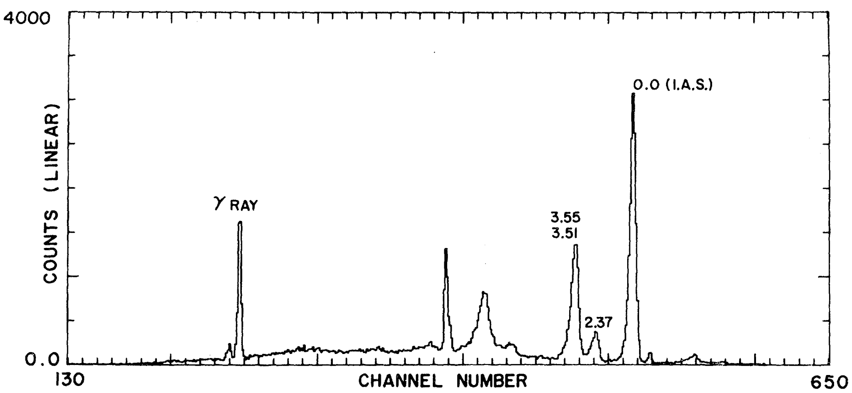

FIG. 1. Time-of-flight neutron spectrum at 10° for the reaction $^{13}C(p,n)^{13}N$ at 22.8 MeV. Only the three peaks leading to low-lying states in ^{13}N are identified.

detector then depends only on the precision of the ^{22}Na standard which was certified to 1%. Data for the positron activities were accumulated by counting over 4 min intervals. At 22.8 MeV the $^{12}C(p,pn)^{11}C$ or $^{12}C(p,d)^{11}C$ reaction yielded a large 20 min activity in addition to the 10 min ^{13}N activity. At 16.3 MeV the ^{11}C activity is not produced, so the background consists of long-lived activity in the ^{58}Ni foil. The activities are shown in Fig. 3. From the bombardment of natural carbon the contribution to the ^{13}N activity from the $^{12}C(p,\gamma)^{13}N$ reaction from the ^{12}C in the ^{13}C target was found to be not more than 1.5%. The curves shown are the result of fitting by χ^2 analysis the activities for ^{13}N and ^{11}C to the decay data.

Determination of absolute cross sections could not be done by measurement of target thickness except in a crude manner. Hence we made use of the $^{12}C(p,pn)^{11}C$ reaction and measurements of the ^{11}C activity to fix the ^{12}C target density and hence the ^{13}C density. Published values of this activation cross section at 21.1 and 30.1 MeV by Cummins,[9] and data from an excitation function given by Aamodt, Peterson, and Phillips,[10] and from Porile,[11] permit the calibration of the target thickness. With the given isotopic abundances of the target material the target density was determined to be 1.10 mg/cm^2 in ^{12}C and 4.31 mg/cm^2 in ^{13}C. The absolute cross section as a result of this method of calibration has an absolute error of about ±20%. The relative errors are indicated on the data points.

The angular distributions of the ground state

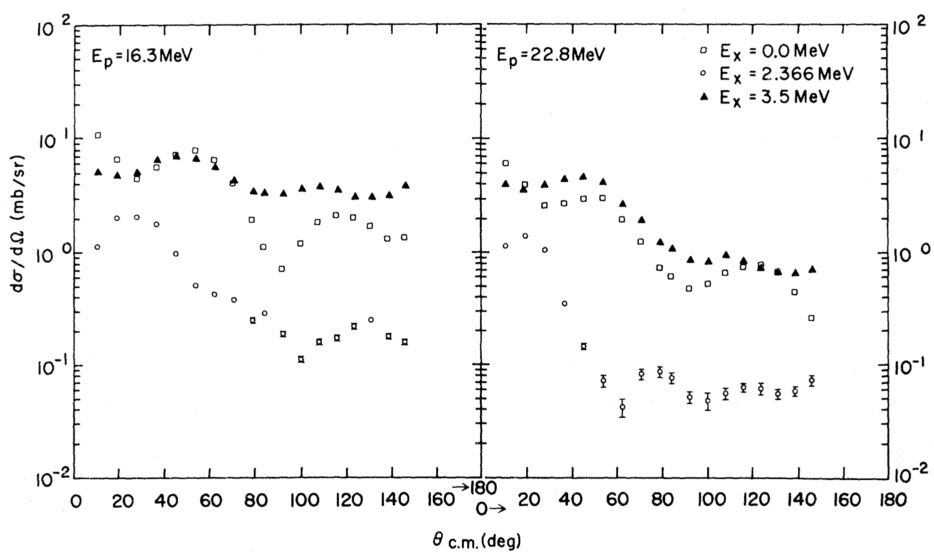

FIG. 2. Angular distributions of neutron groups for the $^{13}C(p,n)^{13}N$ reaction at 16.3 and 22.8 MeV. Excitation energies for the ^{13}N are indicated.

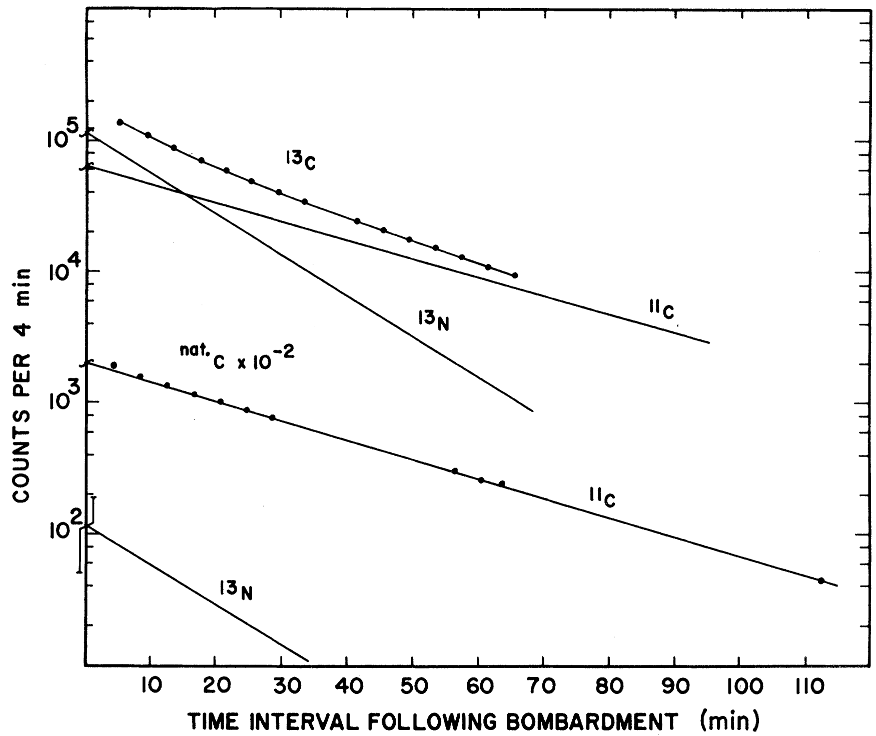

FIG. 3. Positron decay activities observed with an enriched ^{13}C target and a natural carbon target showing the decomposition into ^{13}N and ^{11}C activities.

neutron group were integrated from 0 to 180° by extrapolation, since data are available between 10° and 145° only. For the 22.8 MeV case the error in the integrated cross section because of uncertainty in assumed cross sections is not more than 3% and at 16.3 MeV not more than 5%. Actual distorted-wave Born-approximation (DWBA) fits were not used since the usual straightforward procedures gave very unsatisfactory fits at forward angles and are considered less reliable at back angles. Table I shows the results obtained. The entries represent the total reaction cross section for the $^{13}C(p,n)^{13}N$ reaction. The two entries at 22.85 and 22.80 MeV represent completely independent determinations since they were taken about a month apart.

The error in the activation measurements arises from decomposition of the complex decay curve for the annihilation radiation and correction for possible $^{12}C(p,\gamma)^{13}N$ activity. In every case the target was deposited on ^{58}Ni foil so there were some other generally long-lived activities associated with the background. From past experience with this type of measurement and the problems associated with them, the error is considered reasonable.

The absolute error in the neutron yield measurements is associated with the neutron detector efficiency calibration which was made with an n-p recoil spectrometer at Los Alamos. Variations in the effective beam on target and the thickness were corrected by use of a proton monitor detector placed at 55°. The yield ratio A/N was normalized by the monitor detector only and is independent in the absolute neutron yield.

The yield ratio A/N indicates that at both 16.3 and 22.8 MeV observation of the ^{13}N activity is a suitable measure of the ground state charge exchange reaction. The first $T=\frac{3}{2}$ state of ^{13}N is at 15.07 MeV and has a γ decay width to the ground state $\Gamma_{\gamma 0}/\Gamma=0.023$. Contributions to the ground state via other γ transitions are not known. In the (p,n) reaction, the $T=\frac{1}{2}$ states are favored

TABLE I. Measured cross sections for the $^{13}C(p,n)^{13}N$ reaction.

Energy (MeV)	Cross section (mb) From ^{13}N yield (Activation)	From ground state neutron group	Ratio A/N
16.30	39.6 ± 0.4	43.0 ± 3.0	0.92 ± 0.07
22.85	16.2 ± 0.2	15.6 ± 1.1	1.04 ± 0.07
22.80	17.3 ± 0.2	16.0 ± 1.1	1.08 ± 0.07

over the $T=\frac{3}{2}$ states by a factor of 2 from isotopic spin coupling alone, whereas the (π^+, π^0) reaction going through the $T=\frac{3}{2}$ resonance favors the $T=\frac{3}{2}$ states in ^{13}N by a factor of 10 over the $T=\frac{1}{2}$ states. Such an enhancement from excited $T=\frac{3}{2}$ states might yield some ground state activity but not a 10- to 20-fold increase needed to be consistent with several of the calculations. At 16.3 MeV the (p, n) reaction is not capable of populating the $T=\frac{3}{2}$ states, while at 22.8 MeV the 15.07 MeV state and a range of 4.5 MeV above may be excited. The ratios of Table I are not incompatible with some ground state activity due to these states, although not with statistical significance.

Although the objective of this experiment was the determination of the yield ratio, we attempted to fit the neutron angular distribution for the ground state group by both macroscopic DWBA and coupled channels calculations involving inelastic excitations. The results were very unsatisfactory, indicating that a microscopic description of the states using detailed wave functions for the system as well as a study of the effect of the two-step reactions such as (p, d) (d, n) might be needed. Reitan[12] made a Glauber model calculation for the (π^+, π^0) reaction using rather specialized nuclear wave functions which gave a very different behavior in the region of the 3, 3 resonance. We have not yet calculated the corresponding results for the (p, n) reaction. For this paper we show no fitted curves to the angular distribution data.

The reaction provides a means for neutron detector efficiency calibration which may be as useful as a proton recoil telescope.

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