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Pion absorption in the $^{13}C(\pi^+, p)^{12}C$ and the $^{12}C(\pi^+, p)^{11}C$ reactions at 75 MeV

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Abstract. The $^{13,12}C(\pi^+, p)^{12,11}C$ reactions were measured at $T_\pi = 75\ MeV$ and $\theta_{lab} = 21°$ with a resolution sufficient to separate several states. Comparison with $^{13,12}C(p, d)^{12,11}C$ reactions at the same momentum transfer indicates similar reaction mechamisms.

1. Introduction

Pion absorption reactions on nuclei with emission of a single nucleon might give some information on several aspects of pion-nucleus physics. In the simplest picture the rest mass of the pion (~ 140 MeV) is released as kinetic energy in the final state and the absorbing nucleon is too energetic to remain bound by the nucleus which is then left in some highly excited single hole state. The elementary vertex to be considered in our case with positive pions is then $\pi^+ + n \rightarrow p$. However, since a pion cannot be absorbed on a single free nucleon, the (π^+, p) reaction in nuclei has a very small cross section compared for example with the $(\pi^+, 2p)$ reaction.

It seems to be generally accepted today that when pions are absorbed in nuclei, some form of intermediate state is present. However, the details of production, propagation and decay of such states is not well understood. In order to gather new nuclear structure information from (π^+, p) reactions, pion absorption and off-shell effects have to be understood. Thus (π^+, p) reactions might yield information regarding correlations nad high momentum components in nuclear wave functions because of the large momentum transfers present, provided a complete understanding of the pion-nucleus interaction including absorption and off-shell effects. In addition the $T = 1$ nature of the pion should allow the excitation of $\Delta T = 3/2$ transfers which are forbidden in nucleon induced reactions such as (p, d). However, as we will see, comparison with (p, d) scattering spectra shows almost identical excitations.

Generally, there is very little (π^+, p) data published. The older (π^+, p) results[1,2]) are of rather poor quality since the resolution was not sufficient to

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separate individual final states. However, recently J. F. Amann et al.[3]) measured the $^{12}C(\pi^+, p)^{11}C$ reaction at 50 MeV with good resolution and compared it with results from the $^{12}C(p, d)^{11}C$ pick-up reaction near the same momentum transfer. In addition R. E. Anderson et al.[4]) measured the ^{12}C and $^{13}C(\pi^+, p)$ reaction at 90 and 170 MeV. Our results on the ^{12}C and ^{13}C comparison at 75 MeV presented here are consistent with the measurements of Anderson et al.

It is possible to obtain information on the (π^+, p) reaction, but to the ground state only, via detailed balance by measuring the pion production (p, π^+) cross section. This reaction was extensively studied at Uppsala,[5]) Indiana,[6]) Orsay,[7]) and Saclay.[8,9])

2. Experimental procedure and results

The experiment was carried out at the Swiss Institute for Nuclear Research (SIN) with the πMI channel and pion spectrometer. Running conditions with a primary proton beam of $\sim 100\ \mu A$ were approximately $1.5 * 10^6$ positive pions per second at 75 MeV incident on a 322 $mg\ cm^{-2}$ 99% enriched ^{13}C target and on a 340 $mg\ cm^{-2}$ natural carbon target. Momentum range of the incident pion beam was $\Delta p/p = \pm 1.4\%$. A standard layout was used with six multiwire proportional chambers; three of them were in the beam line with a fast digital readout. The first chamber allowed the determination of the incident momentum whereas the two others measured the angle incident on target. Protons in the beam were removed with an electrostatic separator. Muons and electrons were accounted for by a beam sampling method allowing continuous monitoring of the beam composition. The scattered protons of $\sim$600 MeV/c momentum were detected in the pion spectrometer which for this purpose was running at a field of approximately 15 *k* Gauss. Overall relative energy resolution was 1 MeV *FWHM* which is significantly worse than in the case of poin scattering because of increased energy loss for protons in the detectors, windows, etc. of the spectrometer. However, the resolution was sufficient to separate the ground states and several excited states of ^{12}C and ^{11}C. Background was negligible. Data were taken at a laboratory angle of 21°. The two spectra are shown in Figs. 1 and 2. They include the full angular acceptance of the system of ±4.5°. Absolute cross section values were obtained by measuring pion elastic scattering on ^{12}C during the same run and comparing with existing data.[10]) The cross sections are consistent with values obtained from the pion flux, target thickness, MWPC efficiency and spectrometer solid angle. We believe that the absolute values contain a normalisation error of ±10% in addition to the quoted mostly statistical error. The results are given in Table 1.

3. Discussion

In the $^{13}C(\pi^+, p)^{12}C$ reaction the ground state (0^+) of ^{12}C, the 4.4 (2^+), 7.6 (0^+), 9.6 (3^-), 12.7 (1^+) and 14.1 (4^+) levels were seen. In addition there is a broad bump around 25 MeV excitation energy. In the $^{12}C(\pi^+, p)^{11}C$ reaction the ground state $(\frac{3}{2}^-)$; of ^{11}C, the 2.0 $(\frac{1}{2}^-)$; and a group including the 4.3 $(\frac{5}{2}^-)$; 4.8 $(\frac{3}{2}^-)$ and states around 6.5 and 8.5 MeV were detected. Furthermore there is a state around 14 MeV excitation energy. General features for both reactions are the low

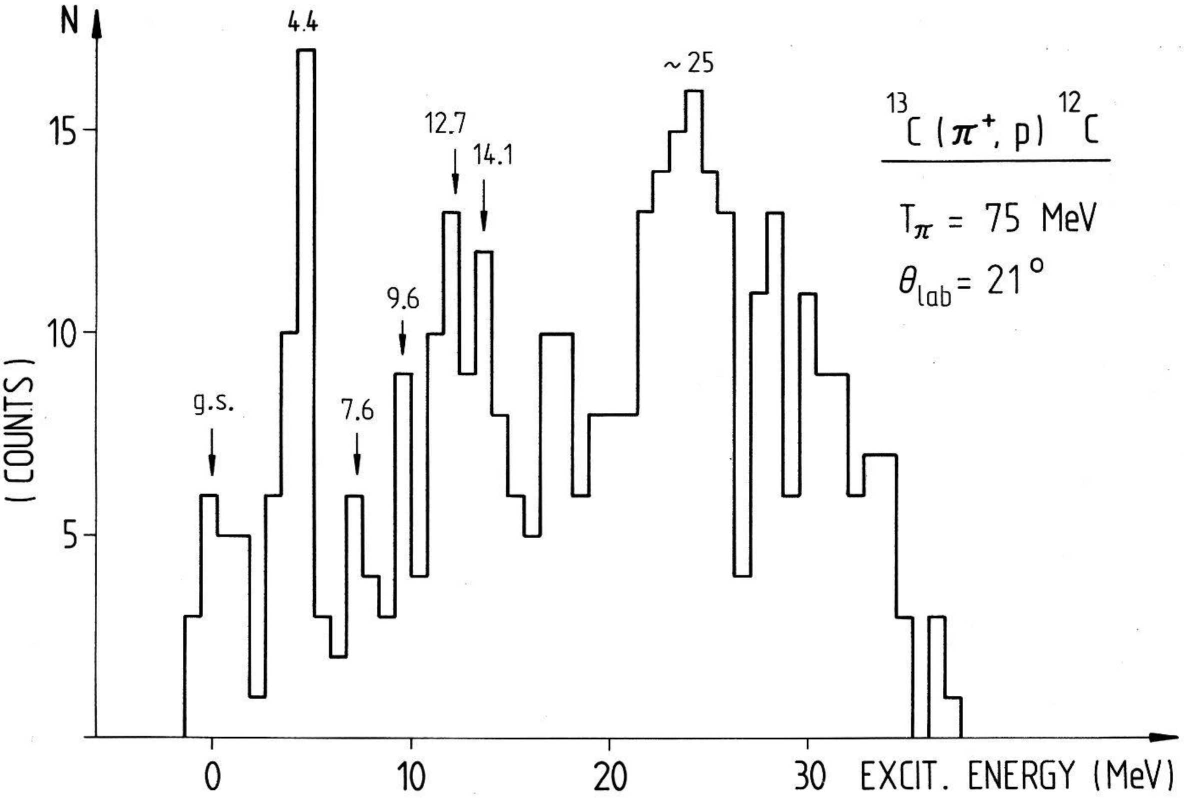

Figure 1
Proton scattering spectrum for the $^{13}C(\pi^+, p)^{12}C$ reaction. The pion incident energy is 75 MeV and the laboratory scattering angle 21°.

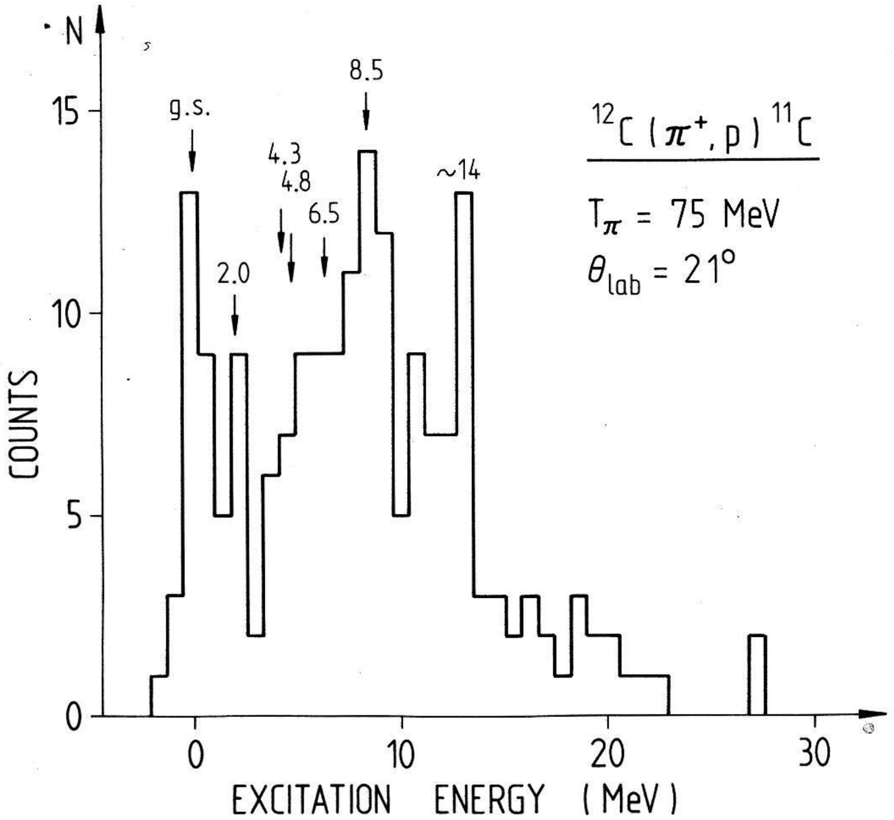

Figure 2
Proton scattering spectrum for the $^{12}C(\pi^+, p)^{11}C$ reaction. The pion incident energy is 75 MeV and the laboratory scattering angle 21°.

Table 1
Cross section values obtained for several states in ^{12}C and ^{11}C via the $^{13}C(\pi^+, p)^{12}C$ and $^{12}C(\pi^+, p)^{11}C$ reaction at $T_\pi = 75$ MeV and $\theta_{lab} = 21°$

Reaction	Excited state of Residual nucleus	Differential cross-section (lab)
$^{13}C(\pi^+, p)^{12}C$	0 MeV	22 ± 6 $\mu b/sr$
	4.43	41 ± 9
	7.65	14 ± 4
	9.65	15 ± 5
	12.7	18 ± 5
	14.1	6 ± 3
$^{12}C(\pi^+, p)^{11}C$	0 MeV	37 ± 8 $\mu b/sr$
	2	11 ± 4
	4.3	–
	4.8	–
	6.48	23 ± 6
	8.5	31 ± 8

cross sections measured. This is readily understood since the main reaction chammel of pion absorption is not on a single nucleon but on a cluster or nucleon pair. In addition the small ground state cross section may be explained with the sizeable momentum transfers involved, leaving the final nucleus preferably in an excited state. However, the comparably strong excitation of the 4.4 MeV (2^+) and in a less pronounced way the 9.6 MeV (3^-) level which both are collective states does not correspond to the naive model of the nucleus being left in some highly excited single hole state. In addition, it can be noticed that the final states of spin $J = 2$ and $J = \frac{5}{2}$ are preferably excited in the residual nuclus of the reactions $^{13}C(\pi^+, p)^{12}C$ and $^{12}C(\pi^+, p)^{11}C$ respectively. This may correspond to a certain angular momentum transfer favorable to either reaction.

The $^{13}C(p, d)^{12}C$[11]) and the $^{12}C(p, d)^{11}C$[12]) reactions were measured at the same momentum transfer than the (π^+, p) reactions and show almost identical scattering spectra. The (p, d) reactions above were satisfactorily described by a conventional DWBA analysis assuming a one nucleon pick-up mechanism for single hole states and a two-step process involving inelastic excitation plus single nucleon pick-up for collective states. This explanation may also apply to the (π^+, p) reaction since (π^+, p) and (p, d) data show similar excitations of the different levels. Thus the (π^+, p) reaction to collective states may be explained via a two-step process involving excitation of the nucleus plus absorption of the pion and emission of a single particle. However, since pions are bosons and absorption was shown to be very important in pion nucleus reactions,[13]) the fact that (p, d) reactions, where no absorption takes place, give almost identical results to (π^+, p) reactions is puzzling and difficult to understand.

4. Conclusions

The reactions $^{13}C(\pi^+, p)^{12}C$ and $^{12}C(\pi^+, p)^{11}C$ were measured at $T_\pi = 75$ MeV and $\theta_{lab} = 21°$. The energy resolution was sufficient to separate several states in the residual nuclei ^{12}C and ^{11}C. Excited levels up to 25 MeV were seen in ^{12}C and up to 14 MeV in ^{11}C. The ground states were weakly excited because of the large momentum transfer involved (>200 MeV/c).

Comparison with the $^{13}C(p, d)^{12}C$ and $^{12}C(p, d)^{11}C$ reactions at the same momentum transfer suggests similar reaction mechanisms in (π^+, p) and (p, d) data. This is difficult to understand, since pions are bosons and absorption was shown to be very important in pion nucleus reactions.

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