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RADIATIVE PION-CAPTURE IN ^{12}C

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The spectrum of high energy gamma rays following the capture of negative pions in ^{12}C was measured with high resolution. The observed structure in the giant resonance region is the first direct experimental proof of the influence of collective excitations in radiative pion capture. This supports recent theories concerning the analogy between this process and muon capture.

Using the hypothesis of partially conserved axial current (PCAC) it can be shown[1)] that the matrix elements for radiative pion capture, i.e. the process $\pi^- N(A,Z) \rightarrow \gamma N(A,Z-1)$, are linked to the axial matrix elements appearing in the weak interactions of μ capture and β decay. In the limit of vanishing pion mass, the two amplitudes are proportional. The formal analogy in the impulse approximation between the effective Hamiltonians in the axial part of the μ capture and radiative π capture[2)], allows one to transfer the well established theory for μ capture to the latter process. It was realized[3)] that in order to explain the total capture rates, μ capture must proceed predominantly through the excitations of collective states in the residual nucleus, namely the $T_3 = -1$ analogous states to the giant resonances seen in photo-absorption and inelastic electron scattering. The excitation of these collective states

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has been inferred in μ-capture on ^{16}O [4] by observing the nuclear rays from the de-excitation of the residual nucleus. In the case of pion capture, an energetic γ ray is emitted instead of a neutrino. Predictions[5] based on the assumptions mentioned earlier show a considerable fine structure in these spectra. The data[6] available do not allow a significant check to be made on the predictions, mainly due to insufficient resolution. The only direct test of the analogy of the matrix elements, by comparing μ^- and π^- capture rates in ^6Li to the ^6He ground state[7], confirmed the theoretical estimates, but within an error of approximately 25%.

In our experiment[8] we have measured the high-energy γ spectrum from π absorption in carbon using a γ ray pair-spectrometer with ∿ 1.5% resolution. The experimental set-up is shown in Figure 1. A π^- beam from the 184 inch Cyclotron was stopped in a 2.5 cm carbon target. The spectrometer was placed to detect γ rays at 90^o to the incident π direction. It consisted of two 46 cm x 91 cm C-magnets combined with a common pole tip to give an analysing area of 218 cm in length and a 33 cm gap. A field of 10 KG was achieved and was measured to an accuracy of 0.2% throughout the volume. The γ rays were converted in a 3% radiation-length gold foil at 109 cms from the target. The directions of electron-positron pairs at entry and exit were measured using six arrays of four gap spark chambers as shown in Figure 1. To minimize multiple scattering and energy loss the spark chambers were constructed of low mass material (20 mg per gap)[9]. Tracks were recorded photographically and have been measured on semi-automatic measuring machines. The trigger for an event was a stopped pion and a coincidence between any two non-adjacent pairs of counters out of the six mounted in front of the magnet. (See Figure 1.) In the analysis an iterative tracking procedure was used to obtain the best-fit momenta to the orbits of the electron and positron.

In order to check the calculated resolution and efficiency of the spectrometer, we performed a calibration experiment using liquid hydrogen. The reaction $\pi^- p \rightarrow n\gamma$ with pions at rest gives a monochromatic γ ray of 129.4 MeV. This provides a measurement of the resolution as well as an independent calibration of the energy scale. The spectrum of γ rays produced in charge exchange ($\pi^- p \rightarrow n\pi^0 \rightarrow n\gamma\gamma$) serves as a check on the low energy end of the efficiency curve. The resulting spectrum is shown in Figure 2 together with the energy dependent efficiency as obtained from a Monte Carlo calculation; this included for electrons or positrons below 25 MeV the energy dependent efficiency observed in the data. We find a Panofsky Ratio of 1.44 ± .16 in agreement with the accepted value of 1.53 ± .05. The absolute yield of the two reactions agrees with the expected one within the statistical error of 10%. The resolution at 129 MeV is 2.0 MeV fwhm and agrees with the calculated value obtained from the Monte Carlo program when measurement errors are included.

The branching ratio for radiative π-capture (about 2%) combined with the acceptance of the spectrometer limited our data sample for carbon to 6500 events obtained in $\sim$ 30 hours beam time. The resulting, uncorrected spectrum is displayed in Figure 3a. There are three clearly resolved peaks around 124, 119 and 117 MeV superimposed on a continuum which extends to the low energy cut off of our spectrometer. The energies of the observed peaks, when corrected for energy loss in the converter and the spark chambers, correspond to γ energies 124.7, 120.3 and 117.0 MeV. The highest peak can be associated with a transition to the ^{12}B ground state ($E_\gamma = 125.0$). This level has its analogy in the $T = 1$, $J = 1^+$ level at 15.1 MeV in ^{12}C. The other two peaks can be interpreted as the $\Delta T = -1$ analogous states to the excitations at 19.5 and the giant-resonance at 22.5 MeV, as seen in inelastic electron scattering on Carbon[10)] and photoabsorption. In order to compute the capture rate to these different states, the shape of the non-resonant background has to be known.

In an earlier paper[8] we have shown that neither simple phase-space with a $^{11}B n\gamma$ final state nor the Fermi gas model can reproduce the shape of the spectrum at lower γ energies. We have used a pole model[11] to describe the direct emission process, which was recently proposed as a competing mechanism to the resonance absorption. The capture occurs on an individual proton in the nucleus and is described by the graph shown in Figure 3a. The calculation contains, besides the normalization another free parameter, the Q value of the $^{12}C \rightarrow$ $^{11}B^* + p$ vertex point. We have chosen a value of 17.3 MeV, corresponding to the ^{11}B ground state.

We have obtained parameters for the three peaks and the continuum by simultaneously fitting to the data a function given by the pole model plus three non-interferring Breit-Wigner resonances. The free parameters are the energies, widths and amplitudes of the peaks, and the normalization of the continuum. Before fitting, the experimental resolution has been folded into the theoretical curve and allowance has been made for the efficiency and for an in-flight background ($\sim$ 10%). This background has been estimated using data taken at 40 MeV pion kinetic energy (see Figure 3b) and normalized assuming events above 130 MeV arise from in-flight pions. In Figure 3c we show the data with the pole model prediction subtracted and the best fit to the three peaks. The parameters of the peaks are given in Table 1, the overall χ^2 for the best fit is 150 for 103 degrees of freedom ($70 \leq E_\gamma \leq 126$ MeV). It should be emphasized that we cannot discount the possibility of the pole model being wrong and that further structure exists below 117 MeV. A more sophisticated approach to the description of the continuum would include a more complete treatment of the initial state of the proton in the nucleus[12].

We compare our subtracted spectrum with predictions by Kelly and Überall[5] who computed the matrix elements using two different particle-hole models[13, 14] for the nuclear levels involved. We have divided their capture rates by the measured total capture rates and weighted them by the relative probability for absorption from a 1s orbit and a 2p orbit[15]. For both models the total theoretical capture rates with excitation of particle-hole states agree with the experimental values within the errors. The theoretical spectrum for the first model[13], folded with the experimental resolution and efficiency is given in Figure 3c. The agreement, mainly with regard to the positions of the dominant states is poor. Since for the alternative model of Lewis and Walecka[14] the widths are not given, we compare in Table 1 the experimental rates with the theoretical predictions. The location of the levels in this case is predicted well. The experimental errors quoted are statistical. Possible systematic errors arise from the inefficiencies in the spark chambers, determination of the number of pions stopped in the target and the evaluation of the product of efficiency and solid angle. An estimate of these errors and the comparison with the calibration run set an upper limit of about 10% for the combination of all these quantities. The uncertainty about the shape of the non-resonant background could, of course, produce a larger effect. The capture rates for the level around 19 MeV disagree by 30%; for the giant-dipole-region they agree very well. It should be mentioned that the rescattering terms and quadrupole excitations in the above theoretical capture rates have been neglected[16].

Since the threshold for $^{12}B \rightarrow {}^{11}B + n$ lies 3.4 MeV higher than the ^{12}B ground state, the measured capture rate to this state is free of any uncertainty in the continuum subtraction. Since the μ capture rate has been measured, the form factors for inelastic electron scattering are known and the ft-value for the β decay to the ^{12}C ground state has been measured, this transition is well suited for a check of the relation between these different processes in an almost model independent way[17]. A theoretical calculation seems, therefore, highly desirable.

The general qualitative agreement between theory and experiment at the present state is gratifying. It can be concluded, that the expected analogy between μ and π capture is indeed fulfilled, and that radiative pion abosrption does offer a powerful tool to study the collective excitations in nuclei.

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Table 1. Experimental and theoretical parameters for observed states in π^- capture in carbon.

$E\gamma$ [e] [MeV] exp.	Γ [MeV] exp.	E [e] ^{12}B [MeV] exp.	E [e] ^{12}C [MeV] exp.	E ^{12}C [MeV] theor. (J^π) [a]	$\frac{\Lambda\pi,\ rad.}{\Lambda\pi,\ tot.}$ [%] exp.	$\frac{\Lambda\pi,\ rad.}{\Lambda\pi,\ tot.}$ [%] theor. [a]
124.65 ± .05	.31 ± .08	.34	15.4	15.1 (1^+)	.097 ± .009	
120.25 ± .05	.45 ± .12	4.80	19.9	19.1 (2^-)	.195 ± .017	.146 ± .013
116.90 ± .11	1.09 ± .13	8.19	23.3	21.6 (1^-) 23.3 (1^-) 22.3 (2^-)	.168 ± .015	.026 ± .002 .089 ± .007 .057 ± .005 } .172 ± .008
Particle - Hole - States					.363 ± .023	.407 ± .034 [a]
Pole Contribution					1.571 ± .114	
ALL					2.03 ± .12 1.60 ± .1 [b]	2.0 [c] 2.3 [d]

a) Kelley and Überall's prediction (Ref. 5) using model of Reference 10.
b) Davies et al, (Ref. 6).
c) Reference 2b.
d) Reference 2c.
e) All errors quoted are the statistical ones only; the possible systematic error in the calibration of the energy scale is .5 MeV.

FIGURE CAPTIONS

FIGURE 1: Experimental Layout. The mirror system for photography of the spark chambers and details of the magnet coils are omitted for clarity. The trigger for an event was $\pi_1 \times \pi_2 \times \pi_3 \times \bar{\pi}_s \times \bar{\pi}_c \times A_i \times B_i \times A_k \times B_k$, $i \neq k$, $k \pm 1$.

FIGURE 2: Energy Spectrum of γ-rays from π^- Capture in Hydrogen. The insert shows the efficiency computed from the Monte Carlo program. The smooth curve was used in the analysis.

FIGURE 3a: Uncorrected Energy Spectrum of γ-rays from π^- Capture in Carbon. The smooth curve is a fitted function using three Breit-Wigners plus a pole model for the continuum in which allowance is made for the efficiency and an in-flight background. The contribution of the pole model beneath the peaks is also shown.

3b: Energy Spectrum for Pions with a Mean Kinetic Energy of 40 MeV. The smooth curve is hand drawn and is used for subtraction of in-flight background for stopped pion data.

3c: Spectrum with the Pole Model Subtracted. The smooth curve is the best fit and the dashed curve is the prediction by Kelly and Überall (Ref. 5) using the Arima model for the giant resonant states (normalized for the number of captured pions and folded with the experimental resolution and efficiency).

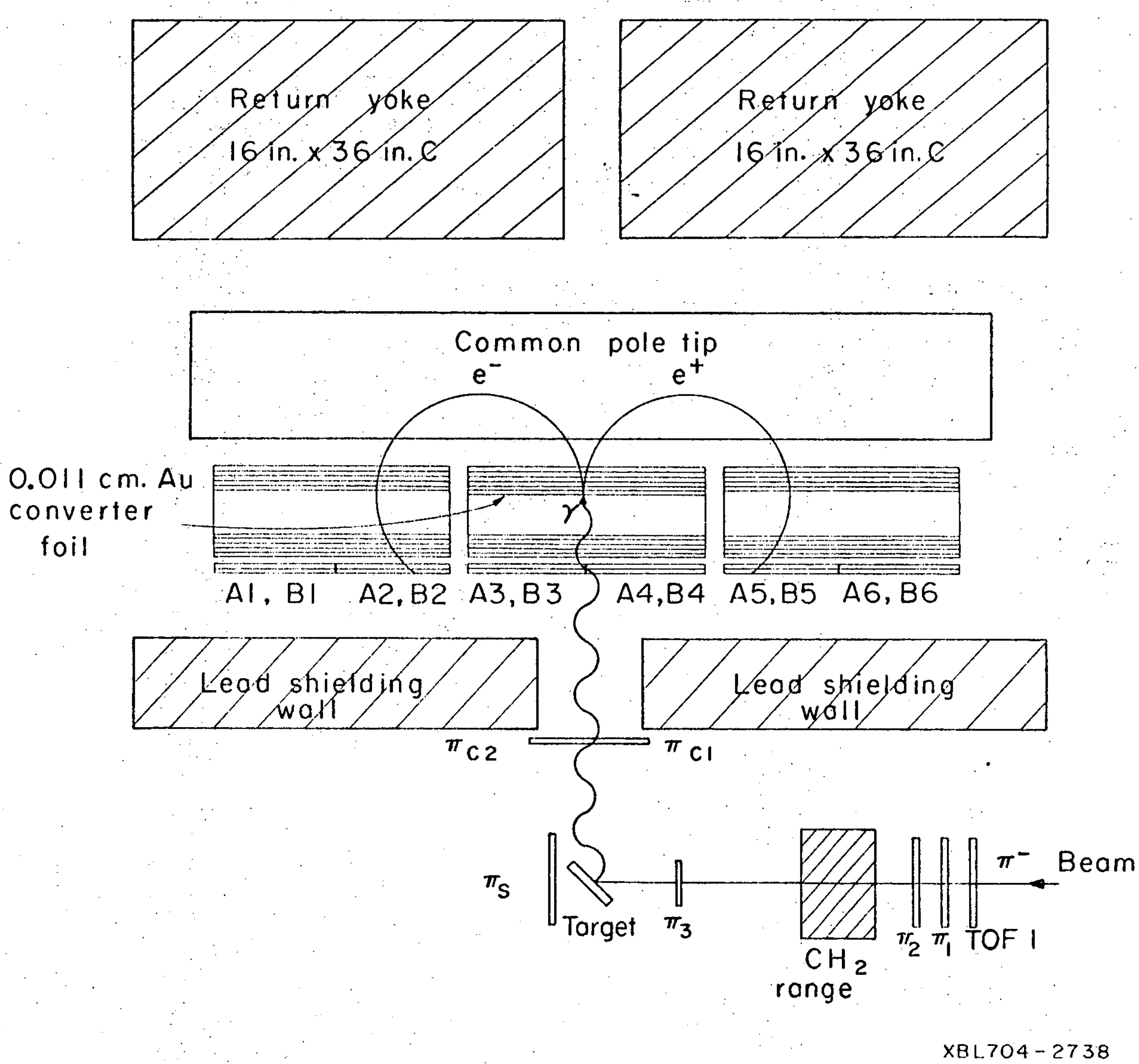
Return yoke
16 in. x 36 in. C
Return yoke
16 in. x 36 in. C
Common pole tip
e⁻
e⁺
0.011 cm. Au converter foil
γ
A1, B1
A2, B2
A3, B3
A4, B4
A5, B5
A6, B6
Lead shielding wall
Lead shielding wall
πc2
πc1
πs
Target
π3
CH2 range
π2
π1
TOF 1
π⁻
Beam
XBL704-2738

Fig. 1

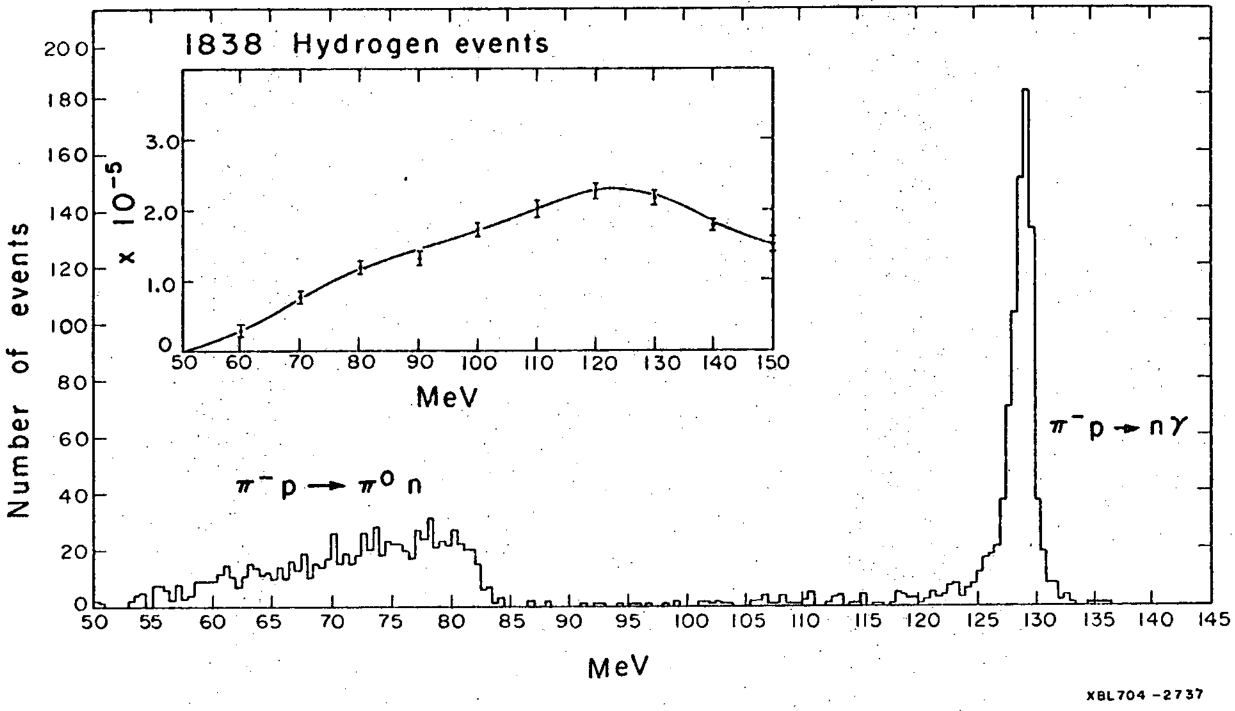
1838 Hydrogen events
x 10^-5
3.0
2.0
1.0
0
50 60 70 80 90 100 110 120 130 140 150
MeV
Number of events
200
180
160
140
120
100
80
60
40
20
0
π⁻p → π⁰n
π⁻p → nγ
50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145
MeV
XBL704-2737

Fig. 2

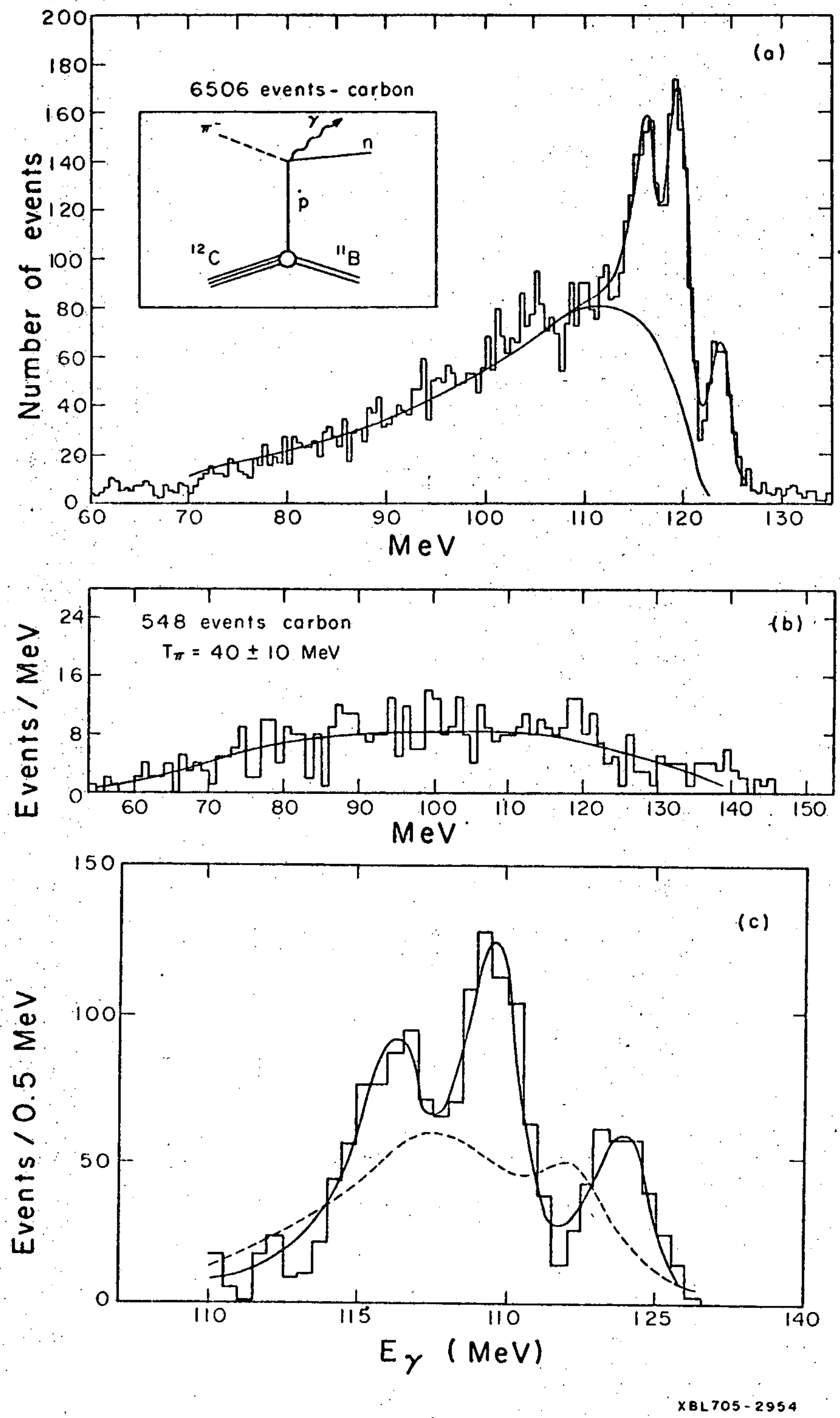
(a)
6506 events - carbon
π⁻
γ
n
p
^{12}C
^{11}B
Number of events
MeV
(b)
548 events carbon
T_π = 40 ± 10 MeV
Events / MeV
MeV
(c)
Events / 0.5 MeV
E_γ (MeV)
XBL705-2954

Fig. 3

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