^{14}Be via pion double charge exchange

R. Gilman and H. T. Fortune
University of Pennsylvania, Philadelphia, Pennsylvania 19104

L. C. Bland, Rex R. Kiziah, C. Fred Moore, and Peter A. Seidl
University of Texas at Austin, Austin, Texas 78712

C. L. Morris
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

W. B. Cottingame
New Mexico State University, Las Cruces, New Mexico 88003
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The ^{14}Be nucleus has been produced in the reaction $^{14}C(\pi^-,\pi^+)$. The cross section for the reaction is roughly that which would be expected from the $A^{-4/3}$ mass dependence observed for nonanalog (π^+,π^-) reactions on self-conjugate nuclei. If it is the ground state that we observe, the mass excess of ^{14}Be is $\sim$600 keV smaller (more bound) than expected from systematics.

A recent measurement[1] of the nonanalog pion double-charge-exchange (DCX) cross section at $T_\pi=164$ MeV and $\theta=5°$ (lab) for the reaction $^{18}O(\pi^-,\pi^+)^{18}C$(g.s.) gave a value that was larger (by a factor of about 1.5) than expected from the systematic behavior[2] of DCX cross sections on $T=0$ targets leading to ground states of $T=2$ nuclei. The only $T=1$ nucleus lighter than ^{18}O on which a similar measurement can be carried out is ^{14}C. Its location is midway between ^{12}C and ^{16}O, for which DCX cross sections have been measured, whereas ^{18}O lies between ^{16}O and ^{20}Ne, the latter of which has not been used as a target in DCX. Because the ^{14}C target presents special problems, we report in detail on the experimental procedure.

It is important to note that (π^-,π^+) DCX on *any* stable nucleus will have a Q value less negative than that expected for the $^{14}C(\pi^-,\pi^+)^{14}Be$(g.s.) reaction. With the estimated mass excess of ^{14}Be (Ref. 3; unless otherwise noted, all Q values are calculated with all mass excesses taken from Ref. 4), $\Delta\sim40.69$ MeV, the $^{14}C(\pi^-,\pi^+)^{14}Be$(g.s.) Q value is

$$Q=\Delta_{^{14}\mathrm{C}}-\Delta_{^{14}\mathrm{Be}}-2m_e=-38.69\ \mathrm{MeV}\ .$$

All stable nuclei have Q values less negative than -35 MeV. Thus, all contaminants cause background problems.

Data were obtained at a pion kinetic energy of 164 MeV and a laboratory angle of 5° with the DCX modifications[5] to the Energetic Pion Channel and Spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility (LAMPF). The channel[6] focuses the pion beam to a beam spot on target that is 6 cm wide (by convention, the y coordinate) by 20 cm high (the x coordinate). The beam is momentum dispersed in x with a dispersion of 10 cm/%. Wire chambers in the spectrometer measure both positions and angles of scattered particles, enabling software to ray trace each event and construct a target image. This capability enables simultaneous measurements on multiple targets. The targets are typically horizontal strips of materials, both because of the greater vertical width of the beam and because of the superior resolution in x ($\sim$4 mm in x for a 3.2 mm diameter horizontal rod vs $\sim$9 mm in y for a 3.2 mm vertical rod).

The ^{14}C target[7] consists of 9.17$\pm$0.05 g of carbon powder sealed with 1 cm long CH_2 plugs into two copper cells, each with external dimensions $\sim$6.0 cm $\times$5.0 cm $\times$0.6 cm and 0.0051 cm thick walls. The areal density of carbon powder in each cell is 187$\pm$4 mg/cm^2. The ^{14}C in the carbon powder has been enriched to a ratio of 4.6$\pm$0.4 atoms of ^{14}C per atom of ^{12}C. A recent analysis[8] of elastic and inelastic pion scattering from the ^{14}C target indicates the presence of several contaminants in addition to the ^{12}C. We list in Table I the isotopic composition of the target (taken from Ref. 8) and the Q value for (π^-,π^+) DCX on each isotope.

Figure 1(a) shows the strip target that was used during the first part of the experiment. About 40% of the data were taken with this target configuration. The copper (areal density 1460 mg/cm^2) and ^{12}C (graphite with areal density 516 mg/cm^2) strips were used to estimate background in the ^{14}C target spectrum. The target configuration of Fig. 1(b) was used for the second part of the experiment. With the ^{14}C target oriented vertically, all of the carbon powder was illuminated by the beam, resulting in an $\sim$20% increase of the count rate.

The procedure for calculating absolute normalization factors by measuring $^1H(\pi^-,\pi^-)$ yields on a CH_2 target has been described previously.[1] The use of two different target configurations required measuring the relative acceptance for the two configurations. The acceptance for the first target configuration was measured by replaying data from a full CH_2 target run with software target cuts on x that corresponded to the physical dimensions of the ^{14}C target. For the DCX data runs, slightly wider x target cuts were used because of the finite x resolution and

TABLE I. Composition of carbon powder [the areal density of copper is 107 mg/cm^2; the Q value for ^{63}Cu (^{65}Cu) is -4.75 (-9.11) MeV (Ref. 13)] in a ^{14}C target (Ref. 8).

Isotope	% (by weight)	areal density (mg/cm^2)	Q value (MeV)
^{14}C	73.5±2.2	137.4±7.1	−38.69
^{12}C	16.9±1.8	31.6±4.0	−26.05
^{16}O	4.5±0.5	8.4±1.1	−19.45
^{24,26}Mg	3.1±0.5	5.8±1.1	−9.00, −17.04
Other[a]	2.1±2.9	3.9±5.5	

[a]Other contaminants include ^{13}C, Na, Al, Si, Cl, and Mo.

the gaps between the strip targets. No y target cuts were needed, as both the CH_2 and ^{14}C targets were wider than the beam. For the second target configuration, the acceptance was determined by measuring ^{1}H(π^-,π^-) yields on a CH_2 target that had been cut to the physical dimensions of the ^{14}C target. Software target cuts on x were identical for both the DCX and normalization runs.

Figure 2 shows both the ^{14}C target spectrum and a background spectrum. The background spectrum is the sum of renormalized spectra obtained with the copper and ^{12}C targets. The renormalization factors accounted for the relative amounts of material in the background targets versus in the ^{14}C target, and for the relative acceptance of the spectrometer (at $Q \sim -38$ MeV) for the background targets versus for the ^{14}C target. The contribution of other contaminants to the background is not known. It is not expected to be large, however, as $\sim$90% of the contaminant atoms are either ^{12}C or copper. Also, the background spectra were not shifted to compensate for the differing energy losses in the three targets. These energy losses were measured with elastic scattering to be 1.2 MeV for the copper target, 0.91 MeV for the ^{12}C target, and 0.46 MeV for the ^{14}C target.

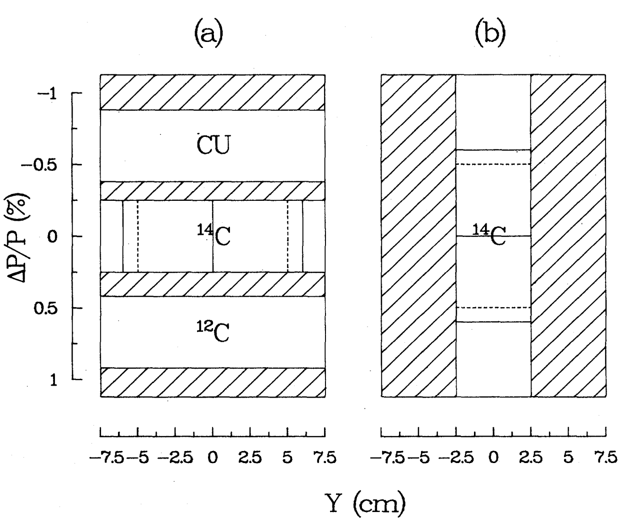

FIG. 1. Diagram of the two target configurations used to acquire data. The solid lines in the ^{14}C target indicate the extent of the copper cells. The dashed lines indicate the inner edge of the CH_2 plugs. The cells were fastened to aluminum holders which were attached to the target frame.

The eight counts centered in our spectrum at $Q = -26.20 \pm 0.18$ MeV (we quote only statistical errors for peak positions, unless otherwise specified) are from the ^{12}C(π^-,π^+)^{12}Be(g.s.) reaction, which has a known Q value of -26.05 MeV. This agreement is surprisingly good, as the g.s. peak was at the edge of the acceptance of the spectrometer ($\delta = p/p_{spec} - 1 = +8.5\%$), where errors in measuring momentum would be expected to be largest. This peak is not seen in the background spectrum because the acceptance of the spectrometer for the ^{12}C background target is reduced at higher outgoing momenta, as the ^{12}C was at the higher incident momentum end of the target. There are no obvious peaks significantly above background until the large peak (23 counts) centered at $Q = -38.10 \pm 0.13$ MeV. We identify this as a state in ^{14}Be.

With background subtraction, we estimate a net yield of 19 ± 5 counts in the ^{14}Be peak, giving a cross section of 733 ± 193 nb/sr. Just to the left of the peak in the spectrum there does appear to be an excess of counts above

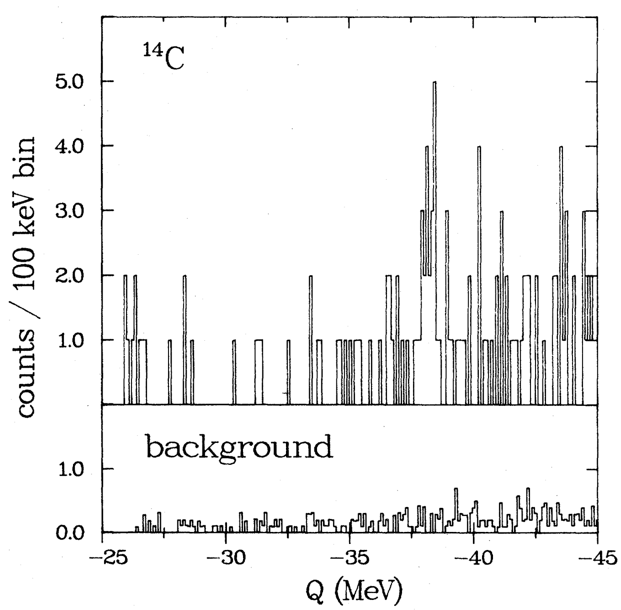

FIG. 2. Spectrum for (π^-,π^+) on a ^{14}C target (top) and copper and ^{12}C background spectrum (bottom). The method used to generate the background spectrum is described in the text.

what would be expected by comparison with the background spectrum. Specifically, in the 2.5 MeV wide region from $Q=-34.5$ to -37.0 MeV, we observe 14 counts, whereas we would have expected about five background counts from ^{12}C and Cu. It may be that the excess of nine counts is a statistical fluctuation, or they may arise from DCX on contaminants in the ^{14}C target that are not present in the background targets. If all the excess counts correspond to a state (or states) in ^{14}Be, the cross section is less than about 350 ± 120 nb/sr.

Ignoring nuclear structure effects, the cross section expected for the ^{14}C$(\pi^-,\pi^+)^{14}$Be(g.s.) reaction, based on the mass dependence[1,2] of $T=0$ to $T=2$ transitions, and ignoring kinematic differences between (π^-,π^+) and (π^+,π^-) reactions, is 591 nb/sr. It is thus likely that the large peak is the ^{14}Be(g.s.) because of the lack of a statistically significant peak at a more positive Q value, a measured Q value that approximately agrees with that expected (-38.10 ± 0.13 vs -38.69 MeV), and a cross section that approximately agrees with that expected (733 ± 193 vs 591 nb/sr).

Assuming that this peak is the ^{14}Be(g.s.), we can now proceed to compare cross sections of $T=1$ to $T=3$ transitions with those of $T=0$ to $T=2$ transitions. This comparison is shown in Fig. 3. The ^{12}C and ^{16}O cross sections have been converted from (π^+,π^-) to (π^-,π^+) by shifting the incident pion kinetic energy by the Coulomb energy difference between π^+ and π^- to $T_{\pi^-}=164$ MeV. (This change is about ten percent, and causes the data points to fall below the curve.) It appears from this comparison that (π^-,π^+) cross sections on $T=1$ target nuclei, leading to ground states of $T=3$ residual nuclei, are larger than those for $T=0$ targets.

The observed ^{14}Be Q value is 0.59 MeV more positive than that calculated for the g.s. from the estimated ^{14}Be mass excess.[3,4] As the primary emphasis of the experiment was on measuring a cross section, no attempt was made to calibrate the absolute energy scale of the spectrometer. This does not imply any large systematic error. We note that, in a recent measurement[1] of ^{18}O$(\pi^-,\pi^+)^{18}$C(g.s.) with a similar setup (channel and spectrometer magnet field settings differed by $<0.6\%$), the Q value (mass excess) was observed to be -26.69 ± 0.06 MeV (24.89 ± 0.06 MeV). This is in good agreement with reported mass excess measurements of $\Delta=24.82\pm 0.30$ MeV (Ref. 9) and 24.91 ± 0.15 MeV (Ref. 10) for ^{18}C.

We have estimated the contributions of several sources of uncertainty in this Q value. The largest source of uncertainty is the statistical error in determining the peak centroid (130 keV). The second largest source of uncertainty is in the determination of the beam energy. Because of preamplifier problems, the nuclear magnetic resonance (NMR) probe usually used to set channel fields was accurate to only ~ 2 G. The channel energy was set with a different NMR that measures the field of a different dipole magnet in the channel. The relative calibration of these two magnets was known to ~ 2 G. We estimate an uncertainty of 60 keV in setting the channel. Additional uncertainties include channel magnet stability (60 keV), spectrometer magnet stability (40 keV), and the determination of energy loss in the target (20 keV). Adding these in quadrature gives a total uncertainty of 0.16 MeV.

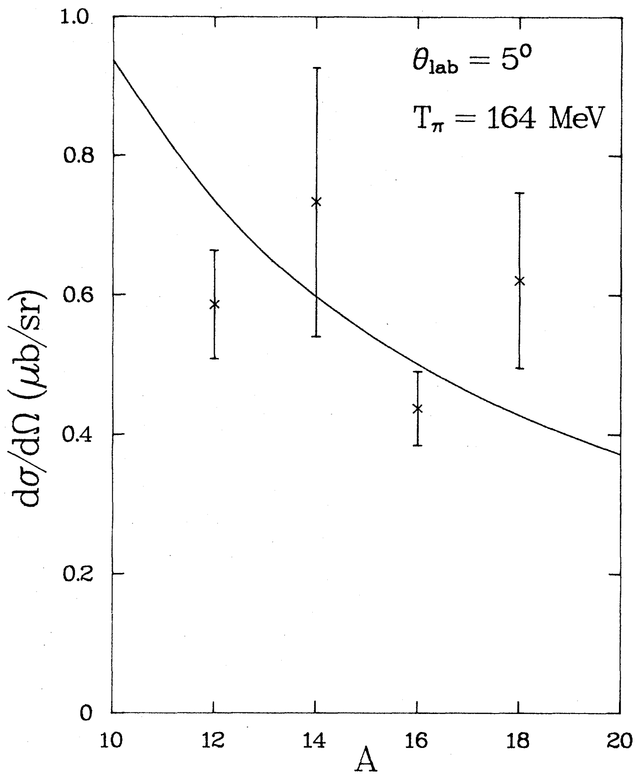

FIG. 3. Measured nonanalog cross sections for light nuclei, $10\le A\le 20$, at $T=164$ MeV and $\theta=5°$ (lab). The ^{18}O point is from Ref. 1. The ^{12}C point has been extrapolated from data in Ref. 2, and the ^{16}O point has been extrapolated from data in Refs. 11 and 12. The curve is a best fit to the A dependence of (π^+,π^-) DCX on self-conjugate targets.

In conclusion, in the reaction ^{14}C(π^-,π^+) at an incident kinetic energy of 164 MeV and a laboratory angle of 5°, the ^{14}Be(g.s.) has been observed with a DCX cross section of 733 ± 193 nb/sr, which is slightly larger than expected, but consistent with population of a 0^+ g.s. The mass excess of ^{14}Be is 40.10 ± 0.16 MeV, which is about 0.6 MeV more bound than expected.

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