Mass of ^{18}C by Pion Double-Charge-Exchange Reaction

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The first observation of the double-charge-exchange reaction (π^-, π^+) to discrete nuclear states is reported. The mass of ^{18}C has been measured using the reaction $^{18}O(\pi^-, \pi^+)^{18}C$ at $T(\pi) = 164$ MeV. The reaction $^{12}C(\pi^-, \pi^+)^{12}Be$, with known $Q_0 = -25.078(15)$ MeV, was used as the calibration reaction to obtain $Q_0 = -25.69(15)$ MeV for the reaction $^{18}O(\pi^-, \pi^+)^{18}C$(g.s.). The mass excess of ^{18}C is thus found to be 24.91(15) MeV.

Very little is known about the light $T_z = 3$ nuclei. The odd-odd nuclei ^{12}Li and ^{16}B are known to be particle unstable. The even-even members of this series, from ^{14}Be to ^{30}Mg, are all known to be particle stable, but it has not been possible so far to measure the mass of any member of this series except ^{22}O. In this Letter, we report on the first successful measurement of the mass of the "exotic" nucleus ^{18}C using the no less exotic double-charge-exchange (DCX) reaction $^{18}O(\pi^-, \pi^+)^{18}C$.

^{18}C was first observed by Artukh *et al.* in 1969 in the bombardment of ^{232}Th by 122-MeV ^{18}O ions and later by 172-MeV ^{22}Ne ions.[1] It was more recently observed by Bowman *et al.* in the fragmentation of uranium by 4.8-GeV protons.[2] These experiments do not lend themselves easily to mass measurements and none were reported. Recently, an attempt was made to measure the mass of ^{18}C in the heavy-ion DCX reaction $^{48}Ca(^{18}O, ^{18}C)^{48}Ti$ but a ^{18}C group could not be unambiguously identified above the background level of ~100 nb/sr and, or course, no mass determination could be made.[3]

Until recently it was believed that DCX reactions would be dominated by double analog transitions. It was therefore thought that (π^+, π^-) reactions between analog states would have much larger cross sections than either the (π^+, π^-) reactions between nonanalog states, or the (π^-, π^+) reactions, which necessarily connect nonanalog states. However, in 0° experiments it was observed that the cross section for the analog reaction $^{18}O_{T=1}(\pi^+, \pi^-)^{18}Ne_{T=1}$(g.s.) is only a factor of 2 larger than that for the nonanalog reaction $^{16}O_{T=0}(\pi^+, \pi^-)^{16}Ne_{T=2}$(g.s.),[4,5] and that for the analog reaction $^{26}Mg_{T=1}(\pi^+, \pi^-)^{26}Si_{T=1}$(g.s.) the cross section is actually smaller than that for the nonanalog reaction $^{24}Mg_{T=0}(\pi^+, \pi^-)^{24}Si_{T=2}$(g.s.).[6] Although not much theoretical understanding of these observations exists, it has, however, become obvious that there are no *a priori* reasons for favoring (π^+, π^-) analog transitions over nonanalog transitions, and, by analogy, the (π^+, π^-) reaction over the (π^-, π^+) reaction. This fact has transformed the (π^-, π^+) reaction from a purely esoteric reaction to a potentially powerful tool for creating and studying highly neutron-rich exotic nuclei. In this Letter we present the results of the first observations of (π^-, π^+) reactions to discrete nuclear states and exploit the potential of this reaction to measure the mass of ^{18}C.

The experiment was performed at the EPICS pion spectrometer facility at the Clinton P. Anderson Meson Physics Facility (LAMPF).[7] A vertically momentum dispersed [~6 cm horizontal × 20 cm vertical] beam of 164-MeV negative pions was incident on ~1-g/cm² thickness targets located in a vacuum chamber. As shown in Fig. 1, the outgoing positive pions were analyzed by the triple-quadrupole–double-dipole magnetic spectrometer, and the energy-loss spectrum was constructed by the on-line computer from the x, y, θ, and φ information provided by four pairs of position-sensitive drift chambers, F_{1-4}, at the front (entrance) of the spectrometer and four position-sensitive multiwire proportional counters, R_{1-4}, at the rear ("focal plane") of the spectrometer. Time of flight through the spectrometer was measured between a $\frac{1}{8}$-in.-thick scintillator, S_1, just in front of the first drift chamber and two $\frac{1}{4}$-in.-thick scintillators, S_2 and S_3, at the focal plane. An overall time resolution of ~1.2 ns was achieved and a large fraction of the electron background was rejected by the time-of-flight cut alone. Further electron rejection was achieved by a Freon-gas

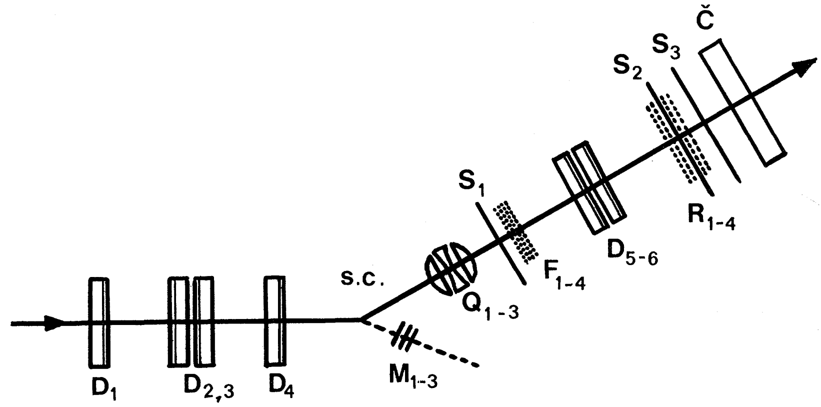

FIG. 1. Schematic of the experimental setup. For explanation, see text.

threshold Cherenkov counter at the end of the entire detection system. The beam-target interactions were monitored by a three-element scintillation counter telescope at ~ – 30° outside the scattering chamber. At forward angles there was substantial heavy-particle flux in the front drift chambers. This was significantly reduced by inserting a $\frac{1}{4}$-in. polyethylene absorber in front of S_1, although this had the effect of degrading the overall energy resolution to about ~ 0.8 MeV (full width at half maximum). All data were taken at a laboratory angle of 11°.

The absolute calibration of neither the channel nor the spectrometer magnets has the accuracy desired for mass measurements. It is therefore essential to find a calibration reaction with well-known Q value, in the vicinity of the expected Q value (≈ – 25.5 MeV) for the reaction ^{18}O(π^-, π^+)^{18}C. Fortunately, such a reaction is conveniently available. The reaction is ^{12}C(π^-,π^+)^{12}Be with Q_0 = – 25.078(15) MeV, based on a recent accurate mass determination of ^{12}Be by Alburger *et al.*[8] The (π^-,π^+) reaction was studied on the targets of ^{18}O and ^{12}C under the same, undisturbed, mechanical and magnetic settings of the channel and the spectrometer. The stability of all six dipoles was monitored throughout the experiment and was found to be better than 1 part in 10^4.

The ^{18}O target consisted of a refrigerated ice

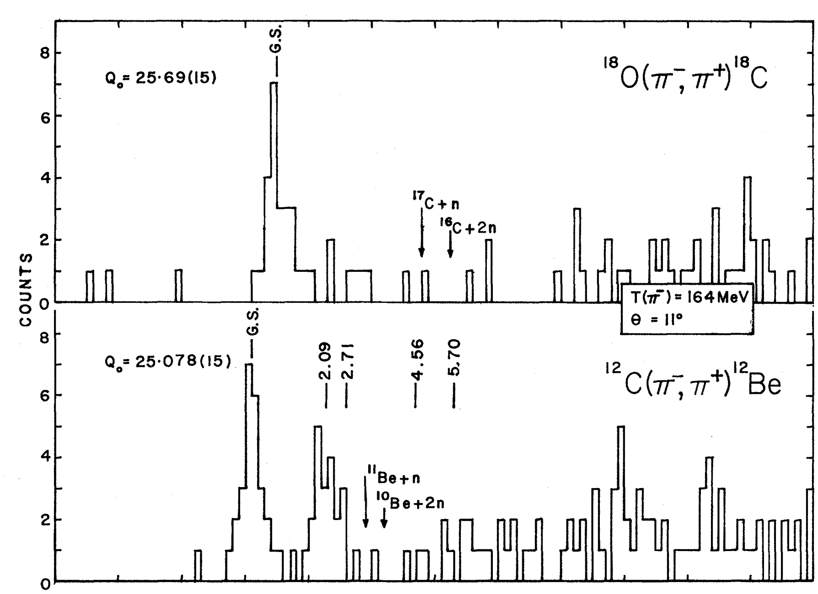

FIG. 2. Spectra of (π^-, π^+) reactions on ^{18}O and ^{12}C at $T(\pi^-)$ = 164 MeV and θ = 11°.

TABLE I. Analysis of errors in ^{18}C mass determination.

Source of error	Contribution to error in ^{18}C mass (in keV)
1. Target-thickness uncertainty	
and nonuniformity: ^{18}C	± 80
^{12}Be	$\pm < 10$
2. Centroid determination: ^{18}C	± 70
^{12}Be	± 70
3. Missing-mass scale, differential	
nonlinearity	± 30
4. ^{12}Be mass	± 15
5. Beam energy	$\pm < 5$
6. Reaction angle	$\pm < 5$
Overall	± 130

target, enriched to 94.9% in ^{18}O, inside thin Mylar windows. Its area was 10 cm $\times$ 21.5 cm. Its thickness was measured on a 1-cm $\times$ 1-cm grid at the end of the experiment and was found to vary, especially towards the edges. A central region ~12.5 cm high was, however, found to have a uniform thickness of 0.90(4) g/cm^2. Cuts in target projection were therefore made in off-line replay of the data so that events from only this region of the target (~80% of total events) were accepted. The carbon target was of area 20 cm $\times$ 20 cm and had a uniform thickness of 0.927 g/cm^2.

The π^+ missing-mass spectra for both ^{18}O and ^{12}C targets are shown in Fig. 2. The ^{18}C(g.s.) transition is seen clearly, with almost no background. The onset of the continuum from $^{17}C+n$ and $^{16}C+2n$ breakup at ~4 MeV is also clear. There is a hint of what might be an excited state at ~2.1 MeV. The ^{12}Be(g.s.) transition is strong and clear, as is the first excited state at 2.09(2) MeV. The 2.71(2)-MeV state is, at best, weakly excited. The other two states at 4.56(2) and 5.70(2) MeV reported by Alburger *et al.*[8] are perhaps weaker still and cannot be identified because of the onset of the continuum.

We have carefully analyzed the contributions of the different sources of error to the final uncertainty in our mass determination. These are summarized in Table I. The largest contributions are due to the nonuniformity of the ^{18}O target and the statistical uncertainty in the determination of the centroids of the ^{18}C(g.s.) and ^{12}Be(g.s.) peaks. All other uncertainties are comparatively negligible. The overall uncertainty turns out to be ± 130 keV. We quote our final results conservatively as $Q_0 = -25.69(15)$ MeV, and a mass excess of ^{18}O of 24.91(15) MeV.

TABLE II. Summary of ^{18}C mass predictions.

Ref.	Author	Mass excess of ^{18}C (in MeV)
9	Groote *et al.*	25.09
9	Beiner *et al.*	22.6
10	Jelly *et al.* (MME)[a]	24.57
10	Jelly *et al.* (GK)[b]	25.50
9	Janecke (GK)	25.53
9	Comay and Kelson (GK)	25.48(19)
11	Thibault and Klapisch (GK)	25.47
9	Wapstra (system.)	25.37(60)
	This paper (GK)	25.04(10)
	Experiment	24.91(15)

[a]Modified mass equation. [b]Garvey-Kelson formula.

It is interesting to compare this result with predictions for the ^{18}C mass in the literature. These are summarized in Table II. It may be seen that all predictions based on the transverse Garvey-Kelson formula give a mass excess which is too large by about 500–600 keV. This trend is similar to that observed in recent measurements of masses of neighboring nuclei, ^{17}C and ^{19}N. This suggests that one should recalculate the prediction of the Garvey-Kelson formula using the latest experimental values for the masses of ^{17}C [21.023(35 MeV][12] and of ^{19}N [15.810(90) MeV].[13] This gives the ^{18}C mass excess as 25.037(98) MeV, which is in excellent agreement with our new experimental result.

In summary we have successfully measured the mass of ^{18}C. ^{18}C is found to be more strongly bound than was hitherto believed, a trend similar to that found for other neutron-rich nuclei in this region. The pion double-charge-exchange reaction (π^-,π^+) has been demonstrated to be a powerful tool in the study of neutron-rich nuclei far from the valley of stability. We propose to use it for the study of other light neutron-rich nuclei in the near future.

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Observation of Pion Interferometry in Relativistic Nuclear Collisions

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We present evidence of an intensity interferometric effect of identical pions in relativistic nuclear collisions. From the observed correlation, we determine the space-time structure of the pion-emitting source.

The principle of intensity interferometry was first developed in radio astronomy, now known as the celebrated Hanbury-Brown–Twiss effect. The idea of utilizing this second-order interferometric correlation effect of identical particles as a probe of the space-time structure of the emitting sources in particle physics has been discussed by Cocconi,[1] by Shuryak,[2] and, in much more detail, by Kopylov and Podgoretsky.[3] Fowler and Weiner[4] further emphasized that such study can also shed light on the equally interesting question of the degree of coherence of the emitting system. Experimental study has been reported recently for pp,[5] πp,[6] and πp, Kp, and $\bar{p}p$[7] systems, while an indirect manifestation of this type of effect was observed by Goldhaber *et al.*[8] as early as 1959.

The possibility of using pion interferometry for the study of relativistic nuclear collisions is particularly appealing, as emphasized recently, for example, by Gyulassy[9] and Yano and Koonin,[10] since the ideas of a pion production mechanism

