Highly Proton-Rich $T_z = -2$ Nuclides: ^{8}C and ^{20}Mg

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Two nuclides with a proton excess of 4 have been produced via the (α, ^{8}He) reaction, and their masses measured. The mass excess of $^8_6$C is 35.30 ± 0.20 MeV, and ^{8}C is therefore unbound with a measured width of 220^{+80}_{-140} keV. The ^{8}C mass excess is 0.57 MeV less than the Kelson-Garvey prediction. For $^{20}_{12}$Mg, a mass excess of 17.74 ± 0.21 MeV is found, indicating that ^{20}Mg is nucleon stable. Knowledge of the ^{20}Mg mass permits for the first time a test of the isobaric multiplet mass equation in an isobaric quintet, and good agreement is found.

The remarkable accuracy with which the isobaric multiplet mass equation[1] (IMME) describes the masses of analog states is well established. Fifteen complete isobaric quartets ($T = \frac{3}{2}$) have now been measured, and in only one case, $A = 9$, is there a small but significant discrepancy—all other $T = \frac{3}{2}$ multiplets fit the equation precisely. Indeed, the IMME appears to apply even when the states involved are unbound and broad, as in mass 7, a surprising fact in view of the expected presence of level shifts which cannot be entirely absorbed into a quadratic equation. The agreement in mass 7 has been dismissed as fortuitous,[1] while the disagreement in mass 9 remains unexplained.[2] There is need for an improved understanding of the IMME both through theoretical work and through more revealing experimental tests.

A new and stringent test of the IMME would be the completion of an isospin quintet ($T = 2$). Not only is it less likely that a quadratic equation will fit five masses fortuitously, but the lighter quintets are expected to include both bound and unbound members. At present no more than three members of any quintet are known because all efforts to observe the $T_z = -1$ and -2 members have been unsuccessful. The observation of isotopes with $T_z = -2$ (a proton excess of 4) presents a formidable experimental problem because of the apparently small cross sections for every known reaction which might produce such nuclei.

Cerny *et al.*[3] have observed the reaction ^{26}Mg(α, ^{8}He)^{22}Mg at $E_\alpha = 80$ MeV with a cross section of 50 nb/sr, and have used it to obtain the mass excess of ^{8}He, 31.65 ± 0.12 MeV. However, in a subsequent search for the $T_z = -2$ nuclide ^{20}Mg by the reaction ^{24}Mg(α, ^{8}He)^{20}Mg, it was possible only to set an upper limit of 25 nb/sr on the cross section.[4] The apparent evidence for production of ^{20}Mg by the reaction ^{20}Ne(α, $4n$) observed by Macfarlane and Siivola has since been traced to a spurious instrumental effect.[5]

This Letter reports the observation of two isotopes with $T_z = -2$, ^{8}C and ^{20}Mg, and the measurement of their masses. The experiments were performed using the Jülich isochronous cyclotron. α particles of 156 MeV induced the (α, ^{8}He) reaction on targets of natural C and 99.9%-enriched ^{24}Mg, and outgoing ^{8}He particles were selected in a double-focusing magnetic analyzer of low dispersion consisting of a dipole element followed by a quadrupole doublet (Fig. 1). The energy of particles accepted by the analyzer was measured with a silicon-detector E-ΔE counter telescope. The time taken for particles to traverse the 4.6-m flight path from target to detector was obtained using the cyclotron rf as a reference. By placing four constraints on the particles observed, namely magnetic rigidity, total energy, energy loss (ΔE), and time of flight, background was reduced to an undetectable level. For each event four parameters, E, ΔE, $E + \Delta E$,

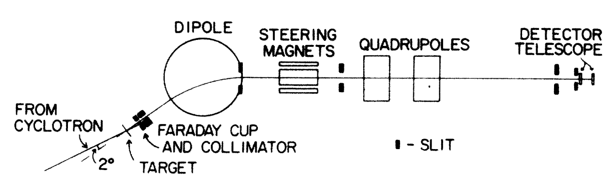

FIG. 1. Schematic diagram of DQQ magnetic analyzer and counter telescope system.

and time of flight, were recorded on magnetic tape for subsequent off-line analysis.

At $E_\alpha = 156$ MeV, outgoing ^{8}He particles from the reactions ^{12}C(α, ^{8}He)^{8}C and ^{24}Mg(α, ^{8}He)^{20}Mg have energies of ~91 and ~95 MeV, respectively. The dispersion of the magnetic analysis system established an energy "window" of approximately 2.6 MeV width in which a ^{8}He group had to lie to be observed. The precise energy of detected particles was determined by calibration of the detector telescope using other α-induced reactions at $E_\alpha = 156$ and 98 MeV. The nonlinearities of the E and ΔE electronic systems were measured with a precision pulse generator. For the calibration reactions, the cyclotron beam was passed through the Jülich double-monochromator system,[6] and the beam energy was calculated from field maps with a conservatively estimated uncertainty of 0.1%.

The low cross sections for the (α, ^{8}He) reactions dictated that for those runs the double monochromator had to be used in a high-transmission achromatic mode which provided little energy analysis. The beam energy could nevertheless be monitored continuously, and compared with that used for the calibration, by means of the (α, ^{6}He) reaction which produced strong groups to low-lying states in ^{10}C (or ^{22}Mg) of the same magnetic rigidity as the ^{8}He groups of interest. Energy resolution for the ^{6}He groups was approximately 330 keV full width at half-maximum.

Three separate experiments were carried out, two on ^{12}C(α, ^{8}He)^{8}C and one on ^{24}Mg(α, ^{8}He)^{20}Mg. However, the first experiment on ^{8}C used a polyethylene target which suffered severe damage under irradiation, and the final result for the ^{8}C mass is taken only from the second run, in which a stack of 24 evaporated 125-μg cm^{-2} carbon foils was used. The results of the three experiments are shown in Fig. 2. The mass predictions of Kelson and Garvey[7] for ^{8}C and ^{20}Mg and of the IMME[1] and of Hardy *et al.*[8] for ^{20}Mg are indicated. Energy resolution for the ^{8}He groups, limited mainly by target thickness, was about 500 keV. The cross sections measured for the reactions ^{12}C(α, ^{8}He)^{8}C and ^{24}Mg(α, ^{8}He)^{20}Mg are exceedingly small, ~20 nb/sr and ~7 nb/sr (lab), respectively, at $\theta_{\rm lab} = 2°$ and $E_\alpha = 156$ MeV.

The measured mass excess of ^{8}C is 35.30 ± 0.20 MeV, and ^{8}C is thus unbound. The mass-8 quintet is especially interesting because its five members range from the bound ^{8}He to the unbound ^{8}C, which will test the IMME sensitively. At present, however, only ^{8}He, ^{8}C, and the $T = 2$ state in ^{8}Be[9]

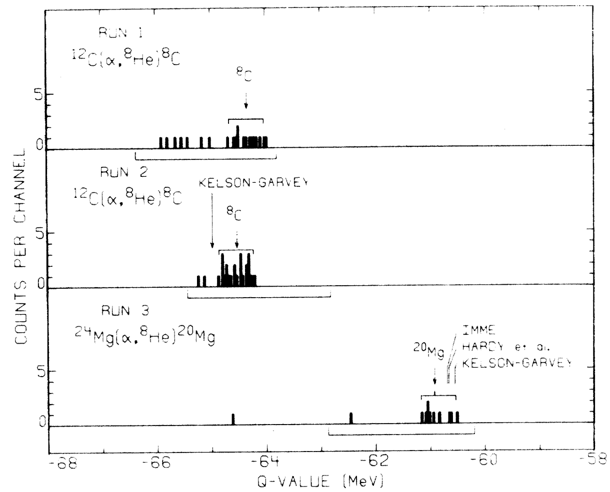

FIG. 2. Spectra of ^{8}He particles observed in α bombardments of C and ^{24}Mg, plotted according to Q value. The channel width is approximately 35 keV. The bracket underneath each spectrum indicates the energy "window" accepted by the magnetic analyzer. In all, 38 events were observed in the ground-state transition to ^{8}C, and 10 to ^{20}Mg. The theoretical predictions are discussed in the text.

are known. Using these known masses, one can predict that the lowest $T = 2$ states in ^{8}B and ^{8}Li will lie at 10.68 ± 0.09 and 10.83 ± 0.06 MeV excitation, respectively. An important question is whether the mass-8 quintet will show a substantial violation of the IMME due to level shifts caused by penetrability effects and spreading of the radial wave functions. In this connection, one can use the method of Kelson and Garvey,[7] which invokes only a general independent-particle model and charge symmetry, to calculate the ^{8}C mass. The result is 0.57 MeV higher than experiment.[10] Kelson and Garvey suggest that one would expect the masses of unbound, proton-rich nuclei to be overestimated by up to 0.5 MeV in their calculations due to level shifts, and indeed the charge-symmetric formula also overestimates ^{6}Be by 0.39 MeV, and ^{7}B by 0.41 MeV. Such an explanation would, however, imply comparable violations of the IMME, whereas ^{7}B fits the IMME. It can perhaps be inferred that the failure of the Kelson-Garvey predictions in these cases must be due to some other cause. For example, the calculated masses of ^{6}Be, ^{7}B, and ^{8}C all depend on the ^{5}Li-^{5}He mass difference,[11] at best an ill-defined quantity. If the discrepancies are attributed entirely to this source (although they seem too large for that to be reasonable), the ^{6}Be, ^{7}B, and ^{8}C masses can be "correctly" described by the Kelson-Garvey prediction, implying the absence of large level shifts. The IMME would then also be expected to describe ^{8}C.

The $^{12}C(\alpha, {}^{8}He)^{8}C$ spectrum (Fig. 2) shows a narrow group and evidence for a break-up continuum at higher excitation in the final state. Phase-space distributions can account for the continuum but not for the narrow group, which is taken to be the ^{8}C ground state. By unfolding contributions from cyclotron and instrumental resolution, target thickness, and kinematic effects, and assuming for ^{8}C a symmetric line shape approximately Gaussian over the region of interest, one finds a width $\Gamma_{c.m.}$ of 220^{+80}_{-140} keV. This is in spite of the fact that ^{8}C is nominally unbound to 1-proton ($1p$) decay by 0.07 MeV, to $2p$ decay by 2.3 MeV, to $3p$ decay by 1.8 MeV, and to $4p$ decay by 3.7 MeV. Consideration of the $1p$ and $2p$ decay mechanisms in the framework of straightforward one-body barrier-penetration theory[12] indicates that the $1p$ decay is (as in the case of ^{6}Be) hindered by the low energy available and the $l=1$ angular momentum barrier, whereas $2p$ decay can in principle proceed as the $l=0$ emission of a "diproton" of somewhat higher energy. The observed width of ^{8}C gives, in this model, an upper limit for the reduced width for $2p$ decay of $0.1\hbar^2/\mu a^2$, where μ is the reduced mass and a the channel radius.[13] The corresponding value for ^{6}Be is $0.02\hbar^2/\mu a^2$.

For ^{20}Mg the measured mass excess is 17.74 $\pm$0.21 MeV, and ^{20}Mg is thus bound. In $A=20$, three members of the $T=2$ multiplet are already known[14] and it is possible to test the IMME for the first time in an isobaric quintet. There is good agreement between the IMME prediction of 17.54$\pm$0.27 MeV and the present experimental result ($\chi^2=0.4$), but to reach the level of significance appropriate to the IMME for bound multiplets it will be desirable to reduce the experimental uncertainties both in ^{20}Mg and $^{20}F(T=2)$. The Coulomb displacement calculations of Hardy *et al.*[8] give 17.51 MeV and the Kelson-Garvey calculation[7] 17.40 MeV for the mass excess of ^{20}Mg. The IMME gives for the excitation energy of the lowest $T=2$ state in ^{20}Na 6.57$\pm$0.06 MeV.

The observation of ^{8}C and ^{20}Mg, the most proton-rich nuclei yet characterized, tests several mass predictions in situations previously unknown. Completion of the mass-8 and mass-20 isobaric quintets is now experimentally feasible and will provide a unique test of the isobaric multiplet mass equation.

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[1]See, for example, G. T. Garvey, in *Proceedings of the Second Conference on Nuclear Isospin, Asilomar–Pacific Grove, California, 1969*, edited by J. D. Anderson, S. D. Bloom, J. Cerny, and W. W. True (Academic, New York, 1969), p. 703.

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[10]The more usual "t" relation [G. T. Garvey and I. Kelson, Phys. Rev. Lett. 16, 197 (1966)] predicts a mass 2 MeV lower, as in the case of ^{8}He.

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[13]The channel radius is taken to be the sum of the equivalent charge radii of the "diproton" and the daughter nucleus. Using the radii of nearby stable nuclei, ^{2}H, ^{4}He, and ^{6}Li, one finds $a=7.9$ fm (^{8}C decay) or 6.4 fm (^{6}Be decay).

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