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COMPLETION OF THE MASS 9 ISOBARIC QUARTET VIA THE THREE-NEUTRON PICKUP REACTION $C^{12}(He^3, He^6)C^9$

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COMPLETION OF THE MASS 9 ISOBARIC QUARTET VIA THE THREE-NEUTRON PICKUP REACTION $C^{12}(He^3,He^6)C^9$ †

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Besides general interest in the existence of highly neutron-deficient isotopes,[1] considerable immediate importance[2] is attached to the accurate measurement of masses of certain $T_z = -3/2$ nuclei, e.g. C^9, which complete $T = 3/2$ isobaric spin quartets and provide a new test of the charge independence of nuclear forces. We wish to report a new nuclear reaction—that of three-neutron pickup via (He^3,He^6) transitions—permitting measurement of the mass of C^9, which completes an isobaric quartet for the first time.

The Berkeley 88-inch, variable-energy cyclotron was used for these experiments. After energy analysis, alpha-particle (for the initial set up) or He^3 beams impinged on solid targets centered in a 36-inch scattering chamber. A 50 mg/cm^2 dE/dx —180 mg/cm^2 E semiconductor counter telescope fed a new type of particle identifier.[3] Alpha particles of 70 MeV were used to set up the electronics through the $Mg^{26}(He^4,He^6)Mg^{24}$ and $Mg^{26}(He^4,Li^6)Na^{24}$ reactions (the Li^6 energy spectra were later used to provide known reference points), and a typical particle identifier spectrum for $Mg^{26} + He^4$ is shown in Fig. 1. Single-channel analyzers on the dE/dx counter eliminated all $He^4 > 46$ MeV prior to identification. Total energy pulses for both He^6 and Li^6 were fed into a Nuclear Data analyzer, each spectrum in a 1024 channel group, and used to establish an energy scale. The lines 2-3 and 5-6 on Fig. 1 bounded the particle identifier spectrum corresponding to the He^6 and Li^6 energy spectra, respectively. Energy spectra of particles bounded by lines 1-2 and 3-4 were also recorded in 1024 channel groups to prevent any possible loss of He^6 ions. Good agreement with the previous investigation[4] of the $Mg^{26}(He^4,He^6)Mg^{24}$ reaction at 40 MeV was found and the cross sections were comparable to those at the lower energy. An average He^6 energy resolution of 190 keV (FWHM) was obtained.

Due to the large negative Q value ($\approx$ -32 MeV) of the $C^{12}(He^3,He^6)C^9$ reaction, a beam of 65 MeV He^3 ions was used. However, to establish the general properties of this three-neutron pickup reaction, the $Mg^{26}(He^3,He^6)Mg^{23}$ reaction—involving known target and product nuclei—was first investigated. This reaction was observed with the $Mg^{26}(He^3,He^6)Mg^{23*}$ (0.449 MeV) transition dominating the ground state transition at forward angles; the cross section of the former is presented in Table 1. Carbon targets were then bombarded and both $C^{12}(He^3,He^6)C^9$ and $C^{12}(He^3,Li^6)B^9$ spectra recorded. Figure 1 also shows the identifier spectrum from $C^{12} + He^3$. Single channel analyzers were reset to eliminate all $He^3 > 22+$ MeV and $He^4 > 28$ MeV from reaching the identifier. Measurement of the Li^6 spectra in conjunction with a pre-established pulser energy scale provided the energy calibration for each run. Four to six hour runs at an analyzed beam intensity of 150 mμa were required.

Figure 2 presents the energy spectrum of $C^{12}(He^3,He^6)C^9$. At present only the ground state transition has been definitely observed and its cross section is also given in Table 1. It is apparent that the $C^{12}(He^3,He^6)C^9$ and $Mg^{26}(He^3,He^6)Mg^{23*}$ (0.449 MeV) cross sections are comparable and quite small, both peaking forward and reaching about 1 μb/sr. The mass-excess of C^9 on the C^{12} scale was determined to be 28.95 ± 0.15 MeV; hence, as expected,[1] C^9 is stable with respect to proton emission. Sharper energy limits could not be set from these data due to transient difficulties in maintaining a constant He^3 beam energy.

Within the framework of charge independence of nuclear forces, it can be shown[2,6] that the masses of an isobaric multiplet are related by

$$M = a + bT_z + c\,T_z^2 \quad .$$

Measurement of the C^9 mass-excess enables us to make the initial check of this relation since, previously, at most only three members of an isobaric multiplet have been available. The other three members of the mass 9, T = 3/2 quartet are Li^9(T_z = +3/2, mass-excess 24.965 ± 0.020 MeV),[7] Be^9(T_z = +1/2, excitation of T = 3/2 state 14.392 ± 0.005 MeV),[8] and B^9(T_z = - 1/2, excitation of T = 3/2 state 14.668 ± 0.016 MeV).[9] Since the experimental error is greatest for the C^9 mass, the coefficients were obtained from the Li^9, Be^9, B^9 states and used to predict the mass-excess of C^9 to be 29.00 ± 0.08 MeV. Excellent agreement between this prediction and the experimental mass is apparent. In fact, though the mass equation has been applied[2,10] to investigate certain relationships between different i-spin multiplets within a given A, this is the most accurate check of the equation for a specific mass number.

Unfortunately, as has been pointed out,[2] this quadratic mass relation is not an extremely sensitive test of charge independence due to the fact that such a relation would also hold for charge dependent forces, provided only that they are two-body forces. Hence further confirmation of this formula for T = 3/2 quartets or T = 2 quintets,[10,11] permitting an analysis of the resulting b and c coefficients and their change with mass number (see, for example, reference 12), would appear to be a most fruitful course to evaluate accurately any charge dependence of nuclear forces.

As has been shown the three-neutron pickup (He^3,He^6) reaction can be used to measure the masses of the T_z = - 3/2 nuclei, so that experimental methods are now available to complete many isobaric quartets. Most of the

$T_z = +3/2$ masses are known and the $T = 3/2$ states in the $T_z = +1/2$ and $-1/2$ members can be readily located through (p,He^3) and (p,t) reactions on appropriate targets.[11,13] In addition, the observation of this reaction offers promise that the fourth and fifth members of the $A = 4n$, $T = 2$ quintets can be measured. Taking the $A = 16$ system as an example, at present $T = 2$ states in the $T_z = +2(C^{16})$, $T_z = +1(N^{16})$, and $T_z = 0(O^{16})$ nuclei are known.[11] Next, one can hope to locate $T = 2$ states in the $T_z = -1$ nucleus F^{16} through the $F^{19}(He^3,He^6)F^{16}$ reaction analyzed in a similar manner to that previously used for the $T_z = +1,0$ isobars, since $\Delta T = 3/2$ is allowed in this reaction. Lastly, if He^8 is particle stable,[14] the success of this three-neutron pickup reaction makes it conceivable that the $T = 2$ quintets can be completed by obtaining the mass of the $T_z = +2$ member via a four neutron pickup reaction, in this case $Ne^{20}(He^4,He^8)Ne^{16}$. The alpha-particle energies which would be required are well within the range of the new variable energy cyclotrons.

FOOTNOTES AND REFERENCES

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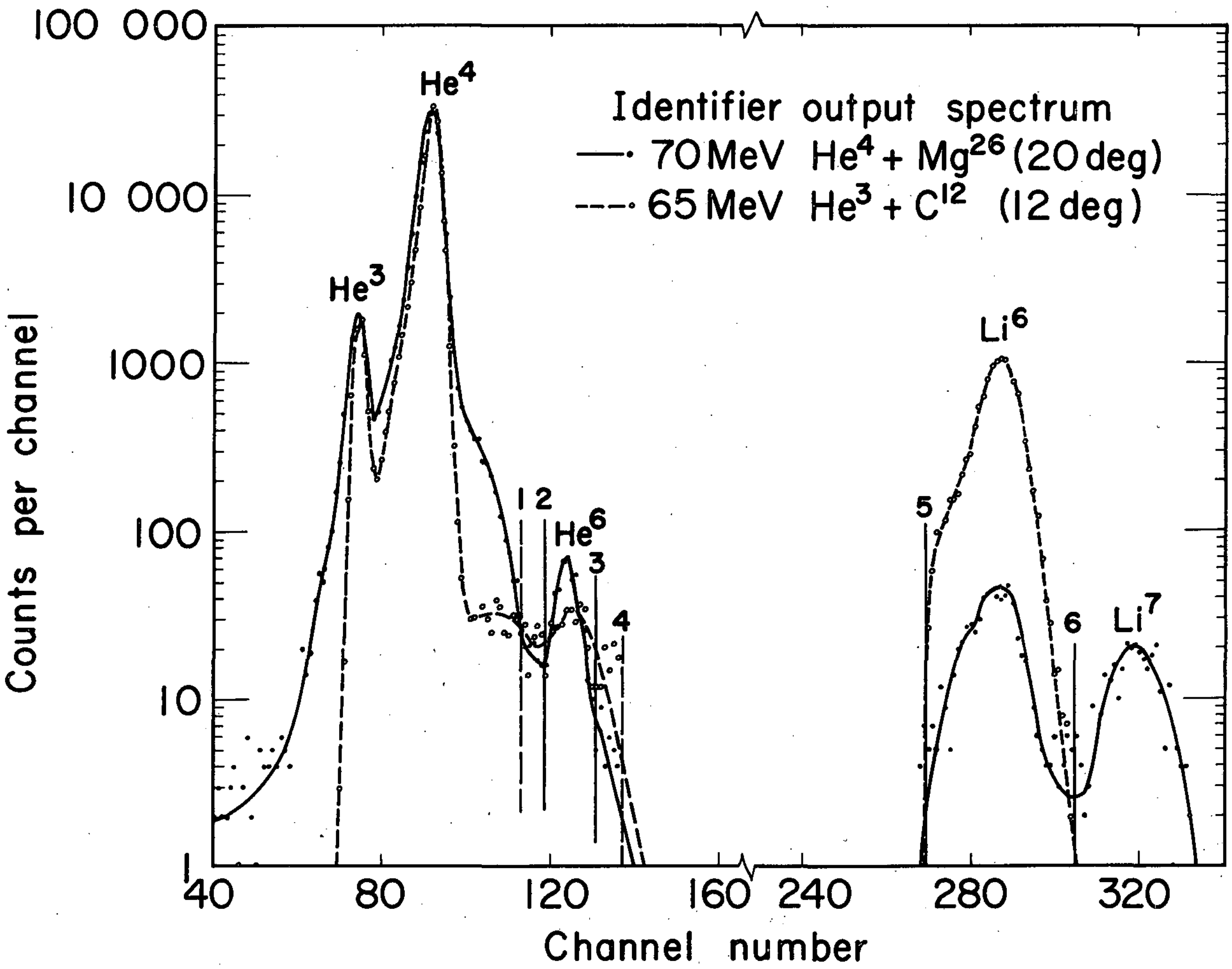
Table 1. Differential cross sections for the $Mg^{26}(He^3,He^6)Mg^{23*}$ (0.449 MeV) and $C^{12}(He^3,He^6)C^9$ g.s. transitions. The absolute accuracy of the cross-sections should be ± 25 percent; statistical errors are indicated.

$Mg^{26}(He^3,He^6)Mg^{23*}$		$C^{12}(He^3,He^6)C^9$	
C.M. angle, deg	σ, μb/sr	C.M. angle, deg	σ, μb/sr
16.2	1.0 ± 0.2	15.8	1.6 ± 0.4
24.6	0.59 ± 0.14	20.7	1.3 ± 0.2
36.4	0.50 ± 0.16	20.7 (see 5)	1.4 ± 0.3
		25.7 (see 5)	1.3 ± 0.2
		33.9	0.23 ± 0.07

FIGURE CAPTIONS

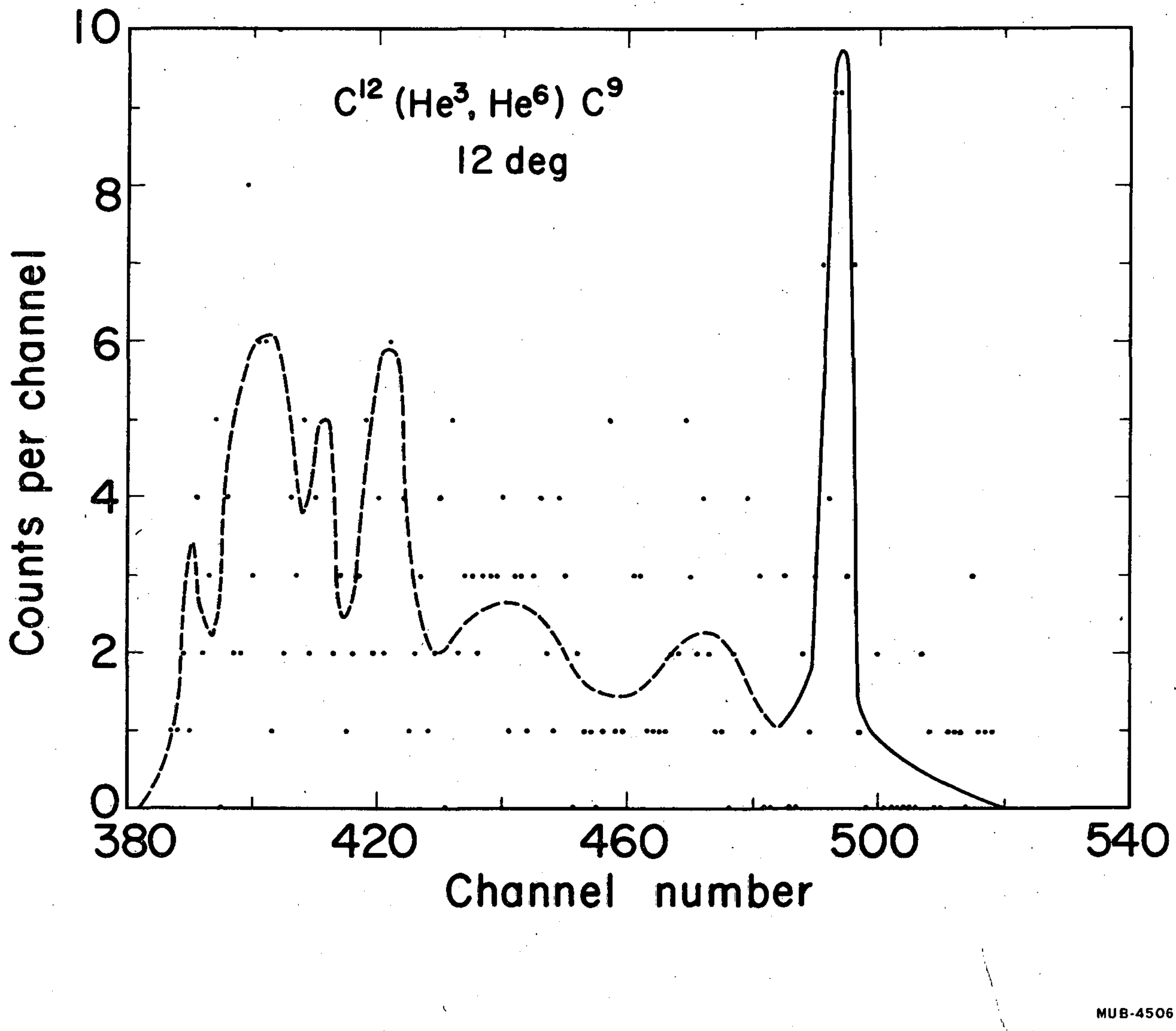
Figure 1. Particle identifier spectra from 70 MeV He^4 on Mg^{26} and 65 MeV He^3 on C^{12}. Lines 1 through 6 represent discriminator settings as determined from the $He^4 + Mg^{26}$ data. The spectrum for $He^3 + C^{12}$ arises when all discriminators but number 1 are set.

Figure 2. An energy spectrum from $C^{12}(He^3,He^6)C^9$ at 12 deg. The dashed line at lower channels than the C^9 g.s peak merely represents an average of the scattered counts in this region.



MUB-4505

Fig. 1



$C^{12}(He^3, He^6)C^9$
12 deg
Counts per channel
Channel number
0
2
4
6
8
10
380
420
460
500
540
MUB-4506

Fig. 2