Title
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Berkeley, California
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COMPLETION OF THE MASS 9 ISOBARIC QUARTET VIA THE THREE-NEUTRON PICKUP REACTION $^12\text{(He}_3,\text{He}_9)^9$.

Joseph Cerny, Richard H. Pehl, Fred S. Goulding and Donald A. Landis

November 1964
COMPLETION OF THE MASS 9 ISOBARIĆ QUARTET VIA THE THREE-NEUTRON PICKUP REACTION Cl²(He³,He⁶)C⁹

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November 1964

Besides general interest in the existence of highly neutron-deficient isotopes,¹ considerable immediate importance² is attached to the accurate measurement of masses of certain Tz = -3/2 nuclei, e.g. C⁹, 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 (He³,He⁶) transitions—permitting measurement of the mass of C⁹, 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 He³ beams impinged on solid targets centered in a 36-inch scattering chamber. A 50 mg/cm² dE/dx – 180 mg/cm² 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 Mg²⁶(He⁴,He⁶)Mg²⁴ and Mg²⁶(He⁴, Li⁶)Na²⁴ reactions (the Li⁶ energy spectra were later used to provide known reference points), and a typical particle identifier spectrum for Mg²⁶ + He⁴ is shown in Fig. 1. Single-channel analyzers on the dE/dx counter eliminated all He⁴ > 46 MeV prior to identification. Total energy pulses for both He⁶ and Li⁶ 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 He⁶ and Li⁶ energy spectra, respectively.⁴ 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 ($\sim -32$ 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 mA 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 $\mu$b/sr. The mass-excess of C$^9$ on the C$^{12}$ scale was determined to be 28.95 $\pm$ 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 that the masses of an isobaric multiplet are related by

\[ M = a + bT_z + cT_z^2 \]

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 \( \text{Li}^9(T_z = +3/2, \text{mass-excess } 24.965 \pm 0.020 \text{ MeV}), \text{Be}^9(T_z = +1/2,\)
excitation of \( T = 3/2 \) state \( 14.392 \pm 0.005 \text{ MeV}), \text{and } \text{B}^9(T_z = -1/2, \text{excitation}\)
of \( T = 3/2 \) state \( 14.668 \pm 0.016 \text{ MeV}). \) Since the experimental error is greatest
for the \( C^9 \) mass, the coefficients were obtained from the \( \text{Li}^9, \text{Be}^9, \text{B}^9 \) states
and used to predict the mass-excess of \( C^9 \) to be \( 29.00 \pm 0.08 \text{ MeV}. \) Excellent
agreement between this prediction and the experimental mass is apparent. In
fact, though the mass equation has been applied 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, 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, 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 \((\text{He}^3, \text{He}^6)\) 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 $(p, \text{He}^3)$ and $(p, t)$ reactions on appropriate targets. 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. Next, one can hope to locate $T = 2$ states in the $T_z = -1$ nucleus $F^{16}$ through the $F^{19}(\text{He}^3, \text{He}^6)F^{16}$ reaction analyzed in a similar manner to that previously used for the $T_z = +1/2$ isobars, since $\Delta T = 3/2$ is allowed in this reaction. Lastly, if He$^8$ is particle stable, 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$^{20}(\text{He}^4, \text{He}^8)\text{Ne}^{16}$. The alpha-particle energies which would be required are well within the range of the new variable energy cyclotrons.
FOOTNOTES AND REFERENCES

† This work performed under the auspices of the U. S. Atomic Energy Commission.


5. Mylar targets were used at two angles to attempt a preliminary measurement of $0^{13}$.


   Private communication from C. A. Barnes.


16. V. I. Goldanskii, Phys. Letters 9, 184 (1964). An accurate mass might be determined through the reaction $^{18}\text{O}^{4}\text{He},^{8}\text{He}^{14}$, for example.
Table 1. Differential cross sections for the $^{26}_{\text{Mg}}$($^{3}_{\text{He}},^{6}_{\text{He}}$)$^{23*}_{\text{Mg}}$ (0.449 MeV) and $^{12}_{\text{C}}$($^{3}_{\text{He}},^{6}_{\text{He}}$)$^{0}_{\text{g.s.}}$ transitions. The absolute accuracy of the cross-sections should be ± 25 percent; statistical errors are indicated.

<table>
<thead>
<tr>
<th>C.M. angle, deg</th>
<th>$\sigma$, $\mu$b/sr</th>
<th>C.M. angle, deg</th>
<th>$\sigma$, $\mu$b/sr</th>
</tr>
</thead>
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<tr>
<td>16.2</td>
<td>1.0 ± 0.2</td>
<td>15.8</td>
<td>1.6 ± 0.4</td>
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<tr>
<td>24.6</td>
<td>0.59 ± 0.14</td>
<td>20.7</td>
<td>1.3 ± 0.2</td>
</tr>
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<td>36.4</td>
<td>0.50 ± 0.16</td>
<td>20.7 (see 5)</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.7 (see 5)</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>33.9</td>
<td>0.23 ± 0.07</td>
</tr>
</tbody>
</table>
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$^9$ peak merely represents an average of the scattered counts in this region.
He

Q)

[Image 0x0 to 599x779]

Identifier output spectrum

- 70 MeV He⁴ + Mg²⁶ (20 deg)
- 65 MeV He³ + C¹² (12 deg)

Fig. 1
\[ C^{12}(\text{He}^3, \text{He}^6) C^9 \]

12 deg

Counts per channel

Channel number

Fig. 2
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