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MONOPOLE EXCITATION OF $^4$He IN $\alpha$-PARTICLE SCATTERING FROM $^{12}$C, $^{13}$C, AND $^{16}$O

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Abstract:

The excitation of the $0^+$ state in $^4$He at 20.1 MeV has been studied in $\alpha$-scattering from $^{12}$C, $^{13}$C, and $^{16}$O at $E_\alpha = 65$ MeV by measuring the decay $\alpha^* \rightarrow p+t$ with a coincidence method. DWBA calculations of this monopole transition using both microscopic and collective model transition densities are presented.

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Monopole excitations of nuclei are of considerable interest. One of the simplest examples of a monopole state is the first excited state of $^4$He, which in the shell model is largely described by a $(1s_{1/2}^{-1} 2s_{1/2})$ particle-hole excitation [1]. This unbound state at 20.1 MeV excitation energy ($\alpha^*, \Gamma = 0.27$ MeV) lies 0.3 MeV above the t+p

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breakup threshold of the α-particle and decays entirely via this channel [2,3].

An experimental system has been developed [4] which is capable of selectively
detecting an α-particle excited to this α\(^*\) state by measuring its correlated
decay products in coincidence and identifying them as a proton and a triton.

In this letter we present a first observation of the monopole (projectile)
excitation of \(^4\)He in 65 MeV α-scattering from light nuclei (\(^{12}\)C, \(^{13}\)C, \(^{16}\)O).

For the (target) ground state transitions, microscopic calculations have been
performed using both microscopic and collective model transition densities.
Although the absolute cross sections in the forward angular region are remarkably
well predicted, this approach fails to reproduce the shape of the experimental
angular distributions, indicating that higher order effects may be significant
in this projectile excitation.

Our experimental setup [4] consisted of two counter telescopes capable
of detecting the two breakup-particles in coincidence. In the laboratory system
the protons and tritons arising from the decay of the α\(^*\) state are emitted into
a cone, which is defined by the lab. energy of the α\(^*\) and by its decay energy.
In order to achieve good detection efficiency, the acceptance angle of the
two telescopes has to be similar to the size of the breakup cone, which is
approximately 12° for 40 MeV α\(^*\) events. Opposing this, energy resolution
considerations require a small angular acceptance. A good compromise has been
made by arranging the two telescopes vertically, thus achieving relatively
good efficiency due to the large vertical acceptance angle and reasonable
energy resolution by limiting the horizontal acceptance angle.

Figure 1(a) shows the α\(^*\) detection system. The ΔE detectors were
phosphorus-diffused silicon, 380 μm thick and the E counters were Si(Li),
5mm thick, all having the same area of 1 x 1.4 cm\(^2\). The divided collimator
subtended a 15° vertical and a 4° horizontal opening angle. Standard particle
identification techniques were used to identify the $\alpha^*$ events. Both telescopes were capable of detecting protons as well as tritons, so that both possible combinations of $\alpha^*$ decay products entering the two telescopes ($p+t$ and $t+p$) were detected, thus doubling the efficiency. In order to reduce random events, a subnanosecond fast coincidence was required (the FWHM of the observed differential time of flight ($\Delta$ TOF) peak was 850 ps as expected from the $\alpha^*$ decay characteristics under our experimental conditions). In addition, fast pileup rejection was utilized so that high singles counting rates could be tolerated in the $\Delta E$ counters (30 kHz). It should be noted that only events arising from the decay of the monopole state ($\alpha^*$) at 20.1 MeV were observed: the efficiency for detecting decay protons and tritons from higher excited states of the $\alpha$-particle, decaying in part via this mode, is small due to the substantially larger decay energy and the correspondingly much bigger breakup cone; furthermore, the few that enter the telescope will be rejected by discriminators placed on the $\Delta$ TOF signal. The calculated efficiency [5] for our geometry for detecting the decay products from this asymmetric $\alpha^*$ decay is about 3% for 40 MeV $\alpha^*$-particles.

Figure 1(b) shows a spectrum of the ($\alpha,\alpha^*$) reaction on $^{12}$C at 20° lab. angle using a 65 MeV beam from the Lawrence Berkeley Laboratory 88-inch cyclotron. The observed energy resolution of 450 keV was primarily determined by kinematic broadening due to the 4° acceptance angle. This spectrum shows appreciable transitions to the ground state, the $2^+$ state at 4.44 MeV, and to the $3^-$ state at 9.64 MeV and a weak transition to the first excited $0^+$ state of $^{12}$C at 7.66 MeV; the latter is particularly interesting insofar as it represents a double monopole (target + ejectile) excitation.

Figure 2 shows experimental angular distributions from the ($\alpha,\alpha^*$) reaction on the $^{12}$C target. (The yield of the transition to the $0^+$ (7.66 MeV) state in $^{12}$C was too low at most angles to permit us to obtain an angular
distribution.) These cross sections are about three orders of magnitude smaller than those observed in $\alpha$-scattering on $^{12}\text{C}$ [6,7], but the relative ratios of cross sections for transitions to the g.s., the $2^+$ state and the $3^-$ state in $^{12}\text{C}$ are moderately similar for these angles in both the $(\alpha,\alpha^*)$ and the $(\alpha,\alpha')$ reactions. Furthermore, the $(\alpha,\alpha^*)$ distributions populating the $0^+$ ground state and the $2^+$ state are clearly out of phase with one another while that to the $3^-$ state lacks the first minimum, all of which are typical of $\alpha$-particle elastic and inelastic scattering [7]. On the other hand, the $(\alpha,\alpha^*)$ diffractive structure is less rapidly oscillatory than observed in normal $\alpha$-scattering.

Microscopic calculations for $\alpha^*$ transitions, which left the several targets undisturbed, were performed in which a target nucleus-nucleon interaction was obtained by folding a nucleon-nucleon force into a target nucleus density distribution. A simple Wigner force of Gaussian form with a range of 1.6 fm and a volume integral of 446 MeV fm$^3$ was used; this interaction successfully describes monopole excitations in sd and f$_{7/2}$ shell nuclei [8] and is consistent with interactions used for few nucleon systems [9]. This force was then folded with target densities yielding rms radii consistent with electron scattering data [10]. For the monopole transition of $^4\text{He}$, transition densities from both a microscopic model and a collective model were used. A microscopic ($l_s^{-1/2} 2s_{1/2}^1$) transition density was calculated using radial wave functions generated in Woods-Saxon potentials with the geometry $r_o = 1.29$ fm, $a = 0.45$ fm. This geometry was chosen to match, with the same range of the nucleon-nucleon interaction, the rms-radius of the (4-1) nucleon system [11]. The potential depth was adjusted to give the experimental binding energy for the $l_s_{1/2}$ orbit, and the $2s_{1/2}$ orbit was taken to be weakly bound in a slightly deeper potential.
This lp-lh density yields a maximum EO matrix element of 1.77 fm\(^2\) which is 60\% larger than the experimental one (1.10±0.16 fm\(^2\)) obtained from electron scattering [12]. This difference indicates that the \(\alpha^*\) wave function contains only part of the lp-lh excitation; multi particle-hole components cannot be directly excited in inelastic scattering. Therefore, the lp-lh density has been normalized to give the experimental EO matrix element.

An inelastic monopole transition may also be described by using a collective model transition density obtained from derivatives of the ground state density [13]. Using a Gaussian density \(\rho(r) = \rho_o \exp(-r^2/a^2)\) (ref. 11) the monopole transition density \(\rho_{TR}\) in first order is given by

\[
\rho_{TR}(r) = \delta\rho_o \frac{d\rho(r)}{d\rho_o} + \delta a \frac{d\rho(r)}{da} .
\]

Note that the orthogonality of the ground and the excited state gives rise to the constraint \(\int \rho_{TR}(r) dT = 0\); this relates the parameters \(\delta\rho_o\) and \(\delta a\). Details of this calculation are given in ref. 13. To obtain the experimental EO matrix element, values for \(\delta\rho_o\) of 0.31 and \(\delta a\) of 0.18 are required. As compared to the lp-lh density, which yields a transition radius of 4.06 fm, the collective density is smaller in range (transition radius 3.35 fm).

However, both transition densities are consistent with the electron scattering results [12].

DWBA calculations have been carried out using these different transition densities folded with the effective interaction discussed above. Optical potentials were used which were obtained from a best fit description of 65 MeV elastic \(\alpha\)-scattering data [6]. These parameters are: \(V_o = 186.1\) MeV, \(r_o = 1.36\) fm, \(a_o = 0.60\) fm, \(W = 53.8\) MeV, \(r_w = 1.20\) fm, \(a_w = 0.71\) fm for \(^{12}\)C and \(^{13}\)C and \(V_o = 179.1\) MeV, \(r_o = 1.31\) fm, \(a_o = 0.59\) fm, \(W = 31.1\) MeV, \(r_w = 1.20\) fm, \(a_w = 0.82\) fm for \(^{16}\)O; the Coulomb parameter was 1.30 fm.
The calculated and experimental angular distributions for \((\alpha, \alpha^*)\) transitions to the ground states of \(^{12}\text{C}\), \(^{13}\text{C}\), and \(^{16}\text{O}\) are shown in fig. 3. The differences in the angular distributions for the microscopic and collective model descriptions are due to the different transition radii in the two descriptions. These differences are very pronounced for scattering on \(^{16}\text{O}\) which is caused by the comparatively small absorption in the \(^{16}\text{O}\) optical potential.

The magnitudes of the calculated absolute cross sections at forward angles are in good agreement with the measured data. (Note that in this description there is no free parameter with which to adjust theory to experiment.) On the other hand the experimental angular distributions do not show the structure predicted by theory, although similar pronounced structure is observed in monopole target excitations of light nuclei [8]. (It is important to observe that, in the same \(\alpha + ^{12}\text{C}\) system studied here, the angular distribution of the monopole excitation of the \(^{12}\text{C}\) target \((0^+, 7.66\ \text{MeV})\) is remarkably well reproduced by a similar microscopic calculation \([14]\).) Even using different optical potentials for the exit channel, e.g. from fitting 42 MeV \(\alpha\) scattering data, results in no improved agreement of this calculation with experiment. This failure of a one-step DWBA approach to describe the experimental angular distributions may be indicative of higher order effects in the projectile excitation.

Finally, we wish to mention that the feasibility of \(\alpha^*\) detection opens up a wide range of unexplored nuclear reactions, e.g., \((^3\text{He}, \alpha^*)\) and \((d, \alpha^*)\) which would be interesting to compare in many respects to conventional \((^3\text{He}, \alpha)\) and \((d, \alpha)\) studies. In addition, as pointed out by Robson [3], this technique of resonant particle detection offers many new spectroscopic probes: \(^2\text{He}\) has already been successfully observed in studies of the \((\alpha, ^2\text{He})\) and \((d, ^2\text{He})\) reactions \([15]\) and detection of such final systems as \(^5\text{He}^*\) and \(^5\text{Li}^*\) offers similar promise.
References

4. R. Jahn, D. P. Stahel, G. J. Wozniak, and J. Cerny, to be published.
5. The program for performing this calculation is available from the authors.
15. R. Jahn, G. J. Wozniak, D. P. Stahel, and J. Cerny, to be published.
Figure Captions

Fig. 1. (a) Schematic diagram of the $\alpha^*$ detection system. See text.
(b) Energy spectrum of the reaction $^{12}\text{C}(\alpha,\alpha^*)^{12}\text{C}$ at an $\alpha$-particle energy of 65 MeV at 20 deg. laboratory angle.

Fig. 2. Absolute differential cross sections for the reaction $^{12}\text{C}(\alpha,\alpha^*)^{12}\text{C}$ at 65 MeV $\alpha$-particle energy. Statistical error bars are shown; the absolute cross section is accurate to 25%. The solid curves are meant to guide the eye.

Fig. 3. Experimental and theoretical angular distributions of the ground state transitions for the $(\alpha,\alpha^*)$ reaction on $^{12}\text{C}$, $^{13}\text{C}$ and $^{16}\text{O}$ at 65 MeV beam energy. The curves correspond to microscopic calculations using $1p-1h$ (solid lines) and collective model (dashed lines) transition densities and are averaged over the experimental angular resolution of 4°.
(a) $\alpha^*$ detection system

(b) $^{12}\text{C}(\alpha,\alpha^*)^{12}\text{C}$

$E_\alpha = 65 \text{ MeV}$

$\theta_{\text{lab}} = 20^\circ$

![Diagram](image)

Fig. 1
$^{12}\text{C}(\alpha,\alpha^*)^{12}\text{C}$

$E_{\alpha} = 65$ MeV

- g.s.; $0^+$
- $4.44; 2^+$
- $9.64; 3^-$

Fig. 2

XBL 764-2814
$(\alpha,\alpha^*)$  $0^+ \ 20.1 \text{ MeV}$

$E_\alpha = 65 \text{ MeV}$

$\alpha + ^{12}\text{C}$

$\alpha + ^{13}\text{C}$

$\alpha + ^{16}\text{O}$

Fig. 3  XBL 769-10682
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