PHYSICAL REVIEW C VOLUME 37, NUMBER 6 JUNE 1988

First observation of the (^{6}Li, ^{8}He) reaction

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(Received 18 February 1988)

We have measured the cross section of the ^{27}Al(^{6}Li,^{8}He)^{25}Si reaction. At a scattering angle of 5.5° and a beam energy of 92.5 MeV, we find the laboratory cross section to populate the ^{25}Si ground state doublet to be 3.6 ± 1.0 nb/sr and the cross section to populate the 0.82 MeV second excited state to be ≈200 pb/sr. We also measured the (^{6}Li,^{8}He) reaction for ^{64}Zn and ^{24}Mg targets. We find yields of ≈250 pb/sr and <300 pb/sr, respectively. This experiment represents the first observation of the (^{6}Li,^{8}He) exotic nuclear reaction.

Various exotic nuclear reactions have proven to be valuable tools to precisely determine the masses of very proton-rich nuclei. Q-value measurements with the (^{4}He,^{8}He) reaction[1,2] have played a fundamental role in extending our knowledge of $T_z=-2$ nuclei and heavier $T_z=-1$ nuclei. More recently, the (^{7}Li,^{8}He) reaction has been utilized[3,4] to determine the mass of ^{57}Cu. The ^{64}Ni(^{3}He,^{8}He)^{59}Ni reaction has also been reported,[5] but the extremely small cross section for this reaction, only $\approx1\%$ of the cross section[6] for the ^{64}Ni(^{4}He,^{8}He)^{60}Ni reaction at a comparable energy, makes it unlikely that this reaction will be useful as a spectroscopic tool.

There are still many proton-rich nuclei of great interest which cannot be produced in reactions that have been observed to date. Two examples are ^{22}Al and ^{62}Ga. The $A=22$ system is the only $A=4N+2$ case in which three members of the lowest $T=2$ quintet have been identified.[7] Thus, a determination of the mass of ^{22}Al would provide us with the first $A=4N+2$ test of the isobaric multiplet mass equation. By contrast, β-decay measurements[8] have already determined the mass of ^{62}Ga to ±26 keV. ^{62}Ga is a member of the series of $N=Z$, odd-odd nuclei that β decay via $0^+\rightarrow0^+$ superallowed Fermi transitions. At present, the heaviest member of this series whose ft value has been determined to better than 1% is ^{54}Co. If the uncertainty in the ^{62}Ga mass could be reduced to <17 keV, we could extend this series, testing our understanding of the Coulomb corrections that must be applied in a higher-Z system. Using ^{24}Mg and ^{64}Zn targets, ^{22}Al and ^{62}Ga may be produced via the (^{6}Li,^{8}He) reaction, a reaction that has not been reported previously. In this work, we report the first observation of this exotic nuclear reaction and discuss its viability as a means to determine the masses of proton-rich nuclei.

The experiment was carried out by observing ^{8}He particles from the (^{6}Li,^{8}He) reaction on targets of ^{27}Al, ^{24}Mg, and ^{64}Zn. All three targets were studied with a 92.5 MeV ^{6}Li^{2+} beam supplied by the Texas A&M 224-cm cyclotron. Additional ^{24}Mg data were taken with a 98.9 MeV ^{6}Li^{2+} beam, the highest energy ^{6}Li^{2+} beam that this cyclotron can produce. Beam currents on target were between 500 and 1000 nA. Reaction products were detected in the focal plane of an Enge split-pole magnetic spectrograph by a 10-cm long resistive-wire gas proportional counter, which provided both position and ΔE information, backed by a 600-μm thick Si solid-state detector, which measured E and time of flight (TOF) through the spectrograph relative to the cyclotron rf. A 150-μm thick Kapton absorber foil was inserted between the gas proportional counter and the solid-state detector during the ^{27}Al and ^{64}Zn measurements. A 75-μm thick absorber was used during the ^{24}Mg runs. The measurements were carried out at a laboratory scattering angle of 5.5° with a spectrograph solid angle of 2.5 msr. The ^{27}Al(^{6}Li,^{6}Li)^{27}Al and ^{27}Al(^{6}Li,^{4}He)^{29}Si reactions were used to calibrate the spectrograph focal plane.

Particle identification was based upon the ΔE, E, and TOF measurements. The particle identification spectra obtained with the ^{27}Al target are shown in Fig. 1. The TOF spectrum [Fig. 1(a)] includes all events with signals above the ΔE and E discriminator thresholds, which were set just above the triton group for this target. The particle groups associated with the various peaks in the spectrum are listed on the figure. The particle assignments for the α^+ and ^{7}Li^{2+} groups were confirmed by taking a short run with a 25-μm thick Kapton stripper foil inserted between the two poles of the spectrograph. Both groups disappeared during this short run. The α^+-^{8}He TOF window used for the subsequent analysis is indicated. The ΔE and E spectra in Figs. 1(b) and (c) include all events that fell within this α^+-^{8}He TOF window. Both the α^+ and the ^{8}He groups are well defined in the E spectrum. They deposit nearly the same energy in the ΔE detector. The primary source of the events above channel 500 in the ΔE spectrum and between the two groups in the E spectrum is ^{8}Li^{2+}. Unlike the α^+ and ^{8}He groups, the ^{8}Li^{2+} group is very spread out in the E spectrum. At the nominal 45° entrance angle, the ^{8}Li^{2+} nuclei lose over 21 MeV in the 150 μm Kapton absorber. The actual angle of incidence at the split-pole focal plane varied from 41°–49° for our setup, producing a substantial straggling effect. These background events were eliminated by the ΔE and E cuts.

Figure 2 shows the ^{8}He spectrum from a 1.5 mg/cm^2 ^{27}Al target along with the position spectrum for all events which passed the E and ΔE discriminator thresholds. The active region of the detector is clearly defined by the total position spectrum. The peak in the ^{8}He spectrum corresponds to the expected location of the ground state doublet in ^{25}Si. The laboratory cross section for the combined yield to the doublet is 3.6±1.0 nb/sr. The single count in channel 500 of the position spectrum is close to the expected location of the second excited state in ^{25}Si at 0.82 MeV. This represents a laboratory cross section of $\approx$200 pb/sr. The ^{25}Si ground state doublet includes $\frac{5}{2}^{+}$ and $\frac{3}{2}^{+}$ states. If we assume that the 0.82 MeV state is the analog of the 1.07 MeV state of ^{25}Na, then it has $J^{\pi}=\frac{1}{2}^{+}$. Since the ^{27}Al+^{6}Li channel spin is ($\frac{3}{2}^{+}$, $\frac{5}{2}^{+}$, and $\frac{7}{2}^{+}$), production of this state may be slightly suppressed by angular momentum matching, which would favor $\Delta L \approx 4$ at our energy and scattering angle, but it is more likely that the yield to this state is reduced by its $2s_{1/2}$ character.

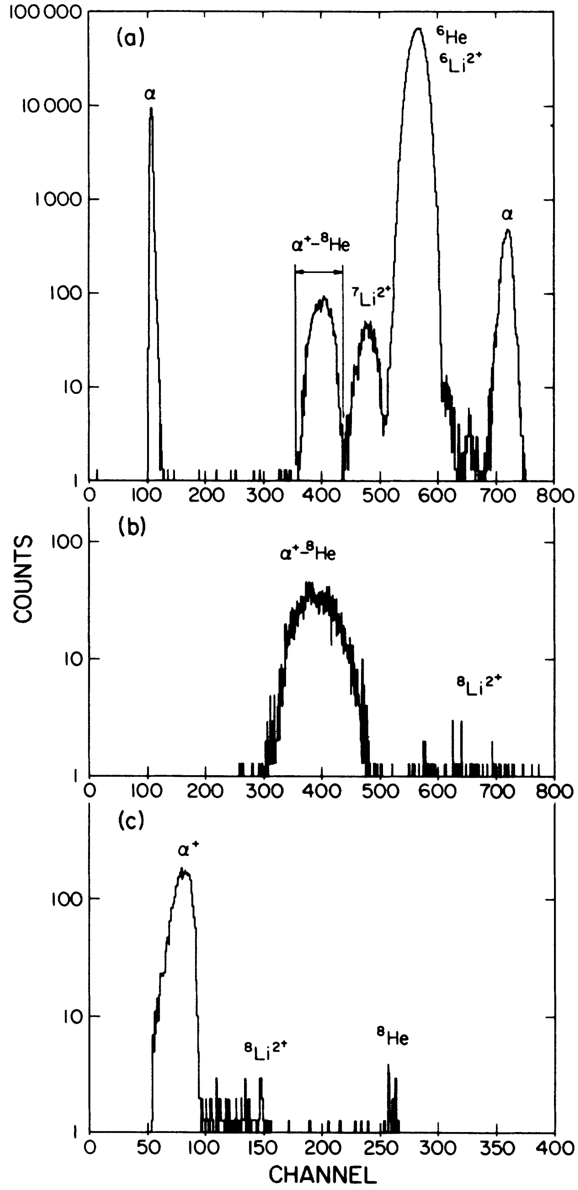

FIG. 1. The particle identification spectra associated with the ^{27}Al(^{6}Li,^{8}He)^{25}Si reaction. Panel (a) shows the TOF spectrum for all events that passed the hardware ΔE and E cuts. The various particle groups are labeled. Panels (b) and (c) show the ΔE and E spectra, respectively, for all particles that fell within the α^{+}-^{8}He TOF window shown in panel (a).

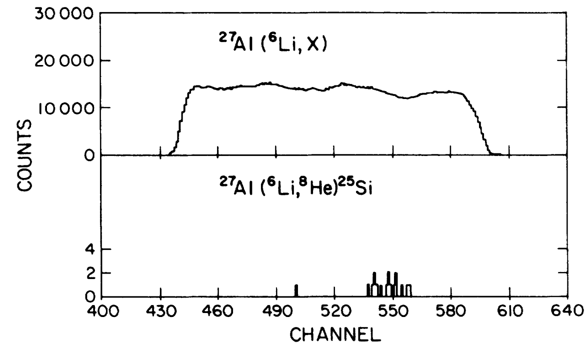

FIG. 2. The position spectra obtained with the ^{27}Al target. The upper curve shows all events that passed the hardware ΔE and E cuts. The counter edges are clearly apparent. The lower curve shows the ^{8}He events. The group near channel 550 is at the expected location of the ^{25}Si ground state doublet, while the single count in channel 500 is near the expected location of the ^{25}Si second excited state.

The ^{8}He yield from the ^{24}Mg and ^{64}Zn targets was much lower than that obtained from the ^{27}Al target. Figure 3 shows the ^{8}He spectrum obtained with a 3.5 mg/cm^{2} ^{64}Zn target. The arrow in the figure indicates the expected location of the ^{62}Ga ground state. The single event in this region corresponds to a yield of about 250 pb/sr, which is too small to improve upon the existing mass determination without several weeks of running time. In addition to its 0^{+} $T=1$ ground state, ^{62}Ga should have low-lying 1^{+} and 3^{+} $T=0$ states. It is doubtful that the six ^{8}He events seen in channels 447–470 of Fig. 3 populate these states since they represent excitation energies of >1 MeV. Angular momentum matching for this reaction favored $\Delta L \approx 2$, so this is not likely the cause of the small yield. Rather, it is probably related to the structure of the ^{62}Ga states and the details of the reaction mechanism. For example, one possible model of the (^{6}Li,^{8}He) reaction would be a two-step process of charge-exchange ^{6}Li$\rightarrow$^{6}He, followed by two-neutron pickup ^{6}He$\rightarrow$^{8}He. In a naive shell model, the ^{64}Zn(^{6}Li,^{8}He) reaction would require these two processes to occur in different subshells in order to populate the low-lying ^{62}Ga states. This may introduce a hin-

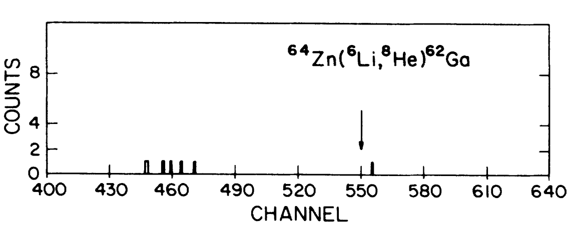

FIG. 3. The ^{8}He position spectrum obtained in the ^{64}Zn(^{6}Li,^{8}He)^{62}Ga reaction. The arrow shows the expected location of the ground state.

drance similar to that noted above for the ^{25}Si 0.82 MeV state.

We observed no unambiguous ^{8}He events in the ground state region of ^{22}Al at either ^{6}Li^{2+} beam energy when using 2.0 mg/cm^{2} ^{24}Mg targets. The more negative Q value of this reaction (approximately -49.5 MeV vs -38.54 MeV and -31.52 MeV for ^{25}Si and ^{62}Ga, respectively) made this investigation far more difficult. Whereas the alpha particle background rate was quite small during the ^{25}Si and ^{62}Ga measurements, it was sufficiently high during the ^{22}Al runs that the gain of the resistive-wire detector was sensitive to space-charge effects. This led to rate-dependent gain shifts in our ΔE determinations and problematic particle identification. To eliminate the possibility of particle misidentification, we inserted a 4-μm thick Mylar stripper foil between the two poles of the spectrograph. This reduced the intensity of partially stripped particles—most importantly ^{7}Li^{2+} and ^{8}Li^{2+}, which could be misidentified as ^{8}He's—substantially. But a small background still remained from ^{4}He, and ^{6}Li ions, which left the target fully stripped, picked up an electron in the Mylar stripper foil, and then reached our detector at the focal plane. Overall, our measurements establish an upper limit of about 300 pb/sr for the cross section to produce ^{22}Al in this reaction. A ^{6}Li beam energy of at least 115 MeV is needed to eliminate the alpha particle background in this reaction. Although beam energies of up to 180 MeV may be produced with the Texas A&M 224-cm cyclotron by using ^{6}Li^{3+} ions, the beam currents available (<30 nA on target) make small cross section measurements impractical.

It is clear from these results that the yield for the (^{6}Li,^{8}He) reaction at our energy and scattering angle is too small to make it of practical use for determining masses of proton-rich nuclei. By both increasing the ^{6}Li beam energy and reducing the scattering angle, it is possible that the reaction yield to nuclei far from stability may improve enough to make it a useful spectroscopic tool. For example, the cross section of the ^{58}Ni(^{7}Li,^{8}He)^{57}Cu reaction[3,4] increases a factor of ≈ 8 from 76.5 MeV and 7° to 174 MeV and 5°. We plan to investigate this possibility when the new Texas A&M $K=500$ superconducting cyclotron and its electron cyclotron resonance (ECR) ion source become available for experiments.

This work was supported in part by the U.S. Department of Energy and the Robert A. Welch Foundation.

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