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MSUCL-1045

SEPTEMBER 1996

Measurement of the $^1H(^6He,^6Li)n$ reaction in inverse kinematics

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(September 11, 1996)

Abstract

The $^1H(^6He,^6Li)n$ reaction was studied at 0° with the NSCL A1200 fragment separator in the energy loss mode. A ^6He secondary beam at E/A = 93 MeV was used to measure the Gamow-Teller and Fermi strengths between the ground state of ^6He and the ground and excited states of ^6Li, in inverse kinematics. At 0“ the ground state cross section is measured to be, $\frac{d\sigma_{gs}}{d\Omega} = 43 \pm 16\frac{mb}{sr}$, which is dominated by systematic error in the secondary beam flux. The ratio of Gamow-Teller to Fermi strength is not sensitive to this error and is found to be (87±6)% of that expected from (p,n) systematics and p-decay. Angular distributions have been measured between 0° and 10° in the center of mass.

21.10.Gv, 25.40.Kv, 25.60.Lg, 27.20.+n

The recent development of intense secondary beams has allowed new studies of the structure of many unstable nuclei. While particular effort has focused on the measurement of interaction cross sections and momentum distributions of halo nuclei, there is growing interest in the investigation of the detailed structure of these and other unstable nuclei using tools developed to study stable nuclei. Direct nuclear reactions, (p,n), (p,p'), and transfer reactions have traditionally been used to measure important quantities in nuclear structure physics, such as weak-interaction transition strengths, energy levels, and nuclear matter density distributions. Up to now, these types of measurements have been very difficult or impossible to perform with unstable nuclei due to the difficulties of constructing targets from short-lived radioactive isotopes. However, inverse kinematics with secondary radioactive beams of short-lived nuclei is a general tool to study these types of reactions involving unstable nuclei.

The $^1H(^6He,^6Li)n$ reaction provides an interesting test case for (p,n) reactions in inverse kinematics. Proton-induced (p,n) reactions have been used extensively to probe weak-interaction strengths. At 0°, the (p,n) cross section has been shown to be proportional to the weak-interaction transition strengths [1] between the ground state of the nucleus $^A(Z)$ and states in the isobaric nucleus $^A(Z+1)$, the two main contributions being $L = 0$, spin-isospin transfer, B(GT)-like (Gamow-Teller), and isospin transfer without spin transfer B(F)-like (Fermi), transitions. The Fermi strength for the transition to the isobaric analog state is given by the simple relation B(F)=N-Z. The (p,n) reaction is also an effective probe of differences in neutron and proton density distributions [2]. Such sensitivity should be particularly useful in reactions with neutron-halo nuclei where the neutron density distribution decreases much more slowly at large radii than does the proton distribution [5]. Since the ^6He nucleus is known to have an extended two valence neutron distribution [6], the differential cross sections for (p,n) could be compared to the (p,p') angular distribution at the same bombarding energy to deduce the difference between the proton and neutron density distributions [2].

The A1200 fragment separator [3,4] at the National Superconducting Cyclotron Laboratory was used to study the (p,n) reaction with ^6He nuclei. Using a primary beam of ^7Li

at E/A=90 MeV incident on a 470 $\frac{\mathrm{mg}}{\mathrm{cm}^2}$ Be target located at the low acceptance position of the A1200, a secondary beam of ^{6}He at E/A=93 MeV was produced, with a momentum full width of 3%. The secondary beam consisted mainly of fully stripped ^{6}He and ^{3}H ions (29% of the beam being ^{6}He) with a very small $^6\mathrm{Li}^{2+}$ contribution. A flux of 3.5×10^5 ^{6}He ions per second was achieved with a 20 pnA primary beam. This secondary beam was focused onto an 18 $\frac{\mathrm{mg}}{\mathrm{cm}^2}$ $(\mathrm{CH}_2)_n$ target at the second dispersive image, and the third segment of the A1200 was set to collect the ^{6}Li ions from the $^1\mathrm{H}(^6\mathrm{He},^6\mathrm{Li})\mathrm{n}$ reaction. The A1200 was operated as a dispersion-matched energy-loss spectrometer [3]. In this mode, the A1200 ion optics from the second dispersive image to the final focal plane provides point-to-point focusing in the horizontal direction and point-to-parallel in the vertical direction [7]. In this mode a 1mm diameter beam spot on the production target can produce a maximum momentum resolution of $\frac{P}{\Delta P}$ (FWHM) = 2000 [4]. Two cathode-readout drift chambers, a position sensitive silicon detector and a fast plastic scintillator were used to determine the position, angle, energy, and particle type at the focal plane. The vertical position is proportional to the vertical scattering angle, and the horizontal scattering angle is reconstructed from the three horizontal position measurements.

There are several limitations to this method for reaction studies. Only long lived states of the ejectile nucleus can be observed, and the energy resolution of the experiment for bound excited states is degraded by the recoil of the ^{6}Li nucleus from the deexcitation γ-rays. The ultimate resolution of this experiment was limited by additional contributions from the ion optical resolution of the spectrometer, the inability to correct completely for the kinematic shift from the measured scattering angles, and the effect of the secondary target thickness needed to get an acceptable counting rate.

In the present experiment, the kinematic shift can readily be seen in Fig. 1. For small scattering angles this shift can be approximated as:

$$\Delta KE_{^6Li}(\theta) = \alpha\theta^2 + \beta\theta^4. \tag{1}$$

and the constants α and β can be calculated from kinematics. At E/A=93 MeV, the values are $\alpha = -3.41 \times 10^{-3} \frac{\mathrm{MeV}}{\mathrm{mrad}^2}$ and $\beta = -1.84 \times 10^{-8} \frac{\mathrm{MeV}}{\mathrm{mrad}^4}$. There are two long lived states in ^{6}Li: the 1^+ ground state, and the 0^+ second excited state at 3.563 MeV [8]. (The 3^+ first excited state at 2.186 MeV decays primarily into α + d.) The 0^+ state is the isobaric analog of the ground state of the ^{6}He nucleus. Only the ground state and the isobaric analog state should be strongly populated by a (p,n) reaction near 0° because (p,n) reactions are dominated by ΔT=1, ΔS=0,1 transitions, that is the τ(F) and $\sigma\tau$(GT) operators, respectively [1]. The ground state will be populated through a Gamow-Teller like transition ($0^+ \rightarrow 1^+$) and the second excited state by a Fermi like transition ($0^+ \rightarrow 0^+$). These states and transitions are indicated in Fig. 2.

Used as a dispersion-matched energy-loss spectrometer, the A1200 has a theoretical maximum momentum resolution of 2000. In the present case, the measured secondary beam momentum resolution was 1700±22, which implies an energy resolution of 630 keV (FWHM). The 32 MeV spread in the ^{6}He beam energy is very effectively cancelled by the dispersion matching. The observed kinematically corrected energy resolution for the ground state is 1080 keV (FWHM) for center of mass scattering angles less than 100 mrad. This width is due to several considerations. The difference in energy loss for ^{6}He and ^{6}Li ions traversing the secondary target leads to a rectangular broadening in the energy distribution of the ^{6}Li reaction products. This broadening is due to differential energy loss and is calculated to be equivalent to 570 keV (FWHM). The remaining 670 keV (FWHM) is due to the initial angular extent of the radioactive beam, which produces an uncertainty in the reconstructed scattering angle. The gamma decay of the second excited state decreases the resolution of the ^{6}Li ions at the focal plane, causing the state to be broadened into a rectangular distribution with a full-width of 3.19 MeV, as shown in Fig. 3.

The carbon in the $(CH_2)_n$ target does not produce any background in this experiment. The large negative ground state Q-values of nearly 10 MeV for ^{12,13}C induced charge exchange reactions means that these reactions produce ^{6}Li ions mainly outside of the excitation energy range of interest. Also the ^{6}Li nucleus has no known particle stable excited states above 3.563 MeV.

The observed energy loss spectrum near zero degrees is shown in Fig. 3. The two expected strong transitions are clearly observed as are a few events from the small ^{6}Li^{++} component in the secondary beam. The spectrum shows only events with a center of mass scattering angles less than 5°. The ground state cross section for center of mass scattering angles less than 3° is measured to be, $\frac{d\sigma_{GS}}{d\Omega} = 43 \pm 16\frac{\mathrm{mb}}{\mathrm{sr}}$. The large systematic uncertainty arises from the normalization of the secondary beam flux.

The strong kinematic forward focusing of the ^{6}Li ions allows the reconstruction of the relative angular distributions of the observed transitions. The angular distributions are shown in Fig. 4. The angular acceptance of the A1200 was measured using ^{4}He events from the breakup of ^{6}He and ion optical calculations, which were then used to correct the observed angular distributions for the acceptance of the spectrometer.

Taddeucci [1] has shown that B(GT) strengths can be extracted from (p,n) cross sections at 0°. Even without an absolute normalization, B(GT) can be extracted by comparison to a Fermi transition to a nearby state in the residual nucleus because the unit cross sections ($\hat{\sigma}_{\mathrm{GT}}$ and $\hat{\sigma}_{\mathrm{F}}$ for Gamow-Teller and Fermi transitions, respectively) have been systematically studied. The ratio of these unit cross sections has been shown to be given by the expression:

$$R^2 = \frac{\hat{\sigma}_{GT}}{\hat{\sigma}_F} = \left(\frac{E_p}{E_0}\right)^2, \text{ [1]} \tag{2}$$

with $E_0 = 55.0 \pm 0.4$ MeV. As the transition to the isobaric analog state in ^{6}Li is thought to be a pure Fermi transition, the ratio of the unit cross sections can be written as

$$R^2 = \frac{\sigma_{GT}(0^\circ)}{\sigma_F(0^\circ)} \frac{B(F)}{B(GT)} \frac{K(E_F - Q)}{K(E_{GT} - Q)}, \text{ [1]} \tag{3}$$

where $K(E_x - Q)$ is the correction factor for kinematics. Using the observed ratio $\frac{\sigma_{GT}(0^\circ)}{\sigma_F(0^\circ)}$ of 5.75±0.35 and Eq. 3 we find that B(GT) for the ground state to ground state transition in the present experiment is 4.13±0.30 compared to 4.77 for the B(GT) observed in $\beta-$decay [8].

For comparison a distorted-wave impulse-approximation calculation was done with the code DW81 [9]. The calculations include only transitions between the $0p_{3/2}$ and $0p_{1/2}$ single particle states. The single particle transition strengths were calculated using the method of Cohen and Kurath [10] in the computer code OXBASH-MSU [11]. The 100 MeV nucleon-nucleon T-matrix parameterization of Love and Franey [12] was also used. The resulting angular distributions are shown in Fig. 4.

The absolute cross section at 0° is in agreement with the (n,p) measurements of [13] and [14], and the relative cross sections for the Gamow-Teller and Fermi transition strengths indicate only a minor variation from systematics. The slightly lower (by 13±6%) than expected ratio of zero degree cross sections, $\frac{\sigma_{GT}(0^\circ)}{\sigma_F(0^\circ)}$, is consistent with the 6% deviations seen in other (N-Z)=2 nuclei for proton bombarding energies greater than 50 MeV [1] A smaller ratio could be indicative of a suppressed Gamow-Teller strength to the ground state of ^{6}Li. Also, it has been proposed that the 3.56 MeV analog state in the ^{6}Li nucleus has an extended matter distribution analogous to the neutron halo in the ^{6}He nucleus [15,16] . This would provide an a near perfect spatial overlap of the ground state of the ^{6}He nuclear wavefunction with the isobaric analog state in the ^{6}Li nucleus (relative to the ground state of the ^{6}Li nucleus) and could lead to a decrease in the ratio of the zero degree cross sections. Wang [13] has observed that at 118 MeV, the 0° cross section for the ^{6}Li(n,p) reaction reproduces the known B(GT) strength well. The current observation is indicative of the effect proposed by Arai [16] and Danilin [15], but due to the 7% uncertainty it can not confirm or refute the possibility that the extended valence neutron distribution in ^{6}He is reflected in the isobaric analog state in ^{6}Li. A recent experiment to measure ^{1}H(^{6}He,^{6}Li)n at lower energy (E/A = 41.6 MeV) also failed to show a substantial signature from the halo structure of the ^{6}He ground state [17].

The results of this experiment demonstrate the viability of the inverse-kinematic technique for studying (p,n) reactions with light exotic nuclei. For example, the neutron halo can be probed not only by the measurement of the momentum distributions and removal cross sections but can also be examined by means of charge exchange reactions combined with elastic scattering data. It is important to note that future improvements in both the tracking of the secondary beam particles and spectrometer are likely to improve the resolution attainable with this technique.

ACKNOWLEDGMENTS

This work was supported by the NSF under grants PHY-92-14922 and PHY-95-28844.

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FIGURES

FIG. 1. Observed kinematic shift of the $^6Li^{3+}$ ions at the A1200 focal plane. The dashed lines are the calculated kinematic shifts for the ground state and isobaric analog state. Reactions from carbon in the target appear as a background at the far left.

FIG. 2. Low lying states in the A=6 system, adopted from Ajzenberg-Selove. The ground state Gamow-Teller transition is shown by the solid arrow and the the transition to the isobaric analog state is marked by a dashed arrow.

FIG. 3. Kinematically corrected energy loss spectrum of the $^6Li^{3+}$ ions at the A1200 focal plane. The ground state, the isobaric analog state and a small background from the stripping of $^6Li^{++}$ ions in the secondary target are indicated.

FIG. 4. Differential cross section for $^1H(^6He,^6Li)n$. The squares indicate transitions to the ground state in ^6Li and the circles indicate transitions to the isobaric analog state in ^6Li. The calculated ratio of cross sections has been scaled to the experimental value.

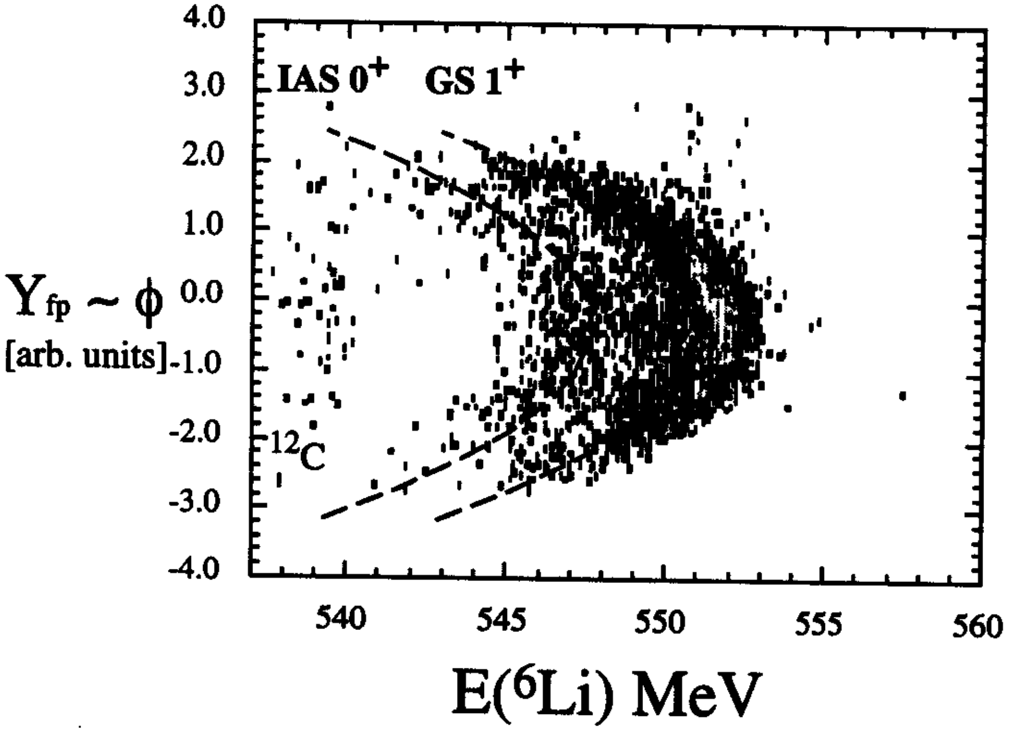
IAS 0+
GS 1+
12C
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
Yfp ~ φ
[arb. units]
540
545
550
555
560
E(6Li) MeV

FIG. 1.

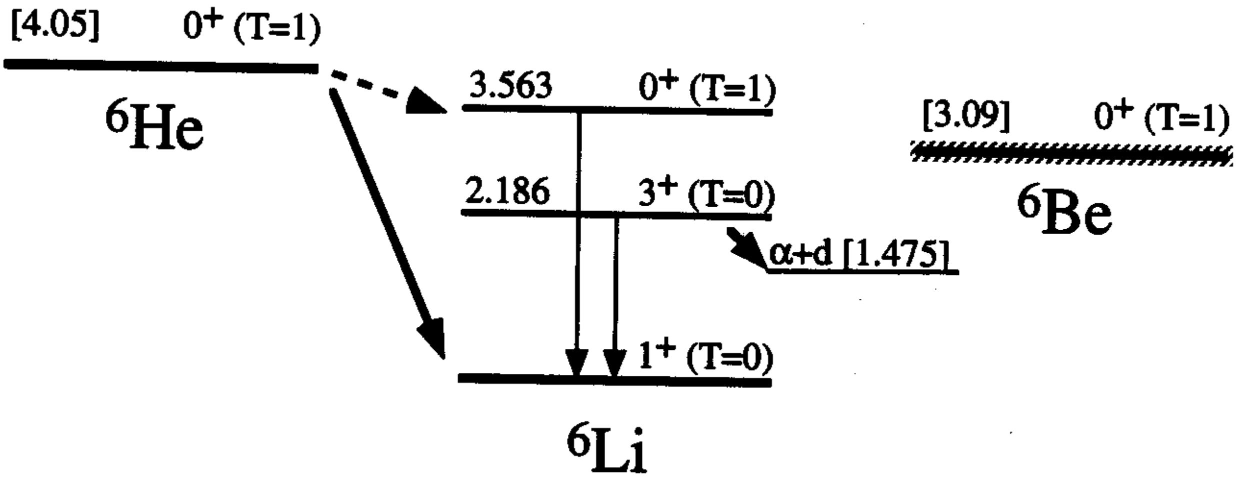

FIG. 2.

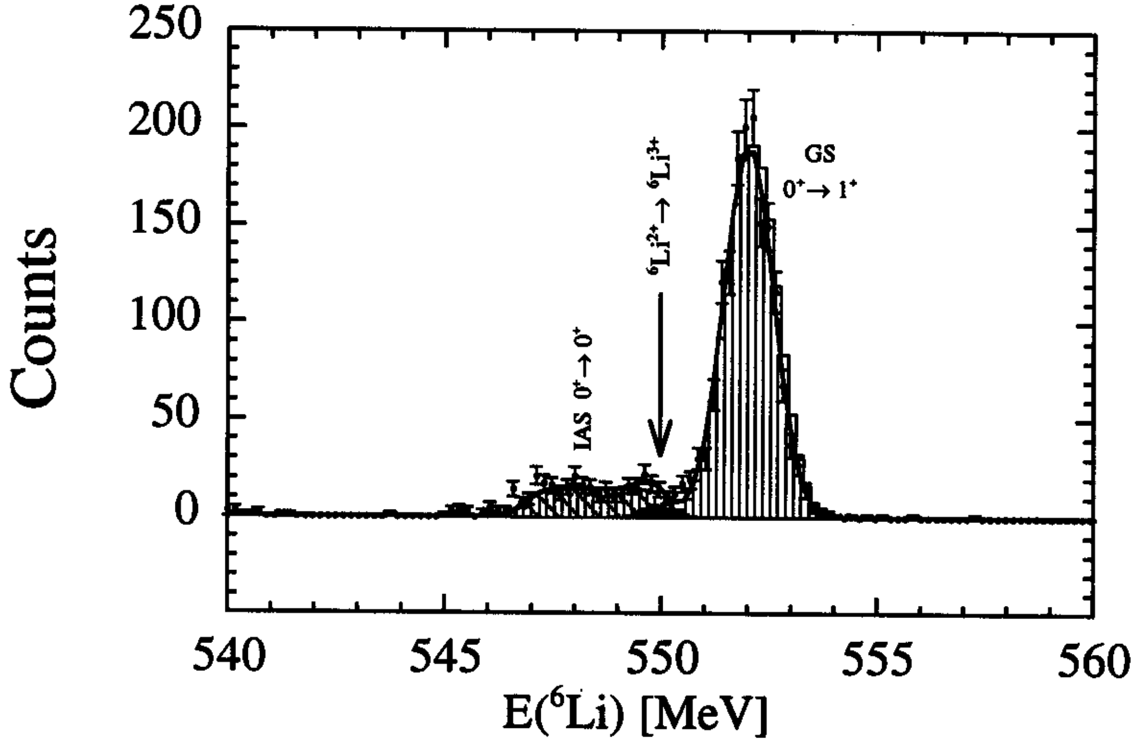
Counts
250
200
150
100
50
0
540
545
550
555
560
E(^{6}Li) [MeV]
IAS $0^+ \to 0^+$
$^6Li^{2+} \to {}^6Li^{3+}$
GS
$0^+ \to 1^+$

FIG. 3.

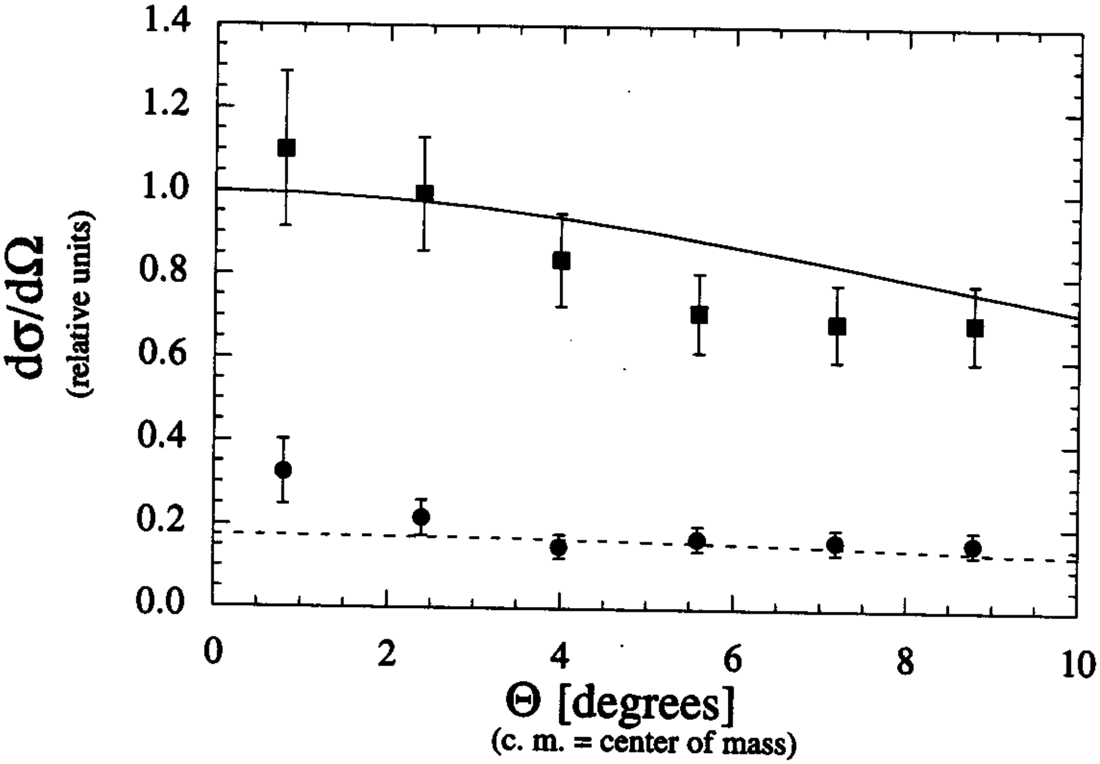
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
dσ/dΩ
(relative units)
0
2
4
6
8
10
Θ [degrees]
(c. m. = center of mass)

FIG. 4.