^{34}P(^{7}Li, ^{7}Be + γ) Reaction at 100A MeV in Inverse Kinematics

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We report on the first successful extraction of a β^+ Gamow-Teller strength distribution from a radioactive isotope in an intermediate-energy charge-exchange experiment in inverse kinematics. The (^{7}Li, ^{7}Be + γ(429 keV)) reaction at 100A MeV was used to measure Gamow-Teller transition strengths from ^{34}P to states in ^{34}Si. The results show that little mixing occurs between sd and pf shell configurations for the low-lying 0^+ and 2^+ states even though ^{34}Si neighbors the island of inversion and low-lying $2\hbar\omega$ intruder states exist. Shell-model calculations in the $sdpf$ model space are consistent with these findings.

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Nuclear charge-exchange (CE) reactions at intermediate energies ($E \gtrsim 100A$ MeV) have long been recognized as an important tool for investigating the spin-isospin response of nuclei [1]. In particular, Gamow-Teller (GT) transitions (orbital angular-momentum transfer $\Delta L = 0$, spin-transfer $\Delta S = 1$), which can be extracted model independently and at excitation energies inaccessible to β decay, have been the subject of intensive studies. The information obtained about nuclear structure also has important applications, for example, for the determination of weak transition rates of relevance for astrophysical scenarios such as late stellar evolution [2].

Because of these properties, the prospect of using such data to better understand nuclear structure away from the valley of stability is very attractive. However, the development of CE experiments at intermediate energies in inverse kinematics (in which the beam containing the rare isotopes of interest is impinged on a target foil holding the probe nuclei) has proven to be a challenge. We report on the first successful extraction of GT strengths through a β^+-type CE experiment in inverse kinematics involving a radioactive isotope beam. The (^{7}Li, ^{7}Be + γ) reaction at 100A MeV was used for investigating transitions from unstable ^{34}P to ^{34}Si.

^{34}Si borders the island of inversion (proton number $Z \sim 12$ and neutron number $N \sim 20$), where the $N = 20$ magicity is broken and the expected ordering of states with sd-shell and pf-shell configurations is inverted [3]. It is known [4–6] that the ^{34}Si 0_1^+ ground state is predominantly of $0\hbar\omega$ (sd-shell) nature, but that the 2_1^+ state at 3.326 MeV has a predominant $2\hbar\omega$ pf-shell structure. Shell-model calculations in the $sdpf$ model space [7,8] support the predominant $0\hbar\omega$ nature of the 0_1^+ state and $2\hbar\omega$ nature of the 2_1^+ state. However, they also predict a $2\hbar\omega$ 0_2^+ state ~1 MeV below the 2_1^+ state. Possible candidates for this 0_2^+ were identified experimentally [5,9], but the existence of the 0_2^+ state below the 2_1^+ state was later almost certainly excluded [10]. More recently, another possible candidate for the 0_2^+ state was identified at 3.996 MeV, 670 keV above the 2_1^+ state [11]. The first 2^+ state (2_2^+) of predominant $0\hbar\omega$ nature is predicted at 5.6 MeV (4.9 MeV) in the $0 - 2\hbar\omega$ shell-model calculations of Ref. [7] (Ref. [8]) and at 4.9 MeV in $0\hbar\omega$ shell-model calculations using the USDB interaction [12]. A candidate for this state was reported in a $2p$ transfer experiment at 5.33 MeV [13] but not confirmed in a similar experiment [14]. The ^{34}P(1^+) ground state is known to be of pure sd-shell nature [15]. The GT transition strengths (B(GT)) to the 0^+ and 2^+ states in ^{34}Si are directly correlated with the $0\hbar\omega$ content in the wave functions of these states; strong $0 - 2\hbar\omega$ configuration mixing would lead to a redistribution of the GT strengths compared the situation where such mixing is largely absent [16].

The (^{7}Li, ^{7}Be) reaction at intermediate energies has been used (see, e.g., [17,18]) in forward kinematics to study Gamow-Teller excitations. Like CE studies using other probes, the method relies on the proportionality between B(GT) and the CE cross section at vanishing linear momentum transfer ($q \approx 0$) [19]. The $^7\mathrm{Li}(\frac{3}{2}^-, \mathrm{g.s.}) \rightarrow {}^7\mathrm{Be}_1(\frac{1}{2}^-(429\ \mathrm{keV}))$ transition ($B(\mathrm{GT}) = 1.12$ [20]) is of particular interest, since spin transfer ($\Delta S = 1$) is ensured. Although transitions with $\Delta J = 2$ can contribute to the $^7\mathrm{Li}(\frac{3}{2}^-, \mathrm{g.s.}) \rightarrow {}^7\mathrm{Be}_1(\frac{1}{2}^-)$ transition, at sufficiently high beam energies and for $q \approx 0$, the $\Delta J = 1$ GT transition dominates the response. Already at $E(^7\mathrm{Li}) =$ 50–65A MeV a good proportionality (error less than

20%) between GT strength and differential cross section at scattering angle $\theta = 0$ ($q \approx 0$) was established [17,18]. At 100A MeV the error will be smaller because the magnitude of the noncentral tensor-τ interaction (which mediates $\Delta L = 2$ contributions) is reduced. In CE experiments performed in inverse kinematics and at $q \approx 0$, the kinetic energy of the recoil nuclei (here ^{7}Be) is sufficiently small (<1 MeV) to stop them in the target. However, with the (^{7}Li, ^{7}Be$_1$) reaction, the 429 keV photon from the decay of the ^{7}Be$_1$ state can be used as a tag for the $\Delta S = 1$ CE reaction. The information needed to reconstruct excitation energies and scattering angles is then obtained from the measurement of the fast residual (here ^{34}Si).

A 900 enA beam of ^{40}Ar was accelerated to 140A MeV at the NSCL Coupled Cyclotron Facility (CCF) and struck a 611 mg/cm^2 Be production target placed at the entrance of the A1900 fragment separator [21]. The momentum acceptance of the A1900 was limited to $dp/p = \pm 0.125\%$ and an aluminum wedge with a thickness of 450 mg/cm^2 was used at the intermediate image to generate a 99%-pure, 100 AMeV secondary ^{34}P^{15+} beam. The ^{34}P beam was directed towards a 2.6 mg/cm^2 $^{\rm nat}$Li (92.4% ^{7}Li) target placed at the pivot point of the S800 spectrograph [22]. The secondary beam intensity was 2×10^6 s^{-1}. ^{34}Si nuclei were identified and momentum analyzed in the S800 focal plane. The beam line towards the S800 was operated in dispersion-matched optics to optimize the resolution of the ^{34}Si energy measurement. Particle identification was performed on an event-by-event basis by using the energy-loss signal measured in an ionization chamber and the time of flight between a thin focal-plane scintillator and the CCF radio-frequency signal. ^{34}Si events were cleanly separated from other nuclei. A 5th-order raytrace matrix was used to reconstruct the angles and momenta of scattered nuclei based on the measurements of positions and angles in two cathode-readout drift chambers in the S800 focal plane. ^{34}P^{14+} charge-state events, in which the ^{34}P nuclei pick up an electron in the Li target, were useful for energy and angle calibration and showed that the intrinsic energy resolution was 1.0 MeV. The angular resolution in the dispersive plane was 1.5 mrad. In the nondispersive direction, the angular resolution was dominated by the angular spread of the incoming beam (20 mrad) limiting the usefulness of this parameter.

The reaction target was surrounded by the Segmented Germanium Array (SeGA) [23]. The setup was optimized for detecting the 429 keV γ-ray from the decay of the ^{7}Be$_1$ state: fifteen 32-fold segmented high-purity Ge detectors were placed with their crystal axes parallel to the beam direction at a distance of 13.2 cm, covering laboratory polar angles between 40° and 140°. Energies and efficiencies were calibrated using standard sources. At $E_\gamma = 429$ keV the photopeak efficiency was $12 \pm 1\%$. An energy resolution of 6% was achieved for γ rays emitted by excited ^{34}Si nuclei after Doppler reconstruction.

In Fig. 1(a), the Doppler-reconstructed γ-ray spectrum gated on all ^{34}Si events in the S800 (of which only a small fraction are due to CE) is shown. The spectrum was fitted to Monte-Carlo (MC) simulations [24] of known transitions in ^{34}Si from previous experiments [4,5,9], as indicated in the figure. In addition, an exponential function is included, representing prompt in-beam background. The signatures of several weak transitions are obscured by the Compton edges of more energetic γ-rays and/or the background. A clean signature of a 5.33 MeV transition is found. Since ^{34}Si was not detected above the neutron separation energy of 7.54 MeV and the first excited state lies at 3.326 MeV, this transition must have a direct decay

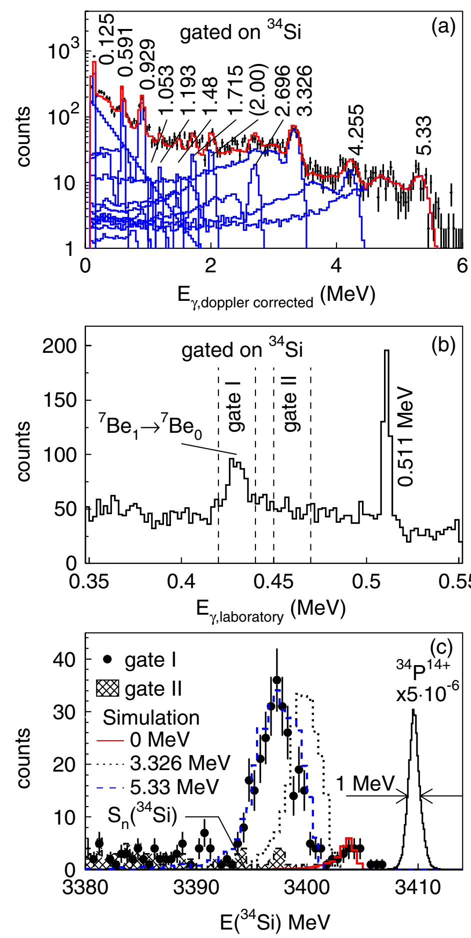

FIG. 1 (color online). (a) Doppler-reconstructed γ spectrum gated on all ^{34}Si events in the S800 spectrograph. The spectrum is fitted with responses for previously reported transitions (blue), plus a 2.00 MeV line (see text). The complete fit is also shown (red). (b) γ-spectrum in the laboratory frame gated on ^{34}Si events. The peak due to ^{7}Be$_1 \rightarrow {}^7$Be$_0$ transitions is indicated, as well as the gates used in the further analysis. (c) ^{34}Si energy spectrum measured in the spectrograph gated on the 429 keV γ-gate (I) and the sideband gate (II). Events gated on the ^{34}P^{14+} charge-state are also shown. S_n(^{34}Si) indicates the threshold for decay by neutron emission for ^{34}Si (E(^{34}Si) $\approx$ 3395 MeV). The ^{34}Si energy spectrum is compared with MC simulations (see text).

branch the ground-state. This is the first observation of this state in a γ spectrum, confirming the measurement reported in Ref. [13]. A new transition at 2.00 MeV was also observed. The placement of this transition in the level diagram is unknown, but it could be due to a decay branch from the 5.33 MeV state to the 2_1^+ state at 3.326 MeV. If so, the deduced relative photon branching ($I_\gamma(2_2^+ \rightarrow 2_1^+)$) is $59 \pm 9\%$ ($I_\gamma(2_2^+ \rightarrow 0_1^+) = 100\%$).

Figure 1(b) shows part of the γ-ray spectrum in the laboratory frame, gated on ^{34}Si events in the S800. A clear peak due to $^7\mathrm{Be}_1 \rightarrow {}^7\mathrm{Be}_0$ transition is found at 429 keV. It is slightly Doppler-broadened (compared to the 511 keV background line), because $^7\mathrm{Be}_1$ nuclei decay before being stopped in the target. Gate I ($E_\gamma = 419$–439 keV) was used to select events in coincidence with the decay of the $^7\mathrm{Be}_1$ state. A sideband gate (gate II: $E_\gamma = 449$–469 keV) was used to create a representative sample of the background under the 429 keV line. About 280 ^{34}Si-$^7\mathrm{Be}_1$ coincidences were recorded, which corresponds to about 2.3% of all ^{34}Si events after taking into account the detection efficiency at 429 keV; the other ^{34}Si events stem from reactions involving other levels in ^{7}Be or completely different mechanisms that produce ^{34}Si in the final state.

In Fig. 1(c), the energy of the ^{34}Si nuclei as measured in the S800 is plotted gated on $^7\mathrm{Be}_1$ coincidences (gate I) and the sideband (gate II). A down-scaled peak gated on $^{34}\mathrm{P}^{14+}$ charge-state events (no γ coincidence) is also shown to illustrate the intrinsic resolution of the energy measurement. In the spectrum with gate I, a small peak at $\sim$3403 MeV, corresponding to the energy expected for the transition to the ground state of ^{34}Si, and a larger peak at $\sim$3398 MeV are observed. The selectivity for CE events in which the $^7\mathrm{Be}_1$ state is populated is very good. Whereas the energy of ^{34}Si nuclei produced in these events is close to the ^{34}P beam energy, ^{34}Si nuclei produced in other processes generally have lower energy. Consequently, events gated on the sideband (gate II) produce few events ($\sim$10) in the energy region of relevance for the charge-exchange channel and mostly fall below the 3380-MeV low-energy boundary of Fig. 1(c). Above the threshold for neutron emission ($S_n(^{34}\mathrm{Si}) = 7.536$ MeV), the rate for events from gate I and gate II become similar, indicating that these events are indeed not due to the (^{7}Li, $^7\mathrm{Be}_1$) reaction and that the events in sideband are representative for the background under the 429-keV peak.

To understand the measured ^{34}Si energy spectrum of Fig. 1(c), MC simulations were performed taking into account the intrinsic energy and angular resolutions of the measurement, the difference in energy loss of ^{34}P and ^{34}Si nuclei in the target, the broadening in energy due to the kinematic correlation between scattering angle and energy, and the effects of decay-in-flight by γ-emission for excited states based on measured decay branching ratios. The MC event generator used center-of-mass angular distributions based on differential cross sections calculated in distorted-wave Born approximation (DWBA) using the code FOLD [25]. The effective nucleon-nucleon interaction of [26] was double folded over the ^{34}P-^{34}Si and ^{7}Li-^{7}Be transition densities, which were calculated with the code OXBASH [27]. The USDB interaction [12] was used for transitions to positive parity states. The WBP interaction [28] in the $spsdpf$ shell-model space was used for transitions to negative parity states in ^{34}Si. This interaction was adjusted following Ref. [15] to account for the lowering of the $f_{7/2}$ and $p_{3/2}$ orbits. Optical potential parameters were taken from Ref. [29]. Aside from the transition to the ground state, these calculations predict that the excitation of the $0\hbar\omega$ 2^+ state dominates the response ($\sim$85%) of the yield at forward scattering angles for states below S_n. Transitions to various states with $J^\pi = (3, 4, 5)^-$ are predicted to make up for the rest the yield.

A good fit to the experimental spectrum was achieved by including only two excitations in ^{34}Si in the MC simulations: to the 0_1^+ ground state [red, solid line in Fig. 1(c)] and to the state at 5.33 MeV (blue, dashed line in Fig. 1(c)]. The transition to the ground state is relatively narrow: compared to the width of the $^{34}\mathrm{P}^{14+}$ peak, broadening only occurred through the additional contributions from the difference in energy loss of ^{34}P and ^{34}Si particles in the target (0.5 MeV) and the kinematical correlation between energy and scattering angle. For the transition to the 5.33 MeV state, the width is dominated by the effects of the decay-in-flight by γ-emission. A significant excitation of the 2_1^+ state at 3.326 MeV can be excluded, as shown in Fig. 1(c) (black dotted line). However, given the limited resolution, contributions from transitions to other levels above 4 MeV cannot be excluded based on energy information only. Therefore, angular distributions were studied as well.

Figure 2(a) shows the laboratory angular distribution for transitions to states which are most likely to contribute to the measured spectrum with $J^\pi = 0^+, 2^+$ ($\Delta L = 0$), $J^\pi = (1, 2, 3)^-$ ($\Delta L = 1$) and $J^\pi = (4, 5)^-$ ($\Delta L = 3$), as calculated in the MC simulation taking into account angular resolution. Since only the dispersive angle could be measured with good resolution, the simulations are integrated over the nondispersive angle. The experimental angular distribution of the transition to the 0_1^+ ground state is consistent with the corresponding MC angular distribution [see Fig. 2(b)]. The half-life for the β decay of ^{34}Si is known (2.77 ± 0.20 s) [30]. Since this is well-reproduced in the shell-model calculation with the USDB interaction (2.80 s), we used the theoretical branching ratio for decay to the ^{34}P ground state (58%) to estimate the B(GT) for the $^{34}\mathrm{P}(1^+) \rightarrow {}^{34}\mathrm{Si}(0_1^+)$ transition (0.051). This value was used to calibrate the proportionality between B(GT) and the differential cross section for GT transitions excited via the (^{7}Li, $^7\mathrm{Be}_1$) reaction.

The angular distribution of the peak at 5.33 MeV was compared to theoretical angular distributions of transitions with various J^π. The experimental angular distribution was consistent with a GT transition associated with $\Delta L = 0$.

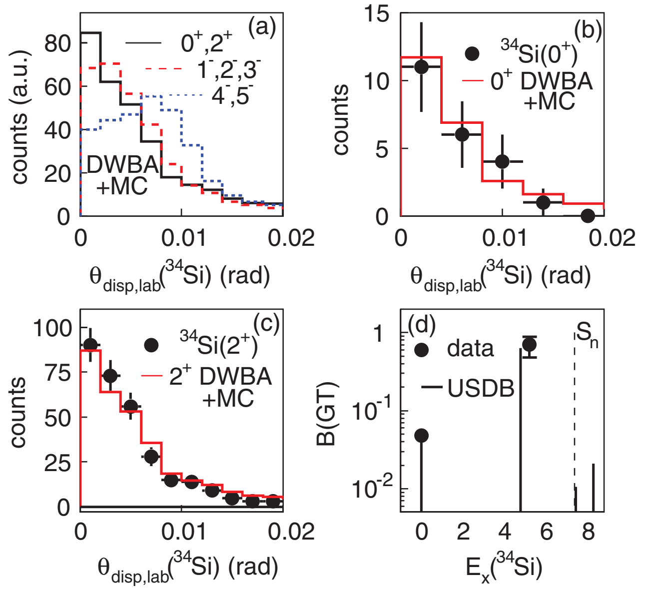

FIG. 2 (color online). (a) Dispersive angular distribution for transitions to states of various multipolarity in ^{34}Si based on DWBA calculation and taking into account experimental conditions in a MC simulation. (b) Comparison between the measured angular distribution for the transition to the ^{34}Si(0^+) ground state and the predicted distribution (scaled to produce best fit). (c) Comparison between the measured angular distribution for the transition to the 5.33-MeV state in ^{34}Si and the prediction (scaled to produce the best fit) for a $\Delta L = 0$ transition to a 2^+ state. (d) Comparison between measured and shell-model B(GT) distributions in ^{34}Si. For energies above the threshold for neutron emission, no data are available.

However, given the statistical errors, a 20% contribution (which is comparable to what was expected based on the DWBA calculations) from transitions associated with $\Delta L = 1$ (e.g. from the 3^- state at 4.255 MeV [4]) could not be excluded and was taken into account as a systematic error. From the proportionality between cross section and B(GT) calibrated with the transition to the ground state, the B(GT) for the transition to the 2^+ state at 5.33 MeV was found to be $0.74^{+0.18}_{-0.18}$(stat) $^{+0.00}_{-0.14}$(syst).

In Fig. 2(d), the extracted B(GT) distribution is compared with shell-model calculations using the USDB interaction. The shell-model calculations have been multiplied by a factor of 0.59 to account for the well-established GT quenching factor in the sd-shell [31]. The data agree well with the shell-model calculations that include only $0\hbar\omega$ configurations. The theoretical predictions of Refs. [7,8], namely, that little mixing occurs between $0\hbar\omega$ and $2\hbar\omega$ configurations in the wave functions of low-lying 0^+ and 2^+ states in ^{34}Si, are also consistent with the data.

In summary, a new method for measuring GT transition strengths in the β^+ direction from rare isotopes has been developed by using the (^{7}Li, ^{7}Be + γ) reaction at 100A MeV in inverse kinematics. As a first case, transitions from ^{34}P, populating states in ^{34}Si, have been studied and theoretical predictions for the mixing between $0\hbar\omega$ (sdshell) and $2\hbar\omega$ (pf-shell) configurations in low-lying 0, 2^+ states in ^{34}Si were tested. Further studies using the (^{7}Li, ^{7}Be + γ) reaction for extracting GT excitations from radioactive isotopes are in progress.

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