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Studying Electron-Capture in Supernovae with the (t,^{3}He) Charge-Exchange Reaction

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Detailed knowledge of the Gamow-Teller strength distribution in medium-heavy nuclei is important for accurately estimating weak transition rates in thermonuclear and core-collapse supernovae. Charge-exchange reactions are an excellent tool to provide empirical information about Gamow-Teller strengths. A secondary, 115 MeV/nucleon triton beam has been developed at NSCL for use in (t,^{3}He) charge-exchange reaction studies. Work is ongoing to extract Gamow-Teller strength distributions, particularly in pf-shell nuclei. We briefly overview the procedure with the ^{64}Zn(t,^{3}He)^{64}Cu reaction as an example.

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1. Motivation

Electron-captures (EC) play a significant role in core-collapse (Type II) [1] and thermonuclear (Type Ia) supernovae [2] where the Fermi energy of degenerate electrons lifts Q-value restrictions on the reaction (see e.g. Ref.[3] for a review). Fuller, Fowler and Newman (FFN), treating valence nucleons in an independent-particle model (IPM), showed that in such environments most EC is on nuclei [4], not free protons. EC rates on intermediate-mass and Fe-group nuclei in white-dwarf Type Ia events can be used, in conjection with observed light curves and ejecta spectra, to constrain important modeling parameters of the explosion [5]. In Type II supernovae, EC on pf- and *sdg*-shell nuclei strongly affects pre-collapse dynamics and properties of the core of the collapsing star [6].

Ground state EC proceeds by a Gamow-Teller (GT) type transition, with nuclear quantum numbers $\Delta L = 0$, $\Delta S = 1$. The reverse process of β-decay, which can be GT or Fermi (F) type ($\Delta L = 0$, $\Delta S = 0$) can also be an important consideration in supernovae. Theoretical determination of the Fermi strength (B(F)) is trivial. Residual *NN*-interactions make determination of the Gamow-Teller strength (B(GT)) more challenging however, as they move the B(GT) centroid and spread the total strength over many more daughter states than anticipated by the IPM used by FFN [7]. Work with modern shell-model techniques have produced more detailed B(GT_+) distributions in EC daughters [8] and associated EC rates [9] which, when used in supernova simulations, lead to significant differences in pre-explosion evolution when compared to use of FFN rates [2, 10].

Measured B(GT_+) distributions are needed to vet theoretical parameterizations of EC rates. The (n,p) charge-exchange (CE) reaction was first used to extract the full B(GT_+) response in nuclei [11]. Subsequently, extraction of B(GT_+) with (n,p)-like composite probes such as (d,^{2}He) [14] and (t,^{3}He) [15] has also been used, with the advantage of improved resolution ($\sim$130 keV and $\sim$200 keV (FWHM) respectively) compared to (n,p) measurements ($\sim$1 MeV). It is important to note that this is the best-case resolution and, since the resolution is mass-dependent, becomes poorer with increasing target mass due to kinematic broadening. Here we discuss the extraction of B(GT_+) in ^{64}Cu from the ^{64}Zn(t,^{3}He) CE reaction, adding to B(GT_+) distributions in pf-shell nuclei determined previously with this probe [16].

2. Method

At the National Superconducting Cyclotron Laboratory's (NSCL) Coupled Cyclotron Facility (CCF) [17] secondary tritons are produced by fast-fragmentation of a 150 MeV/nucleon ^{16}O primary beam on a thick (3500 mg/cm^3) ^{nat}Be production target [15]. The A1900 Fragment Separator [18] is used to momentum-select 115 MeV/nucleon secondary tritons with a 0.84% energy spread ($\sim$3 MeV). The beam purity was 85% and the triton intensity was 3x10^{6}s^{-1}. The triton beam is transported to the target of the S800 Spectrograph [19]. The spectrometer is set at the 0° position relative to the beam axis and the beam line is operated in dispersion-matching mode [20].

In dispersion-matching mode, the contribution from triton energy spread to ^{3}He energy resolution as measured in the S800 Focal Plane [21] is minimized. The focal plane contains two planar, position-sensitive tracking detectors and a series of plastic scintillators. Time-of-flight between the RF-signal of the cyclotrons and the timing signal of the scintillators is combined with

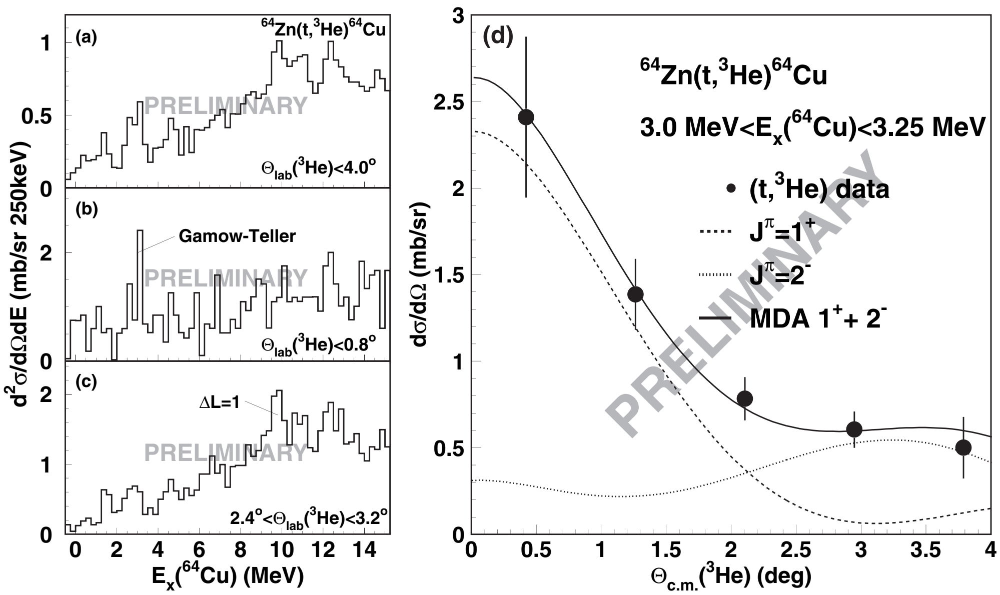

Figure 1: (a) Doubly differential cross section of ^{64}Zn(t,^{3}He)^{64}Cu CE reaction, plotted as a function of E_x(^{64}Cu) and including events with Θ_{lab}(^{3}He) $< 4.0°$. (b) The spectrum gated on forward angles. (c) The spectrum gated around 3°. (d) Differential cross section of the state seen in Fig.1(b) at ∼3.1 MeV, displayed as a function of $\Theta_{c.m.}$(^{3}He).

the energy loss information in the scintillator stack to unambiguously indentify ^{3}He ions. The focal plane tracking detectors are used to determine the hit location and angle of ^{3}He particles. A ray-trace matrix is used to determine momentum and angles of the ^{3}He particle at the target. This information is used to reconstruct the excitation energy in ^{64}Cu in a missing-mass procedure. The excitation-energy resolution achieved in this procedure is 280 keV and the Θ(^{3}He) resolution in the c.m. frame is 10 mrad. The ^{12}C(t,^{3}He) reaction is also measured for calibration purposes. A transition of known absolute cross section, that to the 1^+ ground state in ^{12}B, is used to normalize the ^{64}Cu spectrum, giving absolute differential cross sections of states populated in ^{64}Cu.

Extracting the B(GT) from cross section measurments requires that one distinguish between $\Delta L = 0$ and all other transitions via Multipole Decomposition Analysis (MDA). A basic demonstration of the technique is given in Figure 1. Figure 1(a) shows the ^{64}Cu spectrum for $\Theta_{\rm lab}$(^{3}He) $<$ 4.0°. The spectrum gated on forward angles in Figure 1(b) reveals states that peak near 0°, the signature of GT-transitions ($\Delta L = 0$), such as the state seen at ∼3.1 MeV. In contrast, dipole transtions ($\Delta L = 1$) peak around 3°, such as the state at ∼9.9 MeV seen in Figure 1(c). However, the experimental resolution is often larger than the density of states. Though the signature of a specific value for ΔL may be strong, as with the two example states mentioned above, individual transitions in general can not be separated. Therefore, angular distributions of ^{3}He ions are calculated for $\Delta L = 0$ and several other possible ΔL values in the distorted-wave Born approximation (DWBA). These angular distributions are used to fit the data, using each distribution's overall normalization as the free parameters for the fit. The combination of ΔL distributions that minimize the χ^2 of the fit are taken as the best description. Figure 1(d) shows an example result of this procedure for the 3.1

MeV state already mentioned. The angular cross section of this state is well-described as having strong $\Delta L = 0$ and a weak $\Delta L = 1$ component. These distributions respectively correspond to transitions from the $J^\pi = 0^+$ ^{64}Zn g.s. to 1^+ and 2^- states in ^{64}Cu, both of which have been observed in the ^{64}Cu spectrum in this excitation-energy interval [22].

Extraction of B(GT) for GT-states in the residue is accomplished by exploiting an empirical proportionality [11] between B(GT) and differential cross section in the limit of zero momentum transfer (q). This limit is nearly realized by extrapolating the cross section to $\Theta_{c.m.}$(^{3}He)$= 0^\circ$. Formally, one must also extrapolate the cross section to reaction Q-value$= 0$. However, it constitutes a small correction, so for brevity we neglect its treatment here (see Ref.[16] for details). For the (t,^{3}He) reaction, this proportionality is:

$$\left.\frac{d\sigma(\Delta L = 0)}{d\Omega}\right|_{q\to 0} = \hat{\sigma}_{\mathrm{GT}} B(\mathrm{GT}_+) \tag{2.1}$$

where the proportionality constant $\hat{\sigma}_{\mathrm{GT}}$, called the "unit cross section", has the simple form $\hat{\sigma}_{\mathrm{GT}} = 109A^{-0.65}$ for a target of mass A [23]. From this proportionality, we obtain B(GT$_+$) upon knowing the extrapolated 0° cross section for a $\Delta L = 0$ state. For example, in Figure 1(d) the 0° cross section for the $\Delta L = 0$ partial cross section for the 3.1 MeV state seen in ^{64}Cu is $\sim$2.3 mb/sr. Therefore;

$$B(\mathrm{GT}_+ :^{64}\mathrm{Cu} \quad 1^+ @3.1MeV) = 0.32 \tag{2.2}$$

3. Conclusions

We have briefly overviewed the procedure for extracting B(GT$_+$) in nuclei using the (t,^{3}He) CE reaction measured at forward angles, due to its importance in the treatment of stellar EC in supernova modeling. We have examined the ^{64}Zn(t,^{3}He) reaction to determine B(GT$_+$) for the ^{64}Cu 1^+ state at $\sim$3.1 MeV as an example. From the B(GT$_+$) for this state, the EC $\log ft$ value can be determined as:

$$\log(ft_{\mathrm{EC}}) = \log\left(\frac{K/g_V^2}{(g_A/g_V)^2 B(\mathrm{GT}_+)}\right) = 4.08 \tag{3.1}$$

where g_V and g_A are the vector and axial vector coupling constants, with convenient ratios $|g_A/g_V| = 1.2695 \pm 0.0029$ and $K/g_V^2 = 6146 \pm 6$ [24]. Analysis is ongoing to extract B(GT$_+$) for all low-lying states in ^{64}Cu and build an EC $\log ft$ table for these states. This table will then be used as input for calculation of EC rates on ^{64}Zn, parameterized as a function of stellar temperature and density, using the method of Ref.[25]. Detailed comparisons with modern shell-model calculations will also be made, as in Ref.[16]. The authors look forward to presenting the completed analysis in an upcoming publication.

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