Electron capture in core-collapse supernovae investigated through configuration mixing in neutron-rich nuclei

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Abstract. Electron capture on neutron-rich medium-mass nuclei is a key process where the electrons that impede the collapse of the core of massive stars are captured, thereby producing very neutron-rich nuclei. As the core collapses, the supernova is then initiated. For the electron capture to proceed, however, the allowed Gamow-Teller (GT) transition must be unblocked either by thermal excitations or by mixing of proton configurations from a higher-lying shell into the ground-state configuration of the nucleus. The present paper presents an experiment performed at the National Superconducting Cyclotron Laboratory at Michigan State University, in which we study the configuration mixing in the neutron-rich ^{76}Zn isotope. The experiment utilised single-proton and single-neutron knockout with detection of reaction-residue γ rays and measurement of the parallel momentum of the residue. Through this we investigate the proton components of the ^{76}Zn ground state, with a particular interest in π-g$_{9/2}$, which may unblock the GT electron capture even at low temperatures and thereby open a new pathway for the initiation of the collapse of the pre-supernova stellar core.

1. Introduction
Core-collapse supernovae [1] are some of the most violent explosions in our galaxy. These explosions are prime candidates for the creation of a large fraction of the chemical elements heavier than iron through the rapid neutron-capture process (r-process). In these scenarios, the electron-capture process, in essence $p(e^-, \nu_e)n$, is well-known to be the key driving factor in the pre-supernova collapse of the stellar iron core, as the process removes the degenerate electrons which otherwise impede the collapse [2, 3].

1.1. Nuclear electron capture in core-collapse supernovae
Though originally not thought to play a significant role, the electron capture on heavier nuclei has in recent years been found to be of critical importance [4]. The Gamow-Teller electron capture (GT$_+$) is forbidden in the independent-particle model for nuclei with $Z < 40$ and $N > 40$ as

the available fp-shell protons cannot reach the accessible neutron-$g_{9/2}$ states through an allowed GT_+ transition.

The GT electron-capture on such nuclei may, however, be unblocked either through thermal excitation of the nuclei (studied for example for ^{76}Ge [5]) or through configuration mixing [6, 7]. The configuration mixing may be achieved through correlations across the shell gap in two ways: firstly through mixing of single-particle configurations from the higher-lying proton shell (π-$g_{9/2}$ configurations) into the ground-state, thereby unblocking GT_+ electron capture to the available neutron states (primarily ν-$g_{9/2}$). Secondly, through the opening up of holes in the lower-lying neutron shell (ν-fp configurations). This unblocking is in fact sufficiently strong that the supernova collapse is dominated not by electron capture on the more abundant protons but instead on the less abundant heavy ions.

A recent measurement of this for the stable ^{76}Se isotope [8] has directly confirmed the unblocking of the the GT_+ strength for this nucleus and thereby spurred additional theoretical investigation of the process [9, 10]. This further emphasises the significance of electron capture on medium-mass ions in the collapse of the pre-supernova iron core. In the present experiment we therefore investigate the single-particle structure of ^{76}Zn. Through this study we aim to determine experimentally exactly how exotic the nuclear material may be driven through the unblocked electron-capture in core-collapse supernovae, thereby defining the limits of electron-capture in the stellar collapse.

1.2. Primary goal of the experiment
The present experimental study of single-particle (particularly proton) configurations in ^{76}Zn has been undertaken through proton knockout from ^{76}Zn, populating states in ^{75}Cu. From a previous laser-spectroscopy investigation of this nucleus we know that the ground state is a $5/2^-$ (π-$f_{5/2}$) state [11], with a further identification of two low-energy exited states within $150\,$keV of π-$p_{1/2}$ and π-$p_{3/2}$ nature observed through their isomeric γ decay [12, 13]. In addition, a core-coupled $7/2^-$ state, corresponding to a 2^+ excitation of ^{74}Ni, is expected around $1\,$MeV from systematics, as well as a $9/2^+$ (π-$g_{9/2}$) state in the 2–3 MeV region [14, 15].

The focus of the present experiment is therefore a search for the $9/2^+$ ^{75}Cu excited state and its population through single-proton knockout from ^{76}Zn. The state will be identified through the measurement of the prompt $9/2^+ \rightarrow 7/2^-$ E1 γ decay, and its proton g-wave nature identified through the residual parallel momentum in the knockout.

2. Experiment
In single-nucleon knockout reactions with intermediate-energy ion-beams, the surface-dominated direct reaction may, upon the ion's impact with the light target (here ^{9}Be), instantly remove a nucleon and thereby selectively populate single-hole states in the projectile-like residual nucleus relative to the ground state of the projectile. This process has been established as a high-precision tool to probe the single-particle configurations for exotic nuclei, when utilised for rare-isotope beams [16]. The selectivity between populated final states is obtained through in-beam γ-ray spectroscopy and the parallel-momentum distribution of the residues used to obtain the single-particle properties of the states through the dependency on the angular momentum (ℓ) of the knocked-out nucleon [17, 18]. Single-proton knockout from the short-lived ^{76}Zn nucleus thereby probes the ground-state properties of ^{76}Zn, through which the unblocking of the electron capture may be inferred and compared to that of the stable ^{76}Se and ^{76}Ge isotopes.

For the present experiment, the ^{76}Zn radioactive ion beam was produced at the National Superconducting Cyclotron Laboratory (NSCL, Michigan State University, USA) utilising the Coupled-Cyclotron Facility [19]. The ^{76}Zn ions of interest were produced through the fragmentation of a ^{86}Kr primary beam (140 MeV/nucleon, 20 pnA) impinging on a $425\,$mg/cm^2 ^{9}Be target, and the fragments separated in the A1900 separator [20] at 0.5% momentum

acceptance. The individual species of the resulting cocktail beam were identified on an event-by-event basis through subsequent time-of-flight measurement utilising the timing scintillators of the A1900 extended-focal-plane and S800 object plane (see Fig. 1).
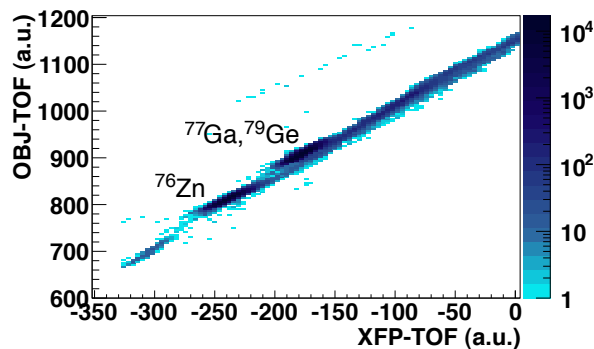

Figure 1. Incoming-beam discrimination through time-of-flight measurement. Timing from A1900 extended focal plane (XFP) and S800 object (OBJ) scintillators.
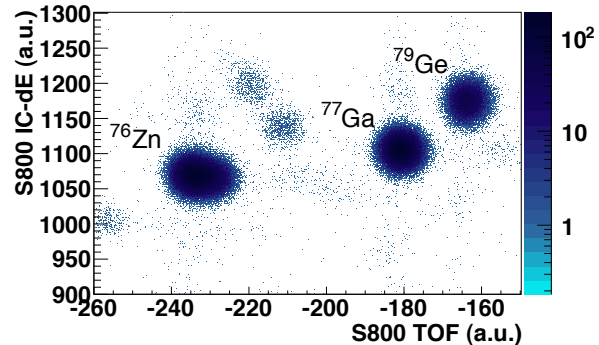

Figure 2. Unreacted beam components measured in S800 spectrometer: flight-path corrected energy loss (measured in ion chamber) against time-of-flight (object to S800 focal plane).

Following the separation, the beam was made to impinge on a $188\,\mathrm{mg/cm^2}$ $^9\mathrm{Be}$ reaction target located at the pivot point of the S800 spectrograph [21], surrounded by SeGA (the Segmented Germanium Array) for coincident γ-ray detection [22]. The residual-particle identification and momentum distribution were characterised using the S800 focal-plane detectors [23], with energy loss measured in the S800 ion chamber, time-of-flight of the residues measured through combination of the object and focal-plane scintillators, and position measurement in the two focal-plane cathode-readout drift chambers (CRDCs). The flight path of the residues through the S800 spectrograph was reconstructed on an event-by-event basis using the optics code COSY [24]. The momentum distribution of the identified knockout residues is thereby calculated from the impact position in the dispersive direction of the focal plane. The particle identification for the unreacted-beam setting of the S800 spectrograph is shown in Fig. 2, through which the cocktail-beam species can be identified, and the $^{76}\mathrm{Zn}$ beam purity evaluated to 33%. Gating on the $^{76}\mathrm{Zn}$ component by time-of-flight (Fig. 1) removes essentially all background components yielding an effective purity of 98.5%.

3. Results and outlook

For the events for which the incoming ion is identified as $^{76}\mathrm{Zn}$, we subsequently identify the residues in the S800 focal plane as described in the preceding, with the S800 rigidity optimised for single-proton knockout to $^{75}\mathrm{Cu}$. The residue identification is shown in Fig. 3, where the two most pronounced features are $^{76}\mathrm{Zn}$ ions in the hydrogen-like (29^+) charge state and the fully-stripped $^{75}\mathrm{Cu}$ one-proton-knockout residues respectively. In addition, some production of $^{74}\mathrm{Cu}$ is seen.

The inclusive momentum distribution for one-proton knockout to $^{75}\mathrm{Cu}$ has been measured, as shown in Fig. 4. Such momentum distributions for each populated state will form the basis for the identification of the proton-$g_{9/2}$ knockout through comparison to momentum distributions calculated in the Eikonal approximation [17, 25]. Through this we will determine the individual components of the $^{76}\mathrm{Zn}$ ground state, thereby for the first time gaining experimental information on the strength of the zero-temperature Gamow-Teller electron-capture on $^{76}\mathrm{Zn}$, probing the limits for electron-capture in core-collapse supernovae.
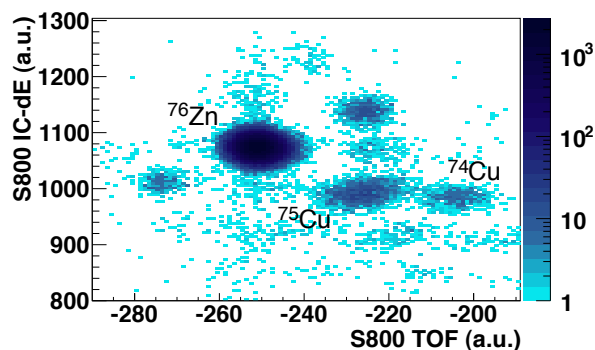
Figure 3. Knockout reaction products identified through flight-path corrected energy loss against time-of-flight. Incoming-beam discrimination (^{76}Zn) through time-of-flight.
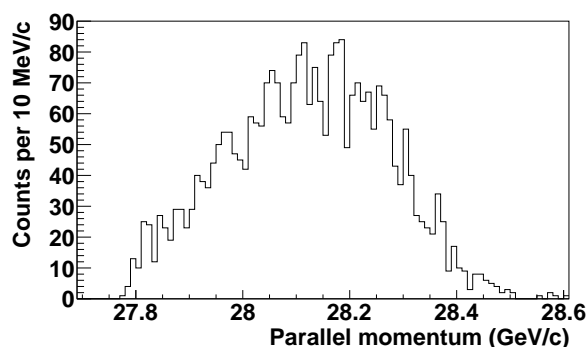
Figure 4. Inclusive parallel-momentum distribution for ^{76}Zn-1p knockout measured in S800 spectrometer.

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