Single-particle structure of radioactive beams from one-nucleon knockout reactions

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Abstract. Studies of the single-particle structure of radioactive beams produced in fragmentation reactions are described. The experiments are based on observing the individual final states of the projectile residues produced in one-nucleon knockout reactions. The measured partial cross sections to the various final states of the projectile residue and the shape of the corresponding longitudinal momentum distributions reflect the single particle properties, spectroscopic factors and the angular momentum l of the removed nucleon. Applications to ^{26,27}P and ^{15}C are discussed.

Investigations of the single particle structure of exotic nuclei are important for understanding the evolution of nuclear structure towards the drip lines. Transfer reactions using low energy stable beams were extensively used in the past to measure the single particle structure of nuclei near the valley of stability. Presently secondary beams of nuclei far from the valley of stability can be produced by projectile fragmentation. Typical energies of these exotic nuclei are around 50 MeV/u and higher. At these energies, the reaction processes tend to become simpler while the cross section for the transfer process decreases rapidly. On the other hand one-nucleon knockout reactions have large cross sections which are almost independent of energy [1]. Exclusive measurements of cross sections and parallel momentum distributions of individual final states populated in the projectile residue after one-nucleon knockout reactions on a light target have been shown to be a powerful way to extract spectroscopic factors and angular momentum assignments [2]. Thick targets and high detection efficiencies involved in these experiments push the sen-

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sitivity of this method to beam intensities of as low as 1 particle/sec.

In this contribution we briefly describe knockout reactions as a tool for spectroscopy of radioactive beams and illustrate the sensitivity and selectivity of this technique with a few examples.

The experiments were performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The required secondary beams obtained from projectile fragmentation of primary beams from the K1200 cyclotron on a thick Be target were purified using the A1200 fragment separator and transmitted to the S800 spectrograph [3] operated in a dispersion matched mode. Intensities of the secondary beams ranged from $\simeq$ 50 particles/sec (^{26}P) to 10^5/sec (^{15}C). The secondary beams with energies of $\simeq$ 65 MeV/u and momentum spreads of 0.5% were incident on thick Be targets. Fragments produced in one-nucleon knockout reactions of the beam were identified and detected using time of flight and the focal plane detectors of the S800. The parallel momentum distributions of the fragments were reconstructed from their measured positions in two x-y position sensitive drift chambers and the known profile of the magnetic fields. Coincident γ rays from the excited fragments were detected using a position sensitive NaI(Tl) array [4] surrounding the target. The γ ray spectrum in the projectile frame was determined from the measured energies and positions in the array. From the above observables the total and partial cross sections after a one-nucleon knockout reaction populating various final states in the projectile residue were obtained.

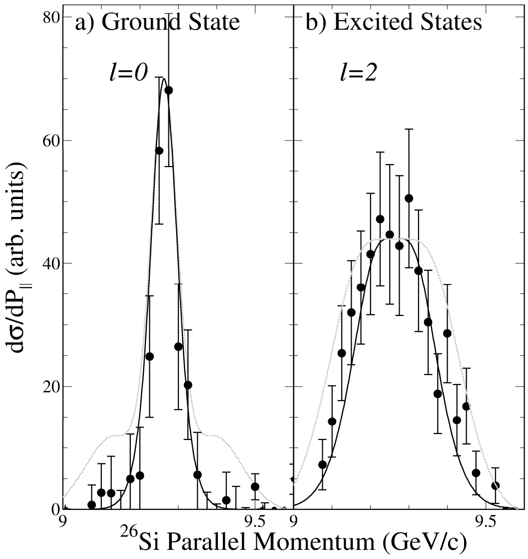

FIGURE 1. Components of the measured parallel momentum distributions after a one-proton knockout from ^{27}P on a Be target. The dark curves correspond to calculations taking into account the effect of shadowing [6] and the grey curves are those obtained neglecting this effect.

The deconvolution of the measured momentum distribution into its components corresponding to ground and excited states was made in two different ways. In the case of ^{27}P the method described in [2] has been used and the results are shown in Fig. 1. For ^{15}C in addition to the above method the momentum distribution for the 1^- excited state at 6.09 MeV was obtained by gating on the deexcitation γ rays and correcting for indirect feeding and the background. The fit to the measured coincidence gamma ray spectrum (Fig. 2a) was obtained by a simulation for the 6.09 MeV γ ray using GEANT [5] and an exponential background. The shape and magnitude of the background were measured independently in knockout reactions where no high energy γ rays were expected (^{12}Be,^{16}C on a Be target). The reliability of the simulation was confirmed by being able to reproduce source intensities to within 5% and also the line shapes. A similar method was used for the 0^- state. The ground state momentum distribution is obtained from a subtraction of the excited states distribution from the inclusive momentum distribution. The present analysis yielded consistent results with those using the method in [2]. Shown in Fig. 2b is the momentum distribution corresponding to the 1^- excited state in ^{14}C. The predictions for the momentum distribution assuming various values of l for the knocked out nucleon obtained from an eikonal model [6] are also plotted. As can be seen from the figure the momentum distribution is characteristic of an l=1 nucleon which corresponds to the removal from the deeply bound p orbit in ^{14}C. This part contributes to 25% of the total one-neutron knockout cross section. Such

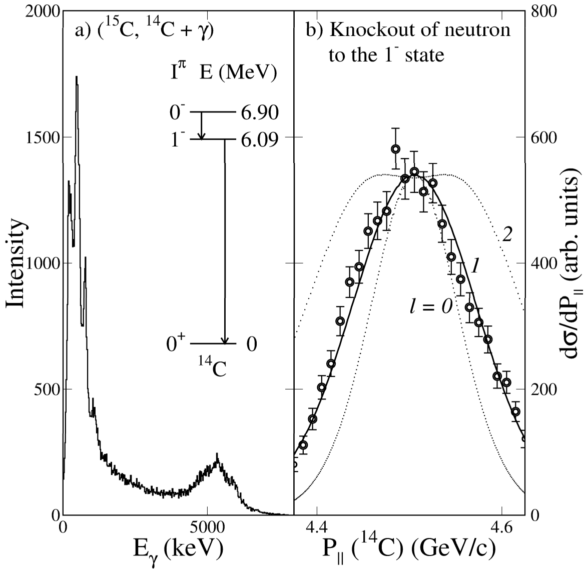

FIGURE 2. a) Doppler corrected γ ray spectrum in coincidence with ^{14}C fragments. b) Parallel momentum distributions corresponding to population of the 1^- state. The calculated momentum distributions for various l values are shown.

a removal from a core leaving the halo nucleon intact was found to have a 15% contribution to the measured total one neutron removal cross section in the case of ^{11}Be on a Be target [7]. The measured ground state distribution is characteristic of a l=0 nucleon knockout.

The measured cross sections to various final states in the projectile residue are compared with a model [2] which incorporates single particle removal cross-sections (σ_{sp}) calculated using a modified eikonal model [1] and spectroscopic factors (C^{2}S) obtained from the shell model. The cross section to a given final state c in the core is expressed as $\sigma(c) = \sum_j \mathrm{C}^2\mathrm{S}(c, nlj)\sigma_{sp}(l_j)$. The measured cross sections for the various states in ^{14}C populated in one neutron knockout reactions are in good agreement with these calculations. The structure of ^{15}C has been well studied using *(d,p)* reactions and the derived spectroscopic factors in the present work are in good agreement with the literature [8] and a recent shell model calculation. Inclusive measurements of ^{15}C have been reported earlier [9]. Detailed results for ^{15}C on Be and various heavier targets will be presented elsewhere [10]. Comparing the experimental results for the total and partial cross sections using this method we have been able to reaffirm the tentative spin assignments of 3^+ and $\frac{1}{2}^+$ for ^{26,27}P. Assuming a spin 1^+ for ^{26}P would give a smaller cross section and be inconsistent with the measured ground state $s_{1/2}$ spectroscopic factors. The significance of the large s-component in the ground state of the neutron deficient phosphorus isotopes is an indication of a proton halo and has been discussed elsewhere [2,11].

The present results and those obtained for ^{11}Be [7], ^{12}Be and ^{16,17,19}C [12] indicate the versatility of this method. Applications at different beam energies for ^{15}C and ^{17}O (studied by complementary methods) will further test the validity of this method. New generation gamma ray detectors and higher beam intensities available after the NSCL upgrade will give us an opportunity to probe the structure near the drip lines for heavier nuclei.

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