SPECTROSCOPY OF RADIOACTIVE BEAMS FROM SINGLE-NUCLEON KNOCKOUT REACTIONS: APPLICATION TO THE SEARCH FOR PROTON HALOS

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Measurements of direct reactions coupled with a theoretical analysis based on the DWBA (for the reaction mechanism) and the shell model (for the nuclear structure) have served as an important tool for nuclear structure studies especially at low bombarding energies and with stable beams [1]. In (d,p)-type transfer reactions at energies above 20 MeV/u the proton angular distributions loose most of their characteristic l-dependence and the magnitudes of the cross sections drop sharply with increasing energy. We present here a new and general method applicable to nuclear spectroscopy of radioactive beams [2]. The technique is applicable at energies greater than approximately 50 MeV/u, characteristic of radioactive beams produced in projectile fragmentation. The method is based on obtaining partial cross sections from the measured γ-ray intensities (identifying the individual final states) arising from the decay of states populated in the projectile residue in single-nucleon removal reactions. An extension [3] of the eikonal model is used for translating the measured cross sections into spectroscopic factors. A signature of the orbital angular momentum involved in the reaction is provided by the longitudinal momentum distribution of the projectile residue observed in coincidence with the de-excitation γ-rays. We expect that the new technique of using high-energy stripping reactions will become a valuable supplement to other methods for studying nuclei far from the valley of stability, such as measurements of interaction cross-sections, momentum distributions (of the valence nucleon or core) and Coulomb excitation.

The present work is motivated by a search for changes in nuclear structure in the sd shell due to the predicted existence of proton halos in the nuclei ^{26,27,28}P. These isotopes have proton separation energies of 0.14(20), 0.897(35) and 2.066(4) MeV respectively. The phosphorus isotopes are the lighest nuclei expected to have a ground state with a dominant contribution of a $\pi s_{1/2}$ orbital. The halo character is expected to manifest itself through relatively large stripping cross sections and narrow longitudinal momentum distributions. The shell-model structure and properties of these nuclei have been discussed in a recent paper [4]. Large halos, strictly speaking, are only possible for neutrons in s and p states, and the effect of the Coulomb barrier will always make a proton halo less extended. The present measurements were extended to include ^{25}Al (S_p= 2.27 MeV) for a comparative study of proton removal from a nucleus differing only by a few nucleons from the phosphorus isotopes but expected to have a negligible $\pi s_{1/2}$ component [5,6].

Radioactive beams of ^{25}Al and ^{26,27,28}P with energies of approximately 65 MeV/u and momentum spreads of 0.5% were produced in fragmentation reactions using a 100 MeV/u ^{36}Ar beam on a 470 mg/cm^2 Be target and were purified using the A1200 fragment separator. The large acceptance S800 superconducting spectrograph, operated in a dispersion matched mode, in conjunction with the focal plane detector setup were used to identify and measure the momentum distributions of the projectile residues produced in one-proton breakup reactions of the radioactive beams on a 14 mg/cm^2 Be target. Time-of-flight information over a distance of 70 m along with energy measurements obtained with a segmented ion chamber and a 5 cm thick plastic scintillator were used to identify and measure the yields of the fragments in the

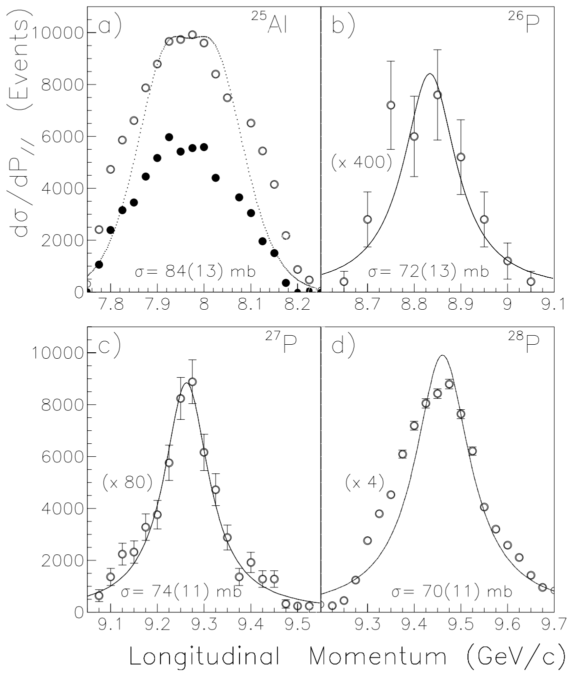

Figure 1: Longitudinal momentum distributions, in the laboratory frame, of the projectile residue formed in a one-proton removal reaction. The integrated total cross-sections are indicated. a)(^{25}Al, ^{24}Mg): the open (filled) circles are the distribution without (with) he integrated total cross-sections are indicated. a)(^{25}Al, ^{24}Mg): the open (filled) circles are the distribution without (with) a coincident γ-ray from the $2^+ \to 0^+$ transition in ^{24}Mg. The dotted line corresponds to a calculated momentum spectrum for an l=2 proton, using a black disk model (see text). The corresponding width is 265 MeV/c. b-d)(^{26,27,28}P, ^{25,26,27}Si): the continuous lines represent Lorentzian fits. The corresponding widths are 137(33), 116(8) and 143(14) MeV/c, respectively.

reaction. Two x/y position-sensitive cathode-readout drift chambers recorded the momentum and angle information of the fragments at the focal plane of the spectrograph. The momentum and scattering angle of the fragments after the reaction were then reconstructed from the known magnetic field and positions at the focal plane using the ion optics code COSY [7]. The measured parallel momentum distributions for ^{25}Al and the ^{26,27,28}P isotopes are shown in Fig. 1. Only statistical errors are shown. The γ-rays in coincidence with the breakup events were measured using the NSCL position-sensitive NaI(Tl) array of 38 detectors placed around the target chamber.

The theoretical nucleon-knockout cross section leading to a given final state n (parity and angular-momentum quantum numbers are implicit in our notation) can be written as a sum over the allowed angular momentum transfers j

$$\sigma(n) = \sum_j C^2 S(j,n) \sigma_{sp}(j, B_n). \tag{1}$$

Each term in the sum in eq. (1) is a product of two factors. $C^2 S(j,n)$, the spectroscopic factor of the removed nucleon with respect to a given core state, is calculated from the shell model [5] and accounts for the intrinsic structure. The reaction factor $\sigma_{sp}(j,B_n)$, the cross section for the removal of a nucleon from a single particle state with total angular momentum j, is calculated in the eikonal model. The assumed nucleon separation energy B_n is the sum of the nucleon separation energy for the ground state and the excitation energy of the state n. The momentum distributions were calculated from the Fourier transform of the wavefunction of the halo particle, taking into account shadowing (black disc approximation) due to the target [8]. In the present calculations the wavefunction was not approximated by its value along the trajectory but a full three dimensional integration was carried out.

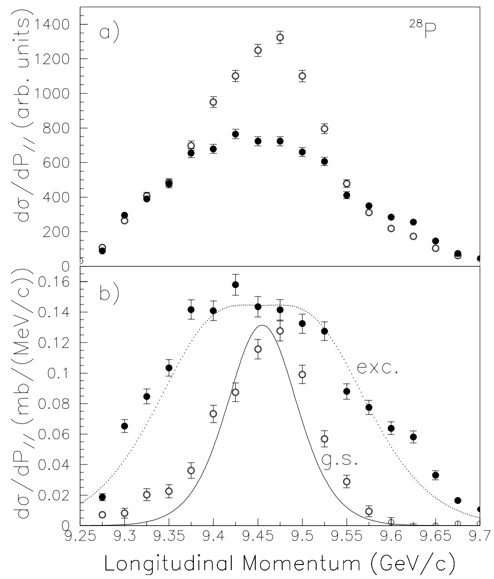

Figure 2: Longitudinal momentum spectra for ^{27}Si projectile residues. a) The open (filled) circles correspond to the absence (presence) of coincident γ-rays in the NaI(Tl) array. b) Derived longitudinal momentum spectrum corresponding to the ground (open) and excited states (filled) in the projectile residue ^{27}Si obtained from Fig. 2a. The continuous and dashed lines are calculated longitudinal momentum distributions with widths 93 and 248 MeV/c, in the laboratory frame, for the s and d states, respectively.

Fig. 1 clearly illustrates the variance in the shapes of the longitudinal momentum distributions for ^{25}Al as compared to the phosphorus isotopes. Fig. 1a shows that the shape of the momentum distribution calculated with an assumption that reactions with ^{25}Al involve essentially pure d-states agrees well with experiment, and also that γ-coincident events give essentially the same characteristic broad shape. Shell model spectroscopic factors[4,5] also predict that the reaction of ^{25}Al essentially involves d-waves. The predictions for the phosphorus isotopes are quite different. Calculations show that the ground state has a dominant s component whereas the excited states mainly involve d components. Thus Figs. 1b-d must represent a superposition of s- and d-components. Fig. 2 shows a direct experimental confirmation of the above for ^{28}P where one can see very dissimilar distributions for the data with and without γ rays in coincidence with the projectile residue (^{27}Si). A linear combination of the two measured momentum spectra of Fig. 2a along with an estimate for the background and γ efficiency were used to construct the individual components shown in Fig. 2b. These momentum distributions are representative of the ground state and of all the various excited states and essentially correspond to pure s and d components respectively. The large cross section and narrow momentum width for the ground-state transition are evidence for the proton halo structure discussed in [4]. The halo contribution is also clearly visible in the momentum spectra in Fig. 1-b,c.

In summary, a new method for experiments with fast radioactive beams combining new experimental and theoretical developments has been reported. Its application to several cases in the sd shell demonstrates that valuable nuclear-structure and angular-momentum information may be obtained from measurements of partial cross sections and linear-momentum distributions in inverse kinematics. This method is presently also being applied to understand in greater detail the structure of the neutron-rich C isotopes [9]. At the present juncture, intensity and γ-ray resolution are serious limitations, but higher beam intensities which will be available with the NSCL cyclotron upgrade and improved detection techniques like the HpGe array expected to be available soon will offer interesting possibilities for studying nuclei far from the valley of stability.

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