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Abstract. The reaction ^{11}Be(p,d)^{10}Be has been studied for the first time, using a secondary ^{11}Be beam of 35.3 MeV/nucleon. Angular distributions up to about 15^{o}_{cm} were measured by detecting ^{10}Be in a spectrometer and coincident deuterons in a position sensitive silicon detector array. Preliminary analysis provides evidence for a large core excitation component in the structure of ^{11}Be$_{GS}$.

I INTRODUCTION

With the development of intense radioactive beams, one-nucleon transfer reactions will certainly represent one of the major tools for investigating the microscopic structure of nuclei far from stability. The feasibility of such experiments in different mass regions, relying on the use of large position-sensitive light particle detectors, has been examined in ref. [1]. The first such transfer experiment is reported here, namely an investigation of the ^{1}H(^{11}Be,^{10}Be)^{2}H reaction performed with the goal of providing a test of the various competing nuclear models for the structure of the halo nucleus ^{11}Be. Theoretical interest has been focussed on this nucleus for several decades, due to the observation of a "parity inversion" -the $J^{\pi}=1/2^{+}$ ground state being in contradiction with the naive shell model prediction of $1/2^{-}$. Several

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calculations of the structure of ^{11}Be have recently been performed, using different theoretical approaches, such as the shell model [2], the variational shell model [3], the Generator Coordinate model [4], and coupling of the neutron with a vibrational core [5–7] or a rotational core [8,9]. Most of them correctly reproduce the parity inversion but make very different predictions about the degree of coupling of the ^{11}Be ground state with the first 2^+ excited state of ^{10}Be at 3.37 MeV, the ratio of spectroscopic factors in the different models $S(2^+)/S(0^+)$ varying from 0.07 to 0.73. In this context, a stringent test of these models can be provided by the experimental determination of this ratio of spectroscopic factors by means of a neutron pick-up reaction.

II EXPERIMENT AND RESULTS

The ^{11}Be(p,d)^{10}Be reaction was studied in inverse kinematics, using a ^{11}Be secondary beam of 35.3 MeV/nucleon produced by fragmentation of ^{15}N in the SISSI device at GANIL. The SPEG spectrometer placed at 0^o was used to analyze the ^{10}Be nuclei from the interaction of ^{11}Be with a $(CH_2)_n$ target of thickness 50 μm. Particle identification and momentum and angle measurements were provided by the standard focal plane detection system (two XY drift chambers, an ionization chamber and a plastic scintillator giving energy loss and time-of-flight information). Information on the incident angle at the target position was provided event-by-event by two XY drift chambers, placed in the beam line before the analysing magnet. Deuterons in coincidence with ^{10}Be were detected using CHARISSA. This array of ten position sensitive sheet-resistive silicon detectors (5 x 5 cm^2 and thickness 500 μm), was located in the target chamber at angles between $\sim 5^o$ and 35^o. The ^{11}Be intensity was $\sim 3.10^4$ pps, and was monitored throughout the experiment in a small plastic detector placed at the high momentum end of the focal plane.

The ^{10}Be spectra were accumulated at two different magnetic field settings differing by 0.9% , for a total exposure of 3.7x10^9 ^{11}Be nuclei. Focal plane spectra are displayed in figure 1. Three peaks are observed in fig.1(bottom), corresponding to the population of known bound states in the ^{10}Be nucleus by the (p,d) reaction. The 2^+ state at 3.368 MeV is well separated from the 0^+ ground state and the unresolved group of states at 5.958 MeV (2^+),5.960 MeV (1^-),6.179 MeV (0^+) and 6.263 MeV (2^-). A large Doppler broadening is observed for excited states in ^{10}Be (v/c=0.28), due to the in-flight emission of γ-rays of several MeV.

The background observed in the singles ^{10}Be spectrum (fig.1-top) is fully removed by the coincidence with CHARISSA detectors. This background primarily originates from the reaction ^{12}C(^{11}Be,^{10}Be)^{13}C on the carbon atoms of the polypropylene target and contributions from breakup of deuterons and ^{11}Be nuclei. The energies of contaminant peaks labelled "C*" in the vicinity of the 0^+ and 2^+ peaks correspond to either excitation of ^{13}C states around 10 MeV or mutual excitation of ^{10}Be and ^{13}C. On the other hand, the (^{11}Be,^{10}Be$_{GS}$) transfer reaction to the ground and first excited states in ^{13}C has a much lower cross section, as the corresponding

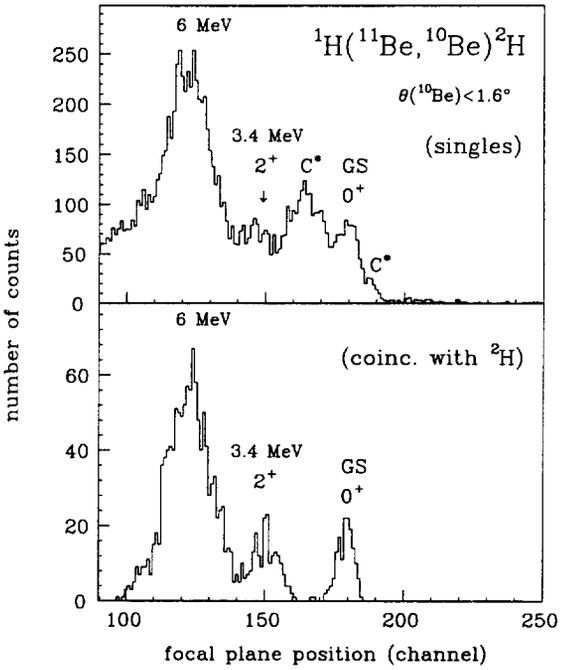

FIGURE 1. Focal plane spectra measured for singles ^{10}Be (top) and ^{10}Be in coincidence with deuterons(bottom), at laboratory angles less than 1.6°.

peaks are not observed. It is to be noted that the inverse kinematics suppresses the (^{12}C,^{13}C) laboratory cross sections by a factor of 22 compared with (p,d).

The strong peak at 6 MeV is most probably dominated by the pickup of one $p_{3/2}$ neutron from the ^{10}Be core, feeding the $\nu(s_{1/2}\text{-}p_{3/2}^{-1})$ 1^- and 2^- states at 5.960 and 6.263 MeV, with contributions from the second 2^+ and 0^+ states at 5.958 and 6.179 MeV. The peak at 6 MeV is superimposed on a background, corresponding to the high energy tails of the ^{11}Be$\rightarrow^{10}$Be+n and d$\rightarrow$p+n breakup reactions near threshold. The contribution of the (p,pn) reaction to the ^{10}Be spectra has been removed by energy conditions applied to CHARISSA detectors which select only coincident recoil deuterons. This (p,pn) contribution at threshold was found to be about 25% of the total ^{1}H(^{11}Be,^{10}Be) cross section in the vicinity of the 2^+ peak.

Angular distributions for the 0^+ and 2^+ states and the 6 MeV multiplets within the central region ($\theta_{LAB} < 1.6^o$) of the angular acceptance of the SPEG spectrometer are shown in fig.2. Cross sections were obtained by using combined results from the coincident and singles data. Data in coincidence with CHARISSA detectors were corrected for the variation of geometrical detection efficiency as function of angle. This efficiency was calculated using a simulation program, accounting for the large emittance and beam spot size of the secondary beam, and for the uncertainties of scattering angle determination. Error bars in fig.2 are only statistical. Systematic errors coming from uncertainties on the scattering angle determination and the efficiency of the detection system are expected to be of comparable size.

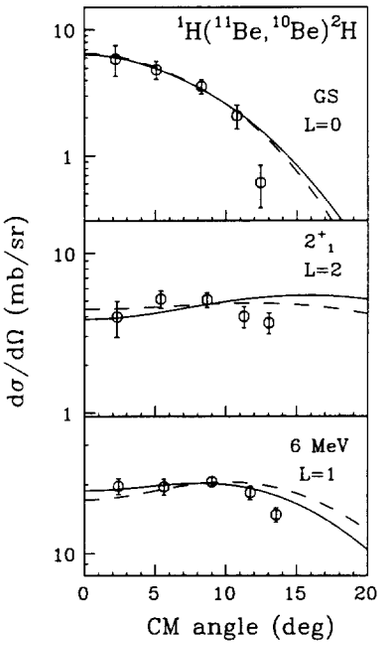

FIGURE 2. *Experimental and calculated angular distributions (see text)*

III ANALYSIS OF ANGULAR DISTRIBUTIONS

Theoretical differential cross sections were calculated using the zero-range DWBA code DWUCK4 [11], with standard corrections for finite-range and non-locality effects. The separation energy method has been used to calculate n+^{10}Be form factors in a Woods-Saxon well with standard geometry r_0=1.25 fm, a=0.65 fm. The halo character of the wave function of the $2s_{1/2}$ neutron coupled to the ^{10}Be ground state comes out naturally from this calculation, due to the low binding energy (0.504 MeV) of the ^{11}Be ground state. One has assumed a pure $d_{5/2}$ transfer to the 2^+ state. Calculations for the 6 MeV peak have assumed a p3/2 neutron pick-up in the ^{10}Be core, exciting the doublet of 1^- and 2^- states. Different combinations of optical potentials for the proton and deuteron channels were used in the calculations in order to test the sensitivity of extracted spectroscopic factors to the input parameters.

Recent proton elastic scattering experiments involving ^{10}Be and ^{11}Be radioactive beams have shown that standard global nucleon-nucleus potentials adjusted for stable nuclei do not reproduce the data unless one reduces the depth of the real Saxon-Woods well [13]. Calculations with potential P1 (table 1) were performed using p+^{11}Be optical parameters derived from the global nucleon-nucleus CH89 [12], with a real well depth reduced by 0.7 [13]. Calculations were also performed for comparison with the proton-nucleus potential from ref. [14], which reproduces elastic scattering data in stable nuclei of the 1p shell (P2), and the global nucleon-

nucleus potential from ref [15] (P3).

Standard DWBA calculations were done using the deuteron potential from ref. [16], deduced from elastic scattering experiments (D3). However, it is well known that (p,d) and (d,p) reactions are generally not correctly described by standard DWBA calculations, which do not account for the effects arising from the breakup of the deuteron in the field of the nucleus. The adiabatic deuteron breakup approximation (ADBA) proposed by Johnson and Soper [10] has provided a simple and successful approach to take these effects into account. This approach consists of using a folding potential derived from proton and neutron optical parameters at half the deuteron energy to generate the distorted wave functions in the deuteron channel, in place of the optical potential deduced from elastic scattering data. Calculations within the ADBA approach were performed using the adiabatic potentials D1 and D2, derived from the global nucleon-nucleus CH89 [12] (with a factor of 0.9 applied to the real well depth [13]) and from the optical potential parameters from ref. [14], respectively.

All these various calculations nicely reproduce the slope of the L=0 angular distribution observed experimentally for the ground state transition, and the nearly isotropic angular distributions observed for the 2^+ and 6 MeV states below 10^o_{cm}. The full and dashed lines in fig.2 correspond to ADBA calculations with the combinations of proton and deuteron potentials P1-D1 and P2-D2, respectively. Spectroscopic factors S were extracted using the relation $\sigma_{exp} = NS\sigma_{calc}/(2J_{tr}+1)$ with a normalization factor taken equal to the usual value of 2.29 [11]. The values obtained for the transitions to the 0^+ ground state and 2^+ first excited state of ^{10}Be using different combinations of proton and deuteron optical potentials are displayed in table 1.

TABLE 1. Results of the analysis of the p(^{11}Be,^{10}Be) reaction (see text)

	S(0^+)	S(2^+)	S(2^+)/S(0^+)
P1-D1	0.52	0.46	0.88
P2-D2	0.42	0.32	0.76
P2-D3	0.57	0.57	1.00
P3-D3	0.72	0.71	0.99

Spectroscopic factors for the ground state transition vary from 0.42 to 0.72 and can be compared with the spectroscopic factors extracted for the inverse transition $^{10}Be_{GS} \rightarrow {}^{10}Be_{GS}$, studied by means of the (d,p) reaction on a radioactive ^{10}Be target, namely 0.73 [17] and 0.77 [18]. This dispersion of spectroscopic factors is outside the commonly accepted value of about 20% on absolute spectroscopic factors extracted from DWBA analyses. On the other hand, ratios of spectroscopic factors do not depend on possible uncertainties on absolute cross sections values, and are typically less dependent on the ingredients of reaction calculations. The

ratio R=S(2^+)/S(0^+) deduced from the present analysis ranges between 0.76 and 1.00. Further analysis is in progress in order to estimate the global uncertainty to be assigned to this preliminary R-value of about 0.9.

Such a large value of S(2^+)/S(0^+) greatly exceeds the predictions of refs. [5,8,9], which range from 0.07 to 0.18, and the value of R = 0.26 from recent shell model calculations [2]. On the other hand, variational shell model calculations from ref. [3] predict a strong coupling of the ^{11}Be ground state with the 2+ excited core of ^{10}Be, giving a value of R of 0.73, in rather good agreement with the present results.

IV CONCLUSION

The p(^{11}Be,^{10}Be)d reaction has been studied in order to determine the ratio of spectroscopic factors R=S(2^+)/S(0^+), which provides a sensitive test of different models for the structure of ^{11}Be. The preliminary results are consistent with a description of the ^{11}Be ground state being very strongly coupled to the first 2^+ state in ^{10}Be, as given by the predictions of ref. [3].

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