NEUTRON DEEP-HOLE STATES FROM THE (p,pn) REACTION

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Résumé - Nous avons mesuré les spectres d'énergies de séparation et les sections efficaces pour les réactions ^2H , ^9Be , ^{16}O , ^{28}Si , ^{58}Ni , et ^{90}Zr (p,pn) à 150 MeV. On essaie d'identifier les énergies des états "trous profonds" de neutrons.

Abstract - We measured separation-energy spectra and cross sections for the (p,pn) reaction on ^2H , ^9Be , ^{16}O , ^{28}Si , ^{58}Ni , and ^{90}Zr at 150 MeV. Energies of neutron deep-hole states are tentatively identified.

I - INTRODUCTION

In the summer of 1980 a Kent State-Maryland-Indiana collaboration performed the first (p,pn) neutron-knockout experiment at the Indiana University Cyclotron Facility (IUCF). That experiment /1,2/, a study of the $^{40,48}\text{Ca}$ (p,pn) reactions at 150 MeV was designed primarily for the spectroscopy of neutrons in the $2s_{1/2}$ and $1f_{7/2}$ shells. However, in the separation energy spectra from that experiment, evidence was seen for neutron deep-hole states at separation energies > 30 MeV. Therefore, a second (p,pn) experiment was undertaken in the winter of 1982, which was designed primarily as a study of deep-hole states. That second experiment, a survey of the (p,pn) reaction on ^2H , ^9Be , ^{16}O , ^{28}Si , ^{58}Ni , and ^{90}Zr is the subject of this paper.

II - EXPERIMENT

The experiment was performed in a co-planar geometry ($\theta_p = 36^\circ$, $\theta_n = -36.7^\circ$) with a 148.8 MeV polarized proton beam. Proton energies were measured with a detector telescope consisting of a 2 mm Si surface-barrier detector followed by a 10 mm and a 15 mm high-purity Ge detector /3/. Neutron energies were measured by the time-of-flight (TOF) technique with two 0.52 m^2 mean-timed NE-102 neutron detectors /4/ placed in a square array at 18 m. An overall neutron separation energy resolution < 1 MeV was achieved for the heavier targets. The separation energy, E_s , is defined as

$$E_s = E_0 - E_p - E_n - P_R^2/2M_R$$

where E_0 is the beam energy, E_p and E_n are the detected proton and neutron energies, respectively, and $(P_R^2/2M_R)$ is the energy of the residual nucleus which was calculated for each event from E_0 , E_p , E_n , and the reaction geometry.

Four factors were important in achieving good separation energy resolution in this experiment:

- 1) the excellent time structure of the IUCF beams (typically < 500 ps burst width),

- 2) the development of high-purity Ge detectors /3/,
 3) the development of fast large-volume neutron detectors /4/,
 and 4) the availability of long flight paths at the IUCF.

III - THEORY

The detector angles ($\theta_n \sim \theta_p = 36^\circ$) were chosen because the j -dependence of the analyzing powers was expected to be strong /5/ for this reaction geometry. [Note that this geometry is optimally momentum-matched for $E_s \sim 30$ MeV at $E_0 = 150$ MeV.] We found, however, that analyzing-power data were of little use in assigning quantum numbers to deep-hole states. We, therefore, used the more traditional approach of comparing the shapes of triple differential cross sections ($d^3\sigma/d\Omega_p d\Omega_n dE_p$) with distorted wave impulse approximation (DWIA) predictions. DWIA calculations were performed with the code THREEDEE /6/, using global optical potentials from Schwandt et al. /7/, Woods-Saxon wavefunctions /8,9/, and on-shell final-energy p - n cross sections.

IV - RESULTS

In Fig. 1 we present separation energy spectra for ^2H , ^9Be , and ^{16}O . The ^2H data, obtained with a CD_2 target, were taken primarily for "tuning up" the experimental apparatus and for checking absolute cross sections. The ^{16}O data were obtained by subtracting data for a pure Be target from the data for a BeO target. The ^9Be and ^{16}O spectra are divided into four and three regions, respectively; these are

Figure 1

labelled with what we believe to be the appropriate neutron hole states. With the exception of the two peaks at $E_S < 10$ MeV for ^9Be , the ^9Be and ^{16}O separation energy spectra are remarkably similar to those reported by Mougey /10/ for ^9Be and ^{16}O (e,e'p) at 500 MeV. Note that the separation energy spectra for ^9Be and ^{16}O in Fig. 1 are enhanced around 30 MeV because the reactions are optimally momentum-matched (i.e., P_R can be zero) only for $E_S = 30$ MeV.

In Figs. 2 and 3 we present experimental and DWIA cross sections for the regions of separation energy indicated by the dashed lines in Fig. 1. Spectroscopic factors for the DWIA curves are indicated on the figures. For ^9Be the spectroscopic factors for the ground and 2.9 MeV states add up to 1 and account fully for the odd neutron in the $1p_{3/2}$ shell. The peak for 17.8 MeV excitation in ^8Be accounts for the other two $p_{3/2}$ neutrons, and the excitation energy band centered around 32 MeV accounts for the full $1s_{1/2}$ spectroscopic strength. Spectroscopic factors for $^{16}\text{O}(p,pn)$ in Fig. 3 are in good agreement with full shell-model strengths.

In Fig. 4, we present analyzing-power data (A_y) for the $p_{1/2}$, $p_{3/2}$, and $1s_{1/2}$ hole states in ^{15}O , along with DWIA predictions. Although the data for the $p_{3/2}$ - $p_{1/2}$ spin orbit partners are reasonably out of phase as expected /5/, the agreement with the DWIA predictions is rather poor. We conclude that A_y data cannot help significantly in determining the quantum numbers of hole states, when the DWIA cannot be used for guidance.

In Fig. 5, we present separation energy spectra for ^{28}Si , ^{58}Ni , and ^{90}Zr . When plotted in finer bins, the lowest separation energy peaks in the Ni and Zr spectra can be resolved into several valence hole states. The spectra were divided into regions (indicated by the dashed lines) which we compared with DWIA calculations. Selected examples are presented in Figs. 6, 7, and 8. For Si and Ni, the spectroscopic factors for valence states are generally in good agreement with results from transfer reactions. The $1s$ and $1p$ spectroscopic factors are unphysically large.

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Data from these regions of separation energy may contain substantial amounts of four-body breakup [11/.

In Fig. 9, we present our results for the separation energies regions where we find strength for neutron deep-hole states. The results for ^{58}Ni and ^{90}Zr must obviously be considered tentative. For the three heaviest targets we do not distinguish between the $1p_{1/2}$ and $1p_{3/2}$ regions, because there is little to distinguish these hole states from each other in our data, without useful j-signatures in the A_y data. The separation of the $1p_{1/2}$ and $1p_{3/2}$ hole states in Figs. 5 through 8 is obviously rather subjective. The solid lines in Fig. 9 (which are meant to guide the eye) indicate the average trends of deep-hole states with neutron number N for different shells. The dashed line in Fig. 9, taken from the work of Jacob and Maris [12/], is the average trend of $1s_{1/2}$ proton-hole states as seen in (p,2p) and (e,e'p) experiments. The energies for proton and neutron $1s_{1/2}$ hole states are seen to be very similar.

Figure 9

REFERENCES

1. WATSON J.W., et al., Phys. Rev. C26 (1982) 961.
2. AHMAD M., Ph.D. dissertation, Kent State University (1982).
3. FRIESEL D.L., FLANDERS B.S., and PEHL R., Nucl. Instr. & Meth. 207 (1983) 403.
4. MADEY R., WATSON J.W., et al., Nucl. Instr. & Meth., in press.
5. JACOBS G., et al., Nucl. Phys. A257 (1976) 517.
6. CHANT N.S., and ROOS P.G., Phys. Rev. C27 (1983) 1060.
7. SCHWANDT P., et al., Phys. Rev. C26 (1982) 55.
8. ELTON L.R.B., and SWIFT A., Nucl. Phys. A94 (1967) 52.
9. MOUGEY J., et al., Nucl. Phys. A262 (1976) 461.
10. MOUGEY J., Nucl. Phys. A335 (1980) 35.
11. CIANGARU G., et al., Phys. Rev. C27 (1983) 1360.
12. JACOB G., and MARIS, TH.A.J., Rev. Mod. Phys. 45 (1973) 6.