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A Study of Proton Hole States in ^{16}O Nuclei

By the (p,2p) Reaction at 4.6 MeV

by

Fred Bertrand, Robert Eisberg,
David Ingham, Motoji Makino and
Charles Waddell

March, 1970

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A Study of Proton Hole States in $1f_{7/2}$ Nuclei

By the (p,2p) Reaction at 46 MeV

by

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ABSTRACT

Proton hole states in the $1f_{7/2}$ nuclei ^{46}Ti , ^{54}Fe , ^{56}Fe , ^{58}Ni , and ^{60}Ni have been studied using the (p,2p) reaction with 46 MeV protons. The measured binding energies and angular correlations are consistent with the binding energies and orbital angular momentum assignments ($1f_{7/2}$, $2s_{1/2}$, and $1d_{3/2}$) obtained from proton pick-up reactions.

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INTRODUCTION

The characteristics of neutron particle and hole states of nuclei have been well determined by studies of neutron stripping and pick-up reactions, but the equivalent information about proton particle and hole states is much less abundant. Proton hole states have been studied by means of the $(p,2p)$ and (e,ep) knock-out reactions and the (n,d) , $(d,^3\text{He})$, and $(t,^4\text{He})$ pick-up reactions. The (n,d) reaction suffers from low beam intensities and relatively poor energy resolution. The $(d,^3\text{He})$ reaction has received a great deal of attention in recent years, and the study of the $(t,^4\text{He})$ reaction is, of course, limited to the few laboratories capable of producing a triton-beam. Most of the early work on proton hole states utilized the $(p,2p)$ reactions with incident proton energies of ~ 100 to 500 MeV.

The $(p,2p)$ reaction is useful in the study of nuclear structure since it selectively excites "single-particle" or hole states. This occurs because in the energy range of interest the incoming proton can, due to its small de Broglie wavelength, be regarded as interacting with individual nucleons in the nucleus. The binding energies of the protons in the various shells is obtained from the difference between the incident proton energy and the sum of the energies of the outgoing protons. Further, in the absence of multiple collisions, the angular distributions of the knocked-out protons makes it possible to distinguish the transitions involving

protons having zero and non-zero orbital angular momentum. At lower energies, ~ 30 - 100 MeV, the basic simplicity of the reaction remains, but the analyses of the angular and energy distributions becomes more complicated because of distortion effects.

Studies of the $(d, {}^3\text{He})$ and $(t, {}^4\text{He})$ proton pick-up reactions have shown these reactions to be very useful for investigating the ground-state wave functions of the target nucleus as well as for determining the binding energy of the "picked-up" proton. The orbital angular momentum of the captured proton and spectroscopic factors can be extracted from distorted wave analysis of the measured angular distributions.

The $(p, 2p)$ measurements have mostly been made with incident energies of ~ 100 - 500 MeV, and consequently the attainable energy resolution is quite inferior to those obtained in the pick-up reactions. In addition, the experimental difficulties associated with the $(p, 2p)$ reactions have necessarily made the angular correlation measurements crude in comparison to the angular distributions obtained in the pick-up reactions. In many cases, assignments were made when no experimental angular correlations were available. For the lighter nuclei where the level spacing is comparable to the attainable energy resolution, the agreement between the assignments has been excellent; but for the heavier elements where the energy resolution was not sufficient to separate the hole-states later observed with the pick-up reactions, there have been areas of apparent disagreement.

In this paper we present the results of the study of five $1f_{7/2}$ nuclei (^{46}Ti , ^{54}Fe , ^{56}Fe , ^{58}Ni , and ^{60}Ni) and compare the results to those previously obtained in the (p,2p) and pick-up reactions.

EXPERIMENTAL SYSTEM

The apparatus used in this experiment was identical in most parts to that described by the authors in a previous paper¹). The reader is referred to this paper for many procedures which were also used in this experiment; in particular, the use of a time-to-pulse height converter for tagging real and accidental coincidences. There are, however, some significant differences brought on by the nature of the present work.

Figure 1 shows a block diagram of the detection and analyzing system. The detector telescopes used on the left and right arms were identical and consisted of a 300 micron silicon surface-barrier ΔE -detector, a lithium-drifted silicon E-detector sufficiently thick to stop the highest energy (p,2p) events, and a veto detector used to eliminate those events in which a particle penetrated the E-detectors, principally elastic scattering.

In the present work, the ΔE -detectors provided both a timing signal for the determination of real or accidental events as previously described in the above reference, and a means of particle identification. Particle identification was necessary since states of higher excitation in the summed (p,2p) proton spectrum than the ground state had to be separated from events such as (p,pd).

As can be seen in Fig. 1, an event was accepted for analysis only when the three coincidences $(\Delta E, E, \bar{V})_{\text{right}}$,

$(\Delta E, E, \bar{V})_{\text{left}}$, and $(\Delta E_L, \Delta E_R)_{\text{fast}}$ were produced simultaneously, and, upon satisfying this condition, signals from each of the 4 detectors were gated into 1024 channel ADC's and the "4-word" event was written on magnetic tape.

The data was analyzed on the UCLA IBM-360/Model 91 computer. For each event, the particle type in each arm was determined by the ΔE method and only the (p,2p) events were retained for analysis. Accidental events, which had been tagged in the computer, were subtracted from the data, leaving a spectrum of real events only.

The 46-MeV proton beam of the Southwest Regional Consortium Cyclotron was used to bombard enriched targets with thicknesses of a few mg/cm^2 . The incident protons, after passing through the target, were collected in a Faraday Cup which, with associated integrator, provided a measurement of the number of incident protons. The energy calibration of the system was provided by two methods: (1) utilization of a precision pulser which had previously been calibrated with known energy sources. And (2) utilization of the known Q-value of the $^{12}\text{C}(\text{p},2\text{p})$ ground state in conjunction with the zero Q-value (p,p) scattering. The uncertainty in the energy measurements given in this paper are ± 0.16 MeV (for ^{46}Ti , ± 0.20 MeV). Since no absolute cross sections are given (typical cross sections for the peaks shown were in the range of $1\text{--}10 \mu\text{b}/\text{sr}^2\text{--MeV}$), the errors shown are statistical only.

RESULTS and DISCUSSION

The (p,2p) spectra were obtained from five $1f_{7/2}$ shell nuclei, ^{46}Ti , ^{54}Fe , ^{56}Fe , ^{58}Ni , and ^{60}Ni . Figure 2 shows the summed proton binding energy spectra for the five targets where the intensity of the peaks are shown in counts and no effort has been made to normalize the data. Data were obtained for equal coplanar angles for the emergent protons (30° - 30° , etc.) and the spectra shown in Fig. 2 consist of the sum of data from several angle pairs ranging from 25° - 25° to 50° - 50° . The similarity between the spectra, all from even-even nuclei, is striking. Two distinct peaks were found for each target at each angle of observation.

In table I are presented the excitation energies of the states observed in this experiment along with the energies obtained in previous (p,2p) work and in the (d, ^3He) and (t, ^4He) pick-up reactions. The Q-value for the first allowed transition ($1f_{7/2}$), which, in each case, agrees within 0.10 MeV with the Q-value calculated from the mass differences, is not included in the table. The states listed in the Table from the pick-up work were selected by choosing the levels with the largest spectroscopic factor (as given in the respective references) for each state. The table lists the ℓ and j values assigned in the references.

As is seen in the table, the binding energy of the second peak in the present experiment agrees with the approximate centroid of the excitation energies of the $2s_{1/2}$ and

$1d_{3/2}$ states observed in the pick-up studies. The resolution of the present experiment, although considerably better than earlier (p,2p) work, is not sufficient to separate the $2s_{1/2}$ and $1d_{3/2}$ states that are clearly resolved in the pick-up experiments. However, the energy resolution of the present experiment is unlike the previous ones, completely adequate to separate the $1f_{7/2}$ excitation from the others, and it was therefore possible to obtain a clean angular correlation for the peaks observed in the present experiment. Figure 3 shows the angular correlation for the two peaks for the ^{56}Fe data. Although classification of target proton hole states with angular momentum greater than zero is ambiguous based on the (p,2p) angular correlations, it is possible to differentiate $\ell = 0$ and $\ell > 0$ states since the $\ell = 0$ correlations have a single maximum at an angle less than 45° ; whereas for $\ell > 0$ there is a minimum in the same angular range. The experimental angular correlation for the ground state, fig. 3, exhibits the minimum characteristic of states with $\ell > 0$, whereas the angular correlation for the second peak is not characteristic of an $\ell = 0$ state alone and we, therefore, surmise that the second peak observed in our data contains a mixture of $\ell = 0$ and $\ell > 0$, namely a mixture of the $2s_{1/2}$ and $1d_{3/2}$ states, in agreement with the results of the pick-up experiments. Earlier (p,2p) work at 156 MeV had classified the second peak as a $2s_{1/2}$ excitation alone.

In summary we find that there exists no discrepancy between the binding energies and orbital angular momenta assignments of the $2s_{1/2}$ and $1d_{3/2}$ proton hole states

obtained from the pick-up experiments and those obtained from this (p,2p) experiment. The measured Q-values for the $1f_{7/2}$ hole states are in agreement with the Q-values for the ground states of the final nuclei determined from the mass differences.

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TABLE I

Target	Present Exp. (p,2p)	Orsay ²⁾ (p,2p)	Karlsruhe ³⁾ (d, ³ He)	Oak Ridge ⁴⁾ (d, ³ He)	Argonne ⁵⁾ (d, ³ He)	Los Alamos ⁶⁾ (t, ⁴ He)
⁴⁶ Ti	0.96±0.20				0.93±0.05 2s _{1/2}	
⁵⁴ Fe	2.88±0.16		2.71 2s _{1/2} 3.01 1d _{3/2}	2.70 2s _{1/2} 3.01 1d _{3/2}		
⁵⁶ Fe	2.56±0.16	2.6±0.3 2s _{1/2}				
⁵⁸ Ni	3.07±0.16	2.6±0.3 2s _{1/2}	3.01 2s _{1/2} 3.59 1d _{3/2}			2.97 2s _{1/2} 3.54 1d _{3/2}
⁶⁰ Ni	2.80±0.16		2.72 2s _{1/2} 3.16 1d _{3/2}			2.72 2s _{1/2} 3.17 1d _{3/2}

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FIGURE CAPTIONS

Fig. 1. Block diagram of detection and analyzing system.

Fig. 2. Summed proton energy spectra -- the abscissa show the difference between the incident energy and the sum of the energies of the two emitted protons.

Fig. 3. Angular correlations for the two peaks observed in the summed energy spectrum from ^{56}Fe .

Fig. 1

Fig. 2

Fig. 3