Excitation of $(p_{3/2})^{-1}$ and $(p_{1/2})^{-1}$ hole states in the $^{16}O(\pi^+,p)^{15}O$ reaction at 66 MeV

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Angular distributions have been measured at 66 MeV for the $^{16}O(\pi^+,p)^{15}O$ reaction leading to the $(p_{3/2})^{-1}$ hole state at 6.18 MeV and the $(p_{1/2})^{-1}$ hole ground state of ^{15}O. The ratio of the two differential cross sections lies between 6 and 13 over the whole measured angular range. A comparison is made with preliminary calculations of Miller. At 45° and 105° a measurement has also been performed on the reaction $^{16}O(\pi^-,p)^{15}C$ at the same incident energy.

[NUCLEAR REACTIONS $^{16}O(\pi^+,p)$, $E_\pi = 66$ MeV, measured $\sigma(\theta)$; comparison with DWBA calculations; reaction mechanism discussed.]

In the simplest plane-wave description, the (π^+,p) reaction can be considered as a neutron pickup reaction, just as the inverse (p,π^+) reaction can be considered as a stripping reaction.[1] We have studied the $^{16}O(\pi^+,p)^{15}O$ reaction, where the two main hole states $(p_{3/2})^{-1}$ and $(p_{1/2})^{-1}$ in the final nucleus are well known and well separated in energy. In fact, in the classical (p,d) and (τ,α) pickup reactions on ^{16}O at intermediate energies,[2] one has observed, for momentum transfers ranging from 1.0 to 2.3 fm^{-1}, that the ratio of excitation of the two states $(p_{3/2})^{-1}/(p_{1/2})^{-1}$ is close to 2, corresponding to the ratio of occupation numbers in the two subshells of a closed shell ^{16}O.

The experiment was performed with a pion beam of the Saclay Linear electron accelerator.[3] The maximum π^+ intensity was about 3×10^5 s^{-1} at a mean energy in the target of 66 MeV, for a total momentum interval of 1.5%, corresponding to a 2% duty cycle, and for a 14 mA peak current electron beam. The measurements have been performed with a range telescope which included 13 scintillators and a carbon absorber of variable thickness (see Fig. 1). Each scintillator was 3 mm thick. Such a setup allowed us to cover, in each measurement, an interval of 16 MeV in the excitation energy of the residual nucleus. The total energy resolution achieved was about 3.2 MeV, with a ^{16}O target consisting of a 14 mm thick cell filled with water. The target angle was set so as to match the pion and proton energy losses. The energy resolution was then determined taking into account the incident beam momentum width, and the energy loss straggling in the absorbers; such a determination was checked experimentally on a pion range spectrum. The 11 signals from the scintillators following the carbon absorber were sent to a pattern unit triggered by a coincidence between the first three scintillators. Lead shielding was used in order to minimize, especially at small angles, the counting rate of the first three scintillators due to the decay muons of the primary pions. The pions scattered by the target did not reach the third scintillator. In order to suppress a possible continuous spectrum of contaminating long range muons arising from scattered pions decaying in flight, we carefully adjusted the $\Delta E/\Delta x$ discrimination on the first three scintillators. The efficiency of this method was first estimated and then checked experimentally with pions scattered by hydrogen. The words of 11 bits formed by the pattern unit were recorded through a multichannel analyzer.

The incident pion beam intensity was measured with a three-scintillator monitor telescope at 90° to the beam. It was calibrated at low intensity with in-beam detectors, for a given set of target angles. The electron contamination of the beam[3] was eliminated by anticoincidence with a gas Čerenkov counter. The energy calibration of the range telescope was checked with the incident pion beam and with the ground-state protons of the $^{12}C(\pi^+,p)^{11}C$ reaction at 67 MeV.[4] The energy calibration for ^{15}O is thus known to better than ±0.3 MeV.

In order to cover the first 15 MeV of excitation energy in ^{15}O we measured systematically at each angle two neighboring overlapping range spectra. Energy spectra, obtained from the range spectra, are shown in Fig. 2. The shape of the three-body (π^+,pp) contribution is also indicated; it has been obtained by the convolution of the corresponding three-body phase space spectrum with the energy resolution. The cross section extracted for the 6.18 MeV state appears not to depend strongly on the normalization of the three-body spectrum. The threshold of the (π^+,pp) reaction is at 7.29 MeV, whereas the threshold of the (π^+,pn) reaction ap-

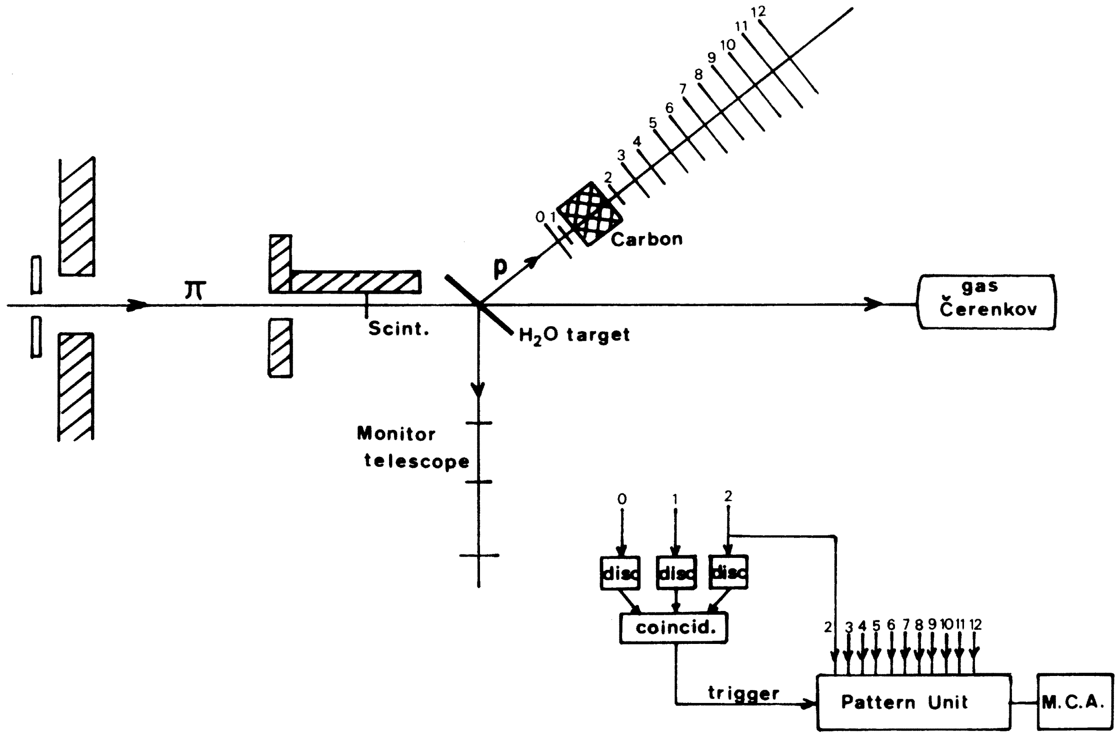

FIG. 1. Experimental setup and electronics block diagram.

pears much higher, at 13.22 MeV. The angular distributions obtained for the two hole states, $(p_{3/2})^{-1}$ at 6.18 MeV and $(p_{1/2})^{-1}$ ground state, are given in Fig. 3. The error bars shown take into account the statistical uncertainties as well as the uncertainties due to the subtraction of the three-body continuum. One cannot exclude small contributions from the positive parity states in ^{15}O, but these would not significantly alter the results. Both angular distributions exhibit a minimum between 70° and 80° followed by a rise at backward angles. The most striking fact is their ratio which oscillates between 6 and 13. This can also explain the low cross section observed by Amato *et al.*[5] which probably did not completely include the 6.18 MeV state. Our $(p_{3/2})^{-1}$ cross section is consistent with measurements for the $(p_{3/2})^{-1}$ ground state of ^{11}C.[5] At some angles we have indications for an excitation of higher states in ^{15}O in the region of the first $T=\frac{3}{2}$ state, but better energy resolution would be needed in order to identify these correctly.

The large ratio between the two angular distributions could be explained in two ways: (a) By a different behavior of $p_{3/2}$ and $p_{1/2}$ neutron wave functions at large momenta; in our experiment the momentum transfer varies between 2.4 and 3.5 fm^{-1}. In classical intermediate energy pickup reactions the angular distributions which fall very rapidly with the angle appear thus to be dominated at large angles (corresponding to the largest momentum transfer) by their small angle behavior, because of distortions (rescattering). A possible difference between $p_{3/2}$ and $p_{1/2}$ wave functions above 2 fm^{-1} would thus not have been observed in the pickup experiments performed until now. (b) By some specific characteristics of the (π^+,p) reaction mechanism. The picture of a single neutron pickup is too simple, and other nucleons of the nucleus appear to be involved in the reaction. Such effects can be taken into account by distortion calculations. The rescattering of the pions in the nucleus—with or without an intermediate resonant Δ state—is especially important.[6,7] It might introduce a difference between $p_{3/2}$ and $p_{1/2}$ neutron transfer.

On Fig. 3 is shown a distorted wave Born approximation calculation by Miller. It has been performed with the standard proton optical parameters and bound neutron wave functions.[6] The pion optical potential used in this first calculation is given by $2E_\pi V^{\rm opt}(\hbar c)^{-2}=(-3.7+1.7i)p^2\rho(r)$. The fit is not yet very good, but seems able to explain the high ratio at larger angles; the introduction of a term in $\overleftrightarrow{\nabla}\cdot\rho(r)\overleftrightarrow{\nabla}$ in the pion optical potential would account for the rise at backward angles.

Two energy spectra have been obtained at 45° and 105° for the reaction $^{16}O(\pi^-,p)^{15}C$ at the same π^-

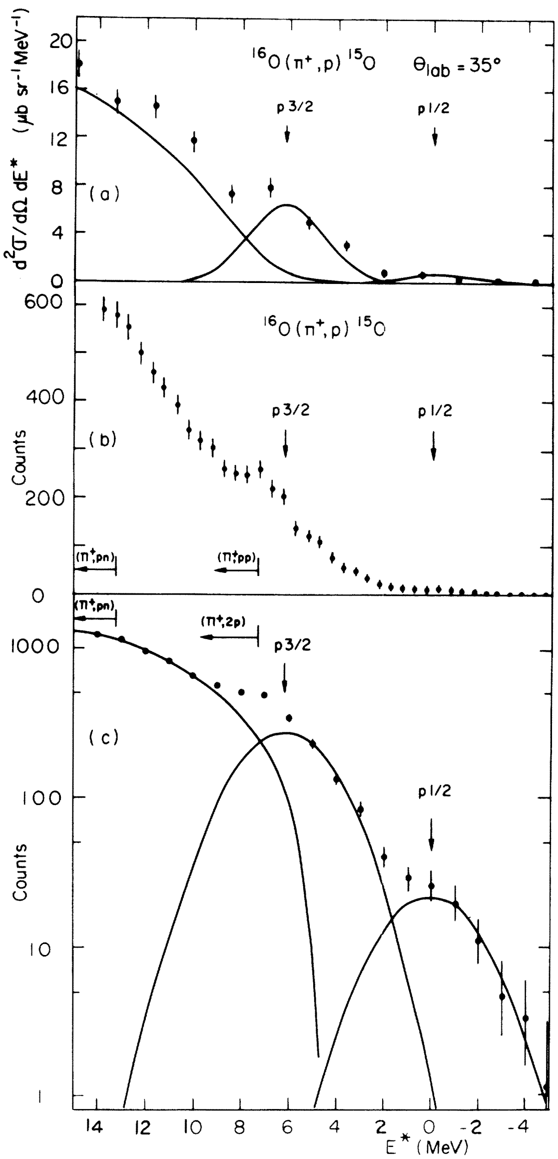

FIG. 2. (a) Typical experimental excitation energy spectrum of ^{15}O. The solid lines indicate the contributions of the two hole states and of the (π^+,pp) continuum. The threshold of the (π^+,pn) continuum is at 13.2 MeV. (b) Summed excitation energy spectrum of ^{15}O. (c) Same as (b) on a semilog scale. The $p_{1/2}$ and $p_{3/2}$ contributions are indicated.

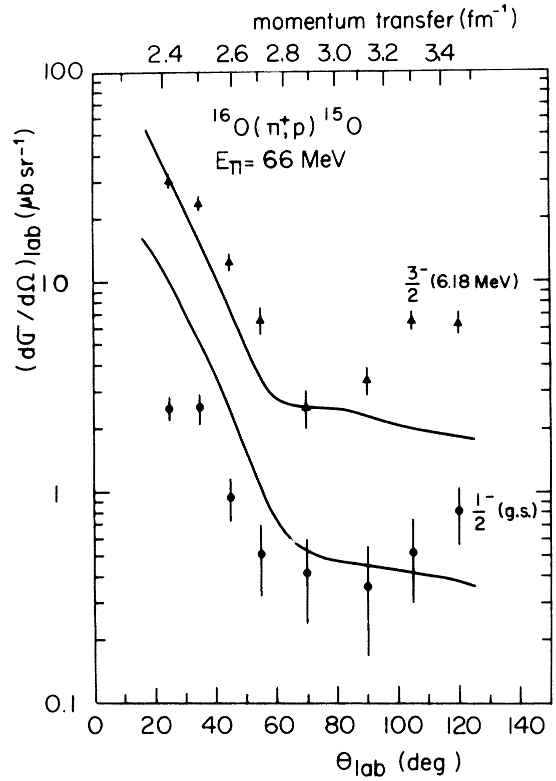

FIG. 3. Angular distributions of the two hole states of ^{15}O. The solid lines show a preliminary calculation by G. A. Miller (see text).

mean energy of 66 MeV. The values obtained for the differential cross sections corresponding to the ^{15}C ground state and first excited state region are much smaller than those of the (π^+, p) cross sections: $0.5 \pm 0.2\, \mu b\, sr^{-1}$ at 45°, and $\leq 0.2\, \mu b\, sr^{-1}$ at 105°.

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