Experimental Study of the Mechanism of (p,t) Reactions at 22 Mev

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Energy distributions of tritons from various elements throughout the periodic table show prominent peaks which can be identified with states in the residual nucleus which result from the removal of two neutrons from single-particle states in the target. This is indicative of a double pickup mechanism for the (p,t) reaction at this energy. The use of this reaction in identifying the position and character of single-particle levels is illustrated. The reaction is also used to determine the mass of Ru^{101}.

INTRODUCTION

A SURVEY of (p,d) reactions at 22 Mev[1] indicated that the most prominent features of the energy and angular distributions of the deuterons could be accounted for by assuming that the reaction proceeds by the pickup of a neutron out of a single-particle bound state. In particular, it was possible to identify the strongly excited residual states with those resulting from the removal of a neutron from a single-particle level in the target.

The present work was undertaken as an extension of the (p,d) work with the hope that the energy distributions of the tritons could be used to identify the nature of the residual states which are excited, and thus to determine the extent to which single-particle structure in the nucleus influences the (p,t) reaction and the extent to which the reaction proceeds as a direct interaction.

Previous work at 22 Mev by Cohen and Handley[2] showed the qualitative result that the triton spectra tend to be peaked toward the high-energy end of the spectrum. While this is indicative of a direct interaction mechanism, the resolution was too poor to resolve any structure in the spectra.

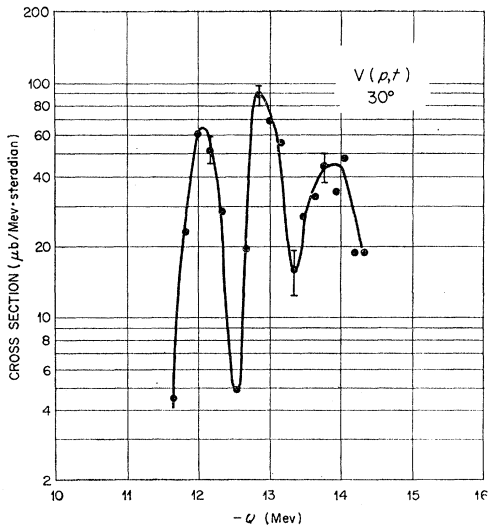

FIG. 1. Triton spectrum from vanadium at 30 degrees.

The present work was performed with an experimental setup having sufficient resolution to permit examination of gross structure effects on the spectra and to allow comparison of the observed levels with anticipated shell-model states.

EXPERIMENTAL METHOD

The experimental apparatus and method were the same as those used in reference 1 except that in the most recent runs, an RIDL Model 34-9 400-channel analyzer was used in place of the 20-channel analyzer. This analyzer, with some auxiliary equipment, is incorporated in a system which permits recording of proton, deuteron, triton, and alpha spectra simultaneously. The system will be the subject of a separate paper.

The 400-channel analyzer has an average dead time of 70 μsec as compared with 2.4 μsec for the 20-channel analyzer. It has been found that the external beam of the cyclotron comes in bursts which are about 70-μsec duration; the duty cycle is less than one tenth of what would be expected from rf beam bunching only. It is not practical to reduce the beam current enough to eliminate the possibility that two particles will be counted in the same burst. The second pulse will, however, usually fall within the dead time following the first pulse and will be lost. Thus, even though the dead-time indicator on the analyzer may read essentially zero, an appreciable fraction of the counts may be lost. Measurements of cross sections and angular distributions must be corrected for this effect.

We have chosen to obtain the correction by using an additional fast single-channel analyzer.[3] This is set to record some convenient portion of the scintillation counter spectrum (usually the elastically scattered protons). The output of the single-channel analyzer drives one scaler directly and another scaler through a gate which is open only during the dead time of the 400-channel analyzer. Thus, the two scalers indicate total and lost counts, respectively, from which the fractional loss of analyzed counts can be inferred.

* Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

[1] C. D. Goodman and J. B. Ball, Phys. Rev. **118**, 1062 (1960).

[2] B. L. Cohen and T. H. Handley, Phys. Rev. **93**, 514 (1954).

[3] E. Fairstein, Rev. Sci. Instr. **27**, 549 (1956).

In the Co(p,t) angular distribution, the correction was between two and five percent for the points shown. In making this correction, it is assumed that there is no time correlation between the tritons and the elastically scattered protons.

The vanadium, cobalt, niobium, rhodium, and gold targets were selected for their isotopic purity and availability in thin rolled foils. The separated zirconium isotope targets were prepared from suspensions of the powdered oxide, as described in reference 1.

RESULTS AND DISCUSSION

The energy spectra of tritons from V, Co, Nb, Rh, and Au are shown in Figs. 1–5. As in the deuteron spectra of reference 1, these triton spectra exhibit a marked structure suggestive of a strong single-particle type interaction. The general features of the spectra

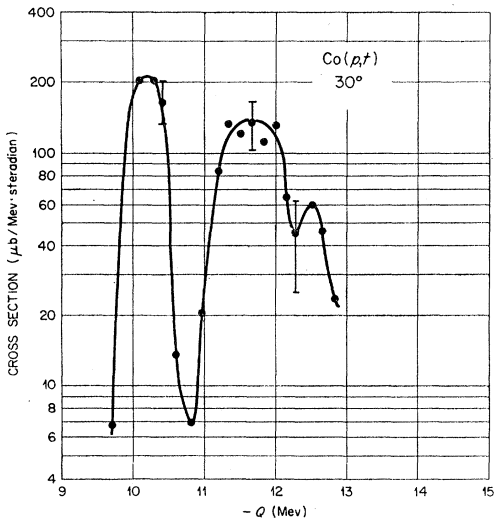

FIG. 2. Triton spectrum from cobalt at 30 degrees.

suggest that the incoming proton interacts with two neutrons in single-particle bound states to form the triton, and that there is little mixing of energy with other states.

To illustrate this interpretation, Fig. 6 shows the energy spectra of tritons from Zr^{90}, Zr^{91}, Zr^{92}, and Nb^{93}. These isotopes span the region of the closed neutron shell at $N=50$ and provide a large energy gap between successive single-particle levels. Because of the poor character of the oxide targets, the curves are not plotted on an absolute cross-section scale but arbitrarily displaced for convenience. Uncertain target thickness makes the energy scale somewhat approximate.

Zr^{90} has fifty neutrons, and the $1g_{9/2}$ level is filled. The observed triton peak has the correct energy to correspond to leaving Zr^{88} in its ground state. This would mean that the incoming proton picks up two of the $g_{9/2}$ neutrons.

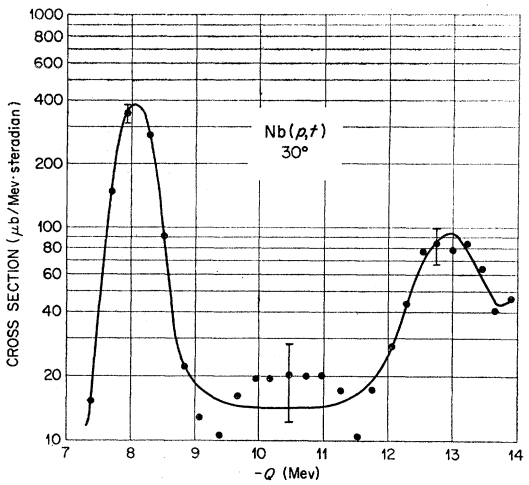

FIG. 3. Triton spectrum from niobium at 30 degrees.

Zr^{91} has the same closed neutron shell configuration as Zr^{90} with the addition of one $2d_{5/2}$ neutron. A (p,t) reaction to the ground state of Zr^{89} would require the pickup of one $d_{5/2}$ neutron and one $g_{9/2}$ neutron. This is observed in the triton spectra at $Q\sim-11.4$. A stronger peak appears at $Q\sim-12.8$, which corresponds in energy to the pickup of two $g_{9/2}$ neutrons as inferred from the Zr^{90} case. This suggests that the pickup of two neutrons from the same shell is more probable than the pickup of two neutrons from different shells. In Fig. 6 the mixed pickup is about three-eigths as strong as the pure $g_{9/2}$ pickup. However, this may overemphasize the mixed pickup by a large factor. The pickup of two $g_{9/2}$ neutrons involves zero angular momentum change and the angular distribution would be sharply peaked at zero degrees. The mixed pickup probably involves an average over several values of angular momentum exchange which could range from two to seven units and the

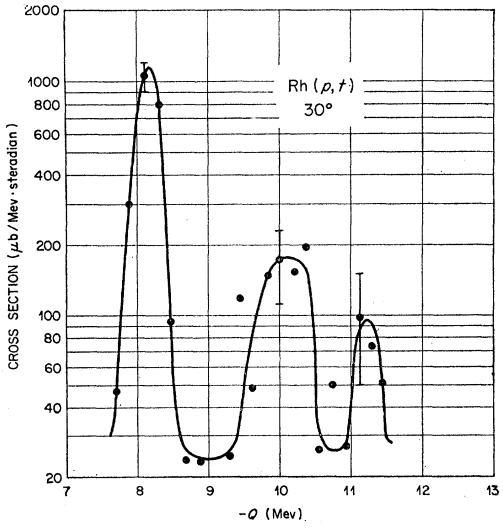

FIG. 4. Triton spectrum from rhodium at 30 degrees.

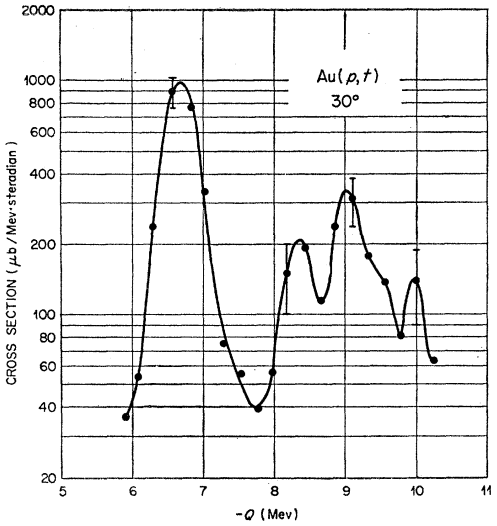

FIG. 5. Triton spectrum from gold at 30 degrees.

angular distribution would be more nearly isotropic or peaked at a large angle.

Zr^{92} and Nb^{93} have a pair of $d_{5/2}$ neutrons beyond the filled $g_{9/2}$ level, and the pickup of this pair accounts for the strong peak at $Q\sim-8$ Mev. No peak appears for Q between -10 and -11 Mev corresponding to the mixed pickup of the Zr^{91} case. This is consistent with our interpretation of the mechanism, since the peak should be shifted by an amount equal to the $d_{5/2}$ pairing energy (about 1.6 Mev),[1] and this would make it unresolved from the peak at $Q\sim-12.8$ Mev.

A further test of the mechanism is to examine the angular distribution of the tritons from a particular state. In general, the ground-state transition is the most favored, but even here the intensity is quite small. Hence, counting rates are quite low, and an angular distribution is very time-consuming to obtain. Table I gives cross-section values for the ground-state transition at 30 deg for the elements studied in this work. Even though the cross sections may be quite angular dependent, there is a very noticeable increase in cross section with increasing mass of the target.

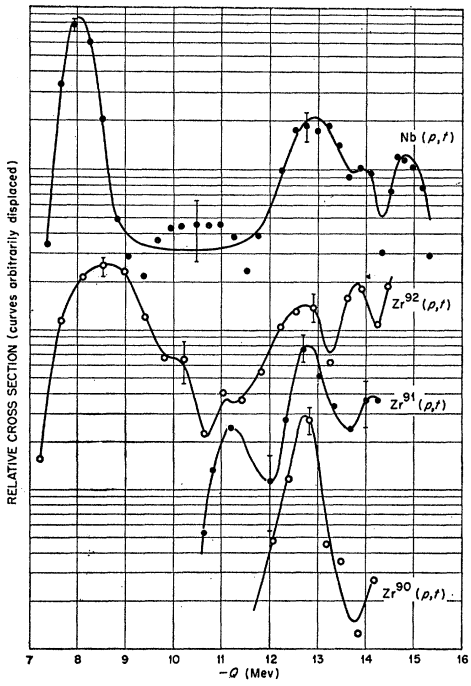

FIG. 6. Triton spectra from niobium and separated zirconium isotopes at 30 degrees. The broadening in the Zr^{92} spectrum is attributed to the poor character of the target.

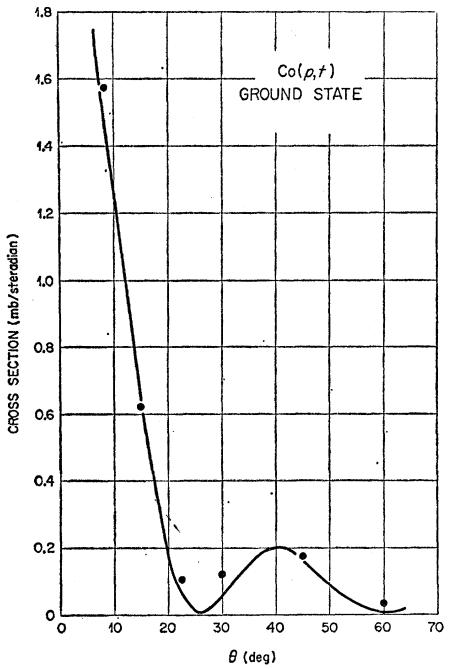

FIG. 7. Angular distribution of the (p,t) ground-state transition on cobalt. The solid line is the function $C[j_0(KR)]^2$ for $R=5.5\times10^{-13}$ cm.

The angular distribution of the tritons from the ground-state transition in Co was examined and is shown in Fig. 7. The target neutron configuration is presumably $(f_{7/2})^8(p_{3/2})^4$. The ground-state peak in the energy spectra is assumed to be due to the pickup of a $p_{3/2}$ neutron pair. Since these two neutrons are paired in the target nucleus, their removal causes no change

TABLE I. Cross sections for ground-state transitions at 30 degrees.

Element	A	Cross section (μb/sr)
V	51	30
Co	59	120
Nb	92	315
Rh	103	445
Au	197	565

TABLE II. Summary of binding energy and pairing energy.

A	Shell	Binding energy (Mev)	Pairing energy (Mev)	$(23/A)\times(2j+1)$[a]
59	$p_{3/2}$	8.5	1.4	1.6
59	$f_{5/2}$	10.0	2.4	2.4
92	$d_{5/2}$	7.5	1.6	1.5
92	$g_{9/2}$	9.0	3.2	2.6
103	$g_{7/2}$	7.5	1.7	1.8

[a] Form of pairing energy dependence suggested by M. G. Mayer, Phys. Rev. **78**, 16 (1950).

in angular momentum between the initial and final states and hence should exhibit an angular distribution characteristic of an $l=0$ transition. The solid curve shown in Fig. 7 is the square of the spherical Bessel function for $l=0$. The data were taken at small enough angles to distinguish between the $l=0$ and the $l=1$ case.

In the interpretation we have given to the spectra we have assumed, as is usually done in the simple version of the nuclear shell model,[4] that the energy required to remove a neutron from a nucleus may be thought of as the sum of two terms, the binding energy to the nucleus as a whole, and the pairing energy with another neutron in the same shell. When one starts with an even number of neutrons in a shell and considers that a (p,d) reaction removes one neutron and a (p,t) removes a pair, then one can write

$$Q(p,d)=2.226-B-P,$$
$$Q(p,t)=8.485-2B-P,$$

where B and P stand for binding and pairing energies, respectively. Thus, if the two Q values are known, both the binding and the pairing energies are determined.

When the residual levels concerned are the ground states for both reactions, the information can be obtained from mass data as well as from the measured Q values. This applies to the $d_{5/2}$ shell in Zr^{92} and Nb^{93} and to the $p_{3/2}$ shell in Co^{59}. For the $g_{9/2}$ shell in Zr^{92} and Nb^{93}, however, mass data cannot be used, but the measured Q values yield the information. A summary of the binding and pairing energy measurements is given in Table II.

The (p,t) reaction may also be used to determine mass values. An example of this is the ground-state transition in Rh. The reaction leads to Rh^{101} which decays to stable Ru^{101} whose mass is undetermined. From the known decay energy of Rh^{101}, the known mass of Rh^{103}, and the measured (p,t) ground-state Q of -8.2 Mev, the mass of Ru^{101} is calculated to be 100.9370 ± 0.0003.

[4] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, New York, 1955).