neutrons is the $d_{5/2}$ level. Because the neutron is in a level with intrinsic spin and orbital angular momentum parallel, and the proton is in a level with intrinsic spin and orbital angular momentum antiparallel, the total spin of the nuclear ground state according to Nordheim's "strong" rule[18] (or later modifications[19]) should be the difference of the individual angular momenta, or $I=2$. Also, since the asymptotic quantum numbers given by Gallagher and Moszkowski are $\Omega_p=\frac{1}{2}$ (parallel spin) and $\Omega_n=\frac{5}{2}$ (antiparallel spin),[20] the collective-model coupling rule predicts $I=2$.

In the jj-coupling limit, the single-particle shell model predicts a nuclear moment given by

$$\mu_s=\tfrac{1}{2}I(g_p+g_n)+(g_p-g_n)\left[\frac{j_p(j_p+1)-j_n(j_n+1)}{2(I+1)}\right]. \quad (21)$$

If the nuclear g factors for the odd proton and neutron are evaluated from the Schmidt formulas, Eq. (21) predicts $\mu_s=-1.609$ nm. This result agrees remarkably well with the experimental value. The collective model in the limit of strong coupling of the nucleon to the surface predicts a magnetic moment given by

$$\mu_c=(g_\Omega\Omega+g_R)I/(I+1). \quad (22)$$

If one estimates $g_\Omega\Omega$ from the expression given by Gallagher and Moszkowski,[20] and takes $g_R\approx Z/A$, the result is $\mu_c=-0.30$ nm. From magnetic-moment considerations, then, the independent-particle shell model appears to be a better representation than the collective model for Y^{90}.

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(p,n) Cross Sections on Ti^{47}, V^{51}, Cr^{52}, Co^{59}, and Cu^{63} from 4 to 6.5 Mev

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Absolute (p,n) cross sections have been measured for Ti^{47}, V^{51}, Cr^{52}, Co^{59}, and Cu^{63} at energies between 4 and 6.5 Mev. These data plus earlier measurements of the cross section for inelastic proton scattering have been used to estimate total proton absorption cross sections for V^{51} and Co^{59}. An optical model calculation using parameters giving a good fit to elastic scattering measurements predicts an absorption cross section in good agreement with the measurements for Co^{59}. For V^{51}, some sets of parameters gave good agreement with the measured absorption cross section, but the fit to the elastic scattering data was only fair.

I. INTRODUCTION

ANGULAR distributions of low-energy protons elastically scattered by V, Cr, Fe, and Co have been measured in this laboratory by Preskitt and Alford.[1] In analyzing these results, it was found that the angular distributions for Co could be fitted with an optical model calculation employing a Woods–Saxon potential well.[2] Good fits to the Co data were obtained for a rather wide range of values for the well depth V_0, provided that the product $V_0R_0^2$ was held constant, where R_0 is the nuclear radius. The calculated absorption cross sections depended rather sensitively on R_0, however, and the present measurements were undertaken in an effort to narrow the range of acceptable values of V_0 and R_0. In the course of the work, measurements were extended to the nuclei Ti^{47}, Cr^{52}, and Cu^{63}, and (p,n) cross sections for these nuclei are reported here also.

II. MEASUREMENTS

All measurements were carried out using the external proton beam of the University of Rochester variable-energy cyclotron. The mean energy of the beam was measured in a calibrated analyzer magnet and was known to within 1%. In most of the measurements, the energy spread in the beam was about 100 kev. The targets used are listed in Table I along with their relevant properties. Target thicknesses were determined by weighing, and are accurate to within ±3%.

Two procedures were used in carrying out the (p,n) cross-section measurements. For Ti^{47}, Cr^{52}, and Cu^{63}, the positron activity produced in a foil by the reaction was measured using a method similar to that described by Howe.[3] Foils of the element to be studied were mounted in light rigid frames, and a stack of foils placed in a holder behind a beam-defining aperture. A pair of

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[1] C. A. Preskitt, Jr., and W. P. Alford, Phys. Rev. **115**, 389 (1959).
[2] R. D. Woods and D. S. Saxon, Phys. Rev. **95**, 577 (1954).
[3] H. A. Howe, Phys. Rev. **109**, 2083 (1958).

TABLE I. Properties of targets used.

Target	Thickness (mg/cm²)	Form	Isotopic (%) abundance	(p,n) threshold (Mev) (c.m.)	Product β^+ branch ratio (%)
Ti^{47}	2.02, 2.14	*a*	7.32	3.78	97
Cr^{52}	1.00, 1.04, 0.691	*a*	83.46	5.9	98.5
Cu^{63}	4.26, 5.03	*a*	69.09	4.14	89.8
	4.43	*b*	99		
V^{51}	1.53	*a*	99.75	1.53	0
Co^{59}	2.34	*a*	100	1.86	0

[a] Self-supporting natural metal foil.
[b] Isotopically enriched target evaporated on 0.1-mil gold foil.

quadrupole magnets, normally used to focus the beam through the aperture, was defocused to irradiate an area somewhat larger than the aperture in order to provide uniform beam intensity over the irradiated area of the foil. The beam passing through the foils was integrated with a simple circuit which was regularly calibrated using a standard battery and resistance. The uncertainty in the integrated current was no greater than 3%.

After bombardment, the foil in its frame was covered on both sides by enough absorber to stop all positrons. Foil and absorbers were then mounted in a holder midway between two sodium-iodide gamma detectors, and the coincidence counting rate due to annihilation radiation was measured. The output of each detector was amplified and pulses in the annihilation photopeak were selected by single-channel anzlyzers. Coincidences between the outputs of the two analyzers were recorded with a standard slow (0.7-μsec resolving time) coincidence circuit and scaler. The advantage of this arrangement is that the counting efficiency is largely independent of the complexity of the decay scheme involved. It is necessary to know the fraction of the decays going by positron emission, and this quantity is usually not accurately measured. For allowed decays, this branching ratio is reliably calculated,[4] however, and uncertainties in this quantity should be small for the decays observed in these measurements. The actual efficiency was determined and the routine operation of the circuit checked during the measurements by using a Na^{22} source having the same dimensions as the irradiated area of the foils, and mounted in an identical frame. The strength of the Na^{22} source was determined by comparing its activity with that of a calibrated standard Na^{22} source obtained from the National Bureau of Standards.

The primary sources of error in these measurements are in the determination of target thickness (3%), the coincidence detector efficiency (3%), and the calibration of the beam integrator (3%). The over-all accuracy of the (p,n) cross sections for Ti^{47}, Cr^{52}, and Cu^{63} is about 6%.

The isotopes produced by a (p,n) reaction on V^{51} and Co^{59} decay by electron capture so that the coincidence method could not be used. Instead, the neutrons were detected directly with a shielded long counter similar to the design of Hanson and McKibben.[5] Using neutrons from the $H^2(d,n)He^3$ reaction, the efficiency of this counter had previously been measured over the range from 2 to 6 Mev.[6] Over this range, the efficiency was constant to within the accuracy of the measurements (10%), and according to published data on counters of this type, was probably constant to within a few percent. As a check in the lower energy region, the long counter was used to measure the yields of neutrons from the Cu^{63} (p,n) reaction from threshold to neutron energies of about 2 Mev. Over this range, the (p,n) cross section calculated on the assumption of constant detector efficiency agreed well with that measured by the stacked foil method, as shown in Fig. 1.

Using the long counter, the (p,n) cross sections for V^{51} and Co^{59} were measured relative to Cu^{63}. Measurements were carried out at 0°, 45°, and 135°. Cross sections at 45° and 135° were always found to be equal within the accuracy of the measurements, while the

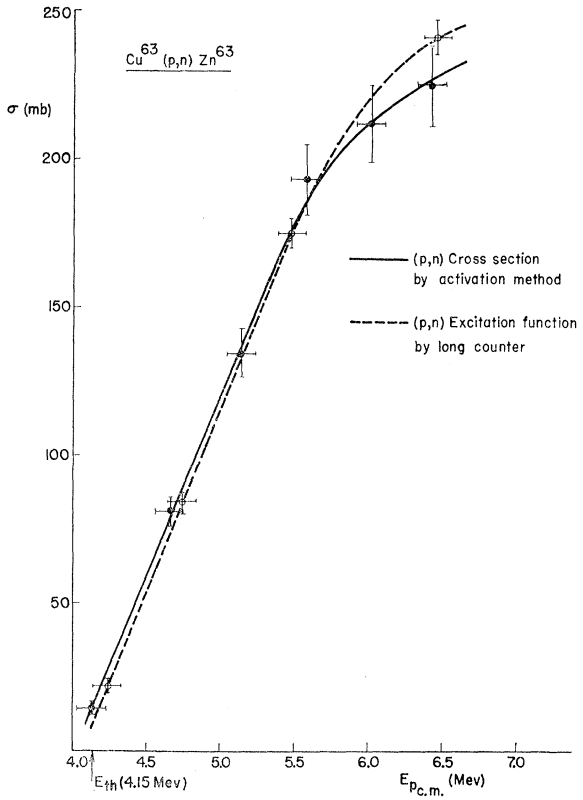

FIG. 1. Comparison of $Cu^{63}(p,n)$ cross sections as measured by coincidence method and by long counter. Bars indicate estimated error from all sources for activation measurements. For the long-counter measurements, statistical uncertainty only is shown. The curves are drawn to connect the measured points.

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[6] I. Slaus and W. P. Alford, Atomic Energy Commission Report NYO-8059, 1958 (unpublished).

cross section at 0° was usually about 20% lower. The total cross section was calculated as 4π times the average of the measured differential cross sections at 45° and 135°. The decrease in the cross section at forward angles would have little effect on the total cross section because of the solid angle factor involved.

The measured cross sections are shown in Figs. 1–3. Where comparisons are possible, these results show satisfactory agreement with other measurements.[3,7–9] The energy scale in these figures refers to the proton energy in the center-of-mass system at the center of the target. The energy spread in each measurement was about 200 kev with roughly equal contributions from target thickness and beam energy spread. With this energy spread, we expect to average over enough levels in the compound nucleus that no pronounced resonance effects will appear. The measured cross sections for V, Co, and Cu do show the expected smooth behavior. It is possible that the shape of the curve for Ti^{47} reflects some sort of resonant effect, however. At the energies used here, the (p,n) reaction on Cr^{52} was found to go mostly to the first-excited state of Mn^{52} because of the very high spin (6) of the ground state.

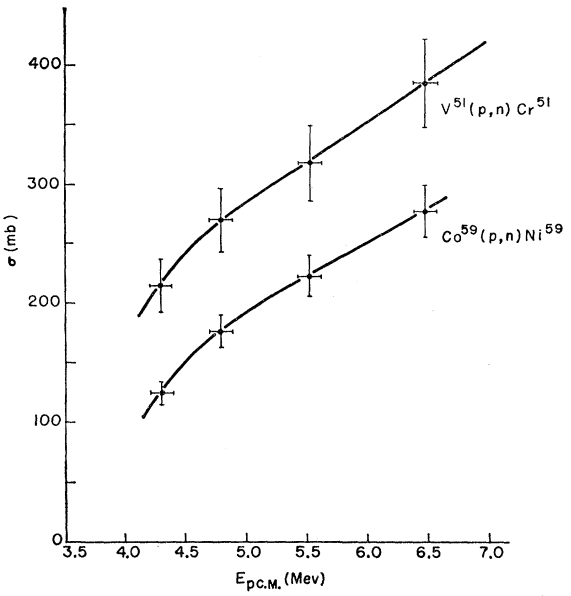

FIG. 3. The (p,n) cross sections for Co^{59} and V^{51}.

III. DISCUSSION

The fact that the measurements for Ti, Cr, and Cu extend for such a short range above the (p,n) threshold makes it unlikely that these cross sections could be fitted with any simple theory in a meaningful way. For V and Co, however, the measurements extend well beyond the (p,n) threshold, and over most of this range the (p,n) cross section is nearly an order of magnitude greater than that for any other reaction because of the smaller barrier penetrabilities for charged particle emission. Thus the measured (p,n) cross sections plus a small correction for competing reactions will equal the total absorption cross section.

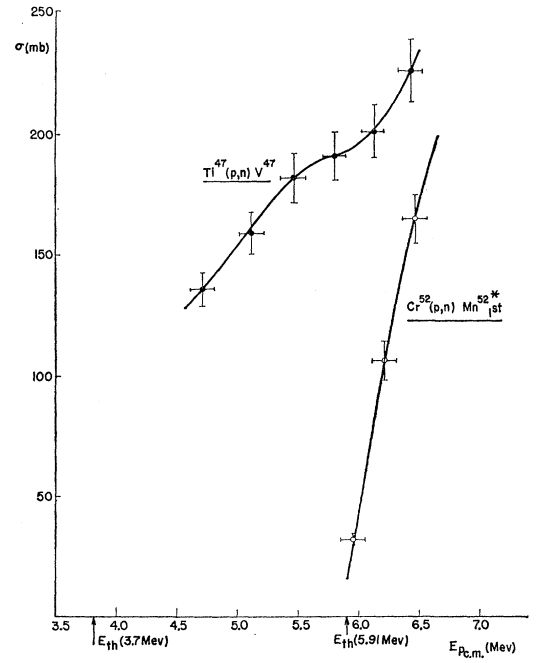

FIG. 2. The (p,n) cross sections for Ti^{47} and Cr^{52}. Over this energy range the (p,n) cross section to the ground state of Mn^{52} was negligible.

The only other reactions energetically possible are inelastic proton scattering, radiative capture, and (p,α) reactions. The last two reactions are expected to have very small cross sections (<10mb) and no attempt was made to measure them. The (p,p') cross section was estimated from data of Seward[10] which had been taken in connection with another study of inelastic proton scattering. The cross section at 90° for inelastic scattering to all states was compared with that for elastic scattering, and the measured elastic scattering cross sections[1] were used to compute the inelastic cross sections at 90°. It was assumed that the cross sections averaged over all excited states were isotropic, and total (p,p') cross sections were obtained by multiplying the 90° cross sections by 4π.

The total proton absorption cross section was taken as the sum of the (p,n) and (p,p') cross sections. A possible contribution from compound elastic scattering was neglected since the cross section to any one level was no greater than about 10 mb. This is shown Figs. 4 and 5 as the solid curve. The error bars represent total error from all sources in both the (p,n) and (p,p')

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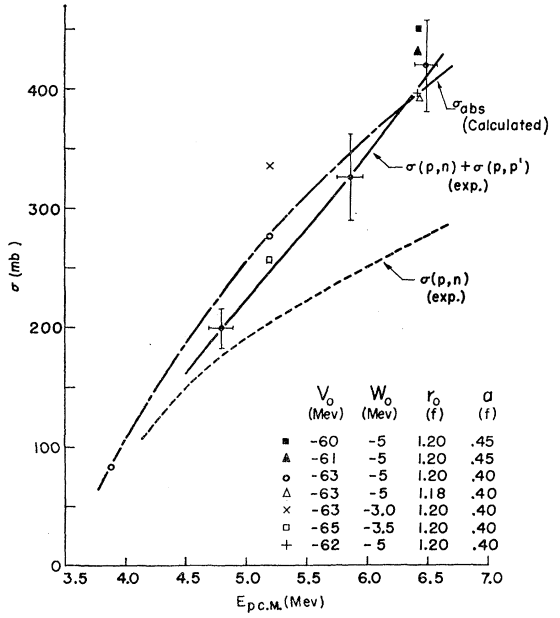

FIG. 4. Absorption cross section for protons on Co^{59}. Calculated cross sections are indicated for several sets of optical model parameters.

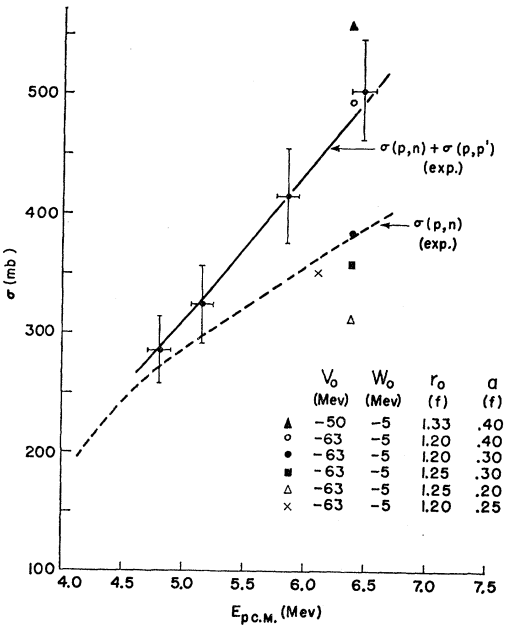

FIG. 5. Absorption cross section for protons on V^{51}.

measurements. Exact phase shifts for the scattering of protons on a complex potential well had been computed earlier by Preskitt and Alford[1] in making an optical model analysis of elastic proton scattering on V and Co. The calculations were carried out for partial waves up to $l=4$, which is quite satisfactory for the energies used here. The potential well was the Woods–Saxon type:

$$V=V_c+(V_0+iW_0)[1+\exp(r-R_0/a)]^{-1},$$

with V_c taken as the Coulomb potential of a uniform spherical charge distribution of radius $R_0=r_0A^{\frac{1}{3}}$. Using these phase shifts, absorption cross sections were calculated for various sets of model parameters, and are shown on Figs. 4 and 5. For Co, the absorption cross section corresponding to the best fit to the elastic scattering is indicated, and it is seen that these calculated cross sections are in fairly good agreement with experiment. It is interesting that the cross sections calculated with the rather small radius parameter $r_0=1.20$ f show such good agreement.

In the case of V, the same set of optical model parameters which gave agreement with the Co data predicts an absorption cross section in good agreement with experiment at 6.39 Mev. However, the angular distribution calculated with these parameters is in poor agreement with the measured distribution. The fit to the angular distribution measurement was improved somewhat by decreasing the diffuseness parameter to 0.20 f, but the calculated absorption cross section is then much too small. In view of the good agreement with the Co data, a systematic search for a set of parameters which would provide fits to both the angular distribution and absorption measurements on V should prove of interest.