Inelastic Scattering of Protons from Isotopes of Sc, Mn, Fe, Ni, and Cu†

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The inelastic scattering of protons from eight nuclides has been studied using a precision 180° magnetic spectrometer. Energy levels in these nuclides were obtained to about 1.6 Mev of excitation. Proton energies of 4.4 to 5.7 Mev were used from the Rice Institute Van de Graaff accelerator. Cross sections for the inelastic scattering processes were obtained.

INTRODUCTION

THE Rice Institute Van de Graaff accelerator, in conjunction with an annular magnet spectrometer,[1] has been used to study inelastically scattered proton groups from some of the isotopes of iron, nickel, manganese, copper, and scandium. The purpose of this paper is to describe these experiments and to report the excitation energies of states in these nuclei.

EXPERIMENTAL METHODS AND PROCEDURES

The magnetic spectrometer was used to determine the momenta of the scattered protons at 180° with respect to the incident beam. The bombarding energy was calculated from the momenta of the elastically scattered groups of protons. Q values for the reactions and the corresponding excitation energies were calculated from equations previously given.[1] The atomic mass values

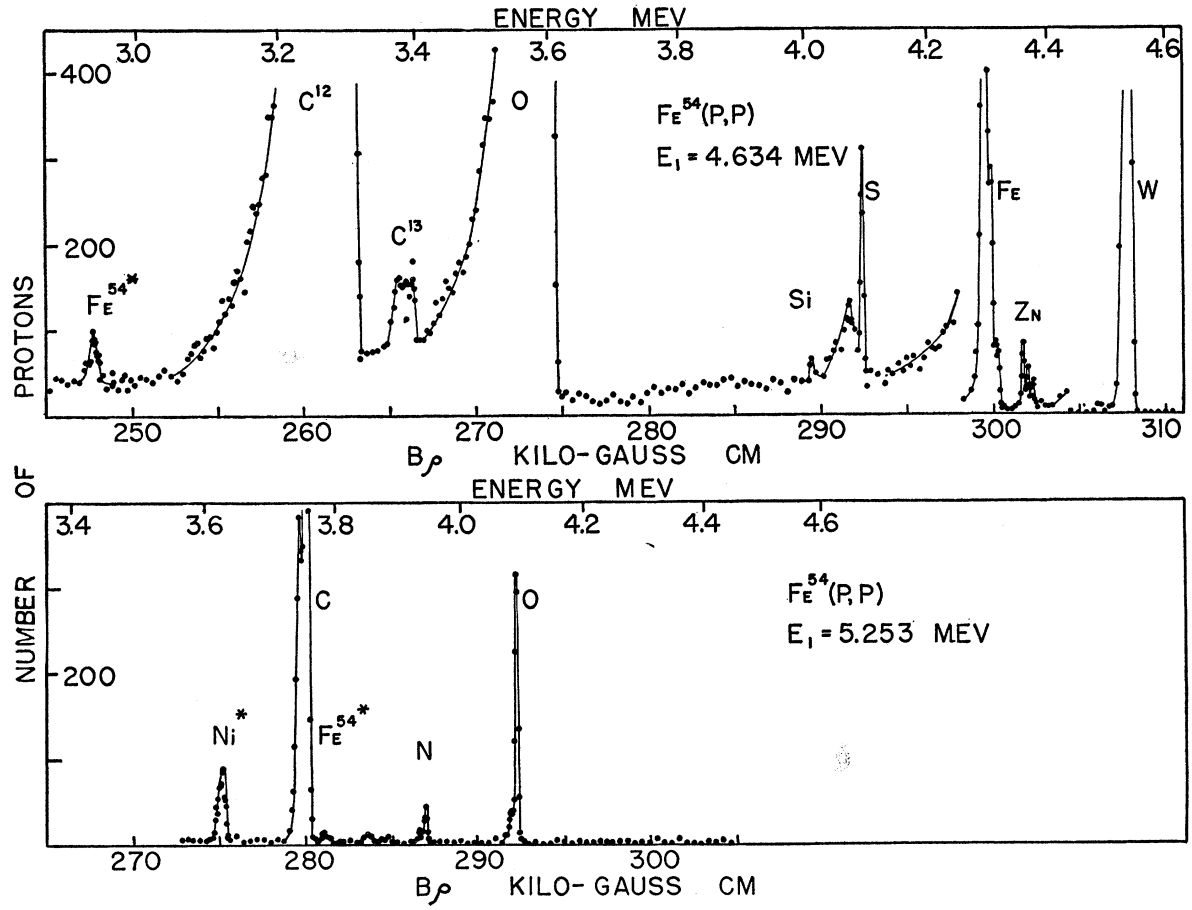

FIG. 1. Number of protons scattered from weighed iron oxide, enriched in Fe^{54}, per momentum interval *versus* the magnetic rigidity $B\rho$. The target backing for the top spectrum was a relatively thick carbon foil. The lower spectrum had a thin Ni foil for a backing.

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[1] Gossett, Phillips, and Eisinger, Phys. Rev. 98, 724 (1955); C. R. Gossett, Ph.D. thesis, The Rice Institute, 1955 (unpublished); K. Famularo, Ph.D. thesis, The Rice Institute, 1952 (unpublished).

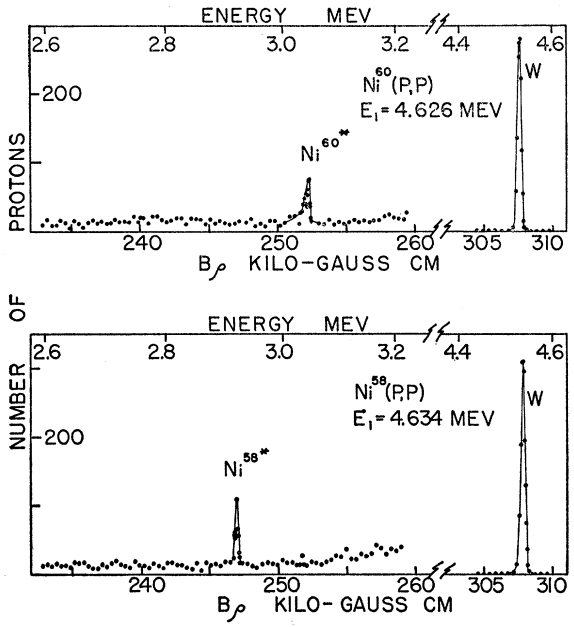

FIG. 2. Number of protons scattered from weighed oxides of nickel, enriched in Ni^{58} and Ni^{60}, on carbon foil backings *versus* the magnetic rigidity $B\rho$. The only elastic peak shown is from the W contaminant produced in the evaporation of the film. The inelastic groups corresponding to the first excited state of each isotope are indicated.

used in these calculations were those tabulated by Bainbridge.[2]

The targets for the experiments were either thin foils of the target material or thin layers of the target material evaporated in vacuum onto foils of nickel or carbon. Thicknesses of the evaporated targets were determined by the change of weight of a foil placed adjacent to the target at the time of evaporation. The target thicknesses were also calculated directly from the spectra, using the stopping power of the target material to protons, and the observed line widths of the particle groups. Where it was possible to compare the values of target thickness obtained in this manner, to the value obtained by weighing, the two methods agreed to about 20%.

For the spectra shown in Figs. 1 to 4 the various proton groups due to elastic scattering from all isotopes in the target are labeled according to the element responsible. Similarly, excited states are indicated on the plots by an asterisk, except for scandium, where the excitation energies are given. The energy scale at the top of each spectrum indicates the scattered proton energy, E_2, while the bombarding energy, E_1, is given on each plot. Excitation energies and cross sections are listed in Table I.

Effects due to contaminant layers on the targets were observed in most cases. The lines due to the contaminants could be identified by changing the bombarding energy. Since in most cases the contaminant lines appeared to be thin surface deposits it was usually possible to differentiate between particle groups due to the target element, and those due to surface contaminants.

1. Fe(p,p')Fe

The top of Fig. 1 shows the spectrum obtained from a target of ~90 μg/cm^2 of iron oxide enriched to about 95% in Fe^{54}.[3] Contaminants of zinc, sulfur, silicon, and tungsten appear on this spectrum. This target was evaporated on a rather thick carbon backing as evidenced by the broad carbon and oxygen lines. The region of excitation that was obscured by oxygen and carbon was studied using another iron target, enriched in Fe^{54}, of ~50 μg/cm^2, on a nickel backing, and is shown on the bottom of Fig. 1. The spectrometer background was very small in this partial spectrum. Similar spectra were obtained for a target of natural iron with about 92% Fe^{56}. The experiments with iron targets indicated lines corresponding to only one level in each isotope up to about 1.6 Mev of excitation.

The data with targets of natural iron (91.6% Fe^{56}) showed the well-known level in Fe^{56} to be at 0.845 Mev. A state was reported at about 0.85 Mev in the decay of Mn^{56} and Co^{56}.[4] Reports of inelastic neutron scattering experiments from Fe^{56} have indicated a number of lower energy γ rays in addition to the γ ray from inelastic scattering to the 0.845-Mev state[5]; however, fewer γ rays were found in other experiments using similar techniques.[6] On the basis of the data obtained with the annular magnet, the low-energy γ rays are probably associated with cascades produced by inelastic scattering from the states above the 0.845-Mev state.

Fe^{54} appears to have its first excited state at 1.413 Mev. A γ ray at 1.37±0.02 Mev has been observed by Sinclair[7] by the inelastic scattering of neutrons from iron enriched in Fe^{54}.

The two isotopes of iron, then, fit the general features of the shell model where 28 neutrons form a closed shell in Fe^{54}. On this basis the first excited state for the semimagic isotope, Fe^{54}, should be higher than the first excited state of Fe^{56}, which is not magic in either protons or neutrons.

2. Ni(p,p')Ni

The isotopes Ni^{58} and Ni^{60} are abundant to 68% and 26% in natural nickel, so that natural nickel foils should produce inelastic proton groups corresponding

[2] K. T. Bainbridge, *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. I, Part V, pp. 745–758.

[3] All of the enriched isotope target materials were obtained from the Oak Ridge National Laboratory.

[4] L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943); Sakai, Dick, Anderson, and Kurbatov, Phys. Rev. **95**, 101 (1954).

[5] Lafferty, Rayburn, and Hahn, Phys. Rev. **96**, 381 (1954).

[6] M. A. Rothman and C. E. Mandeville, Phys. Rev. **93**, 796 (1954); Garrett, Hereford, and Sloope, Phys. Rev. **91**, 441(A) (1953); G. L. Griffith, Phys. Rev. **98**, 579 (1955).

[7] R. M. Sinclair, Phys. Rev. **98**, 1147(A) (1955).

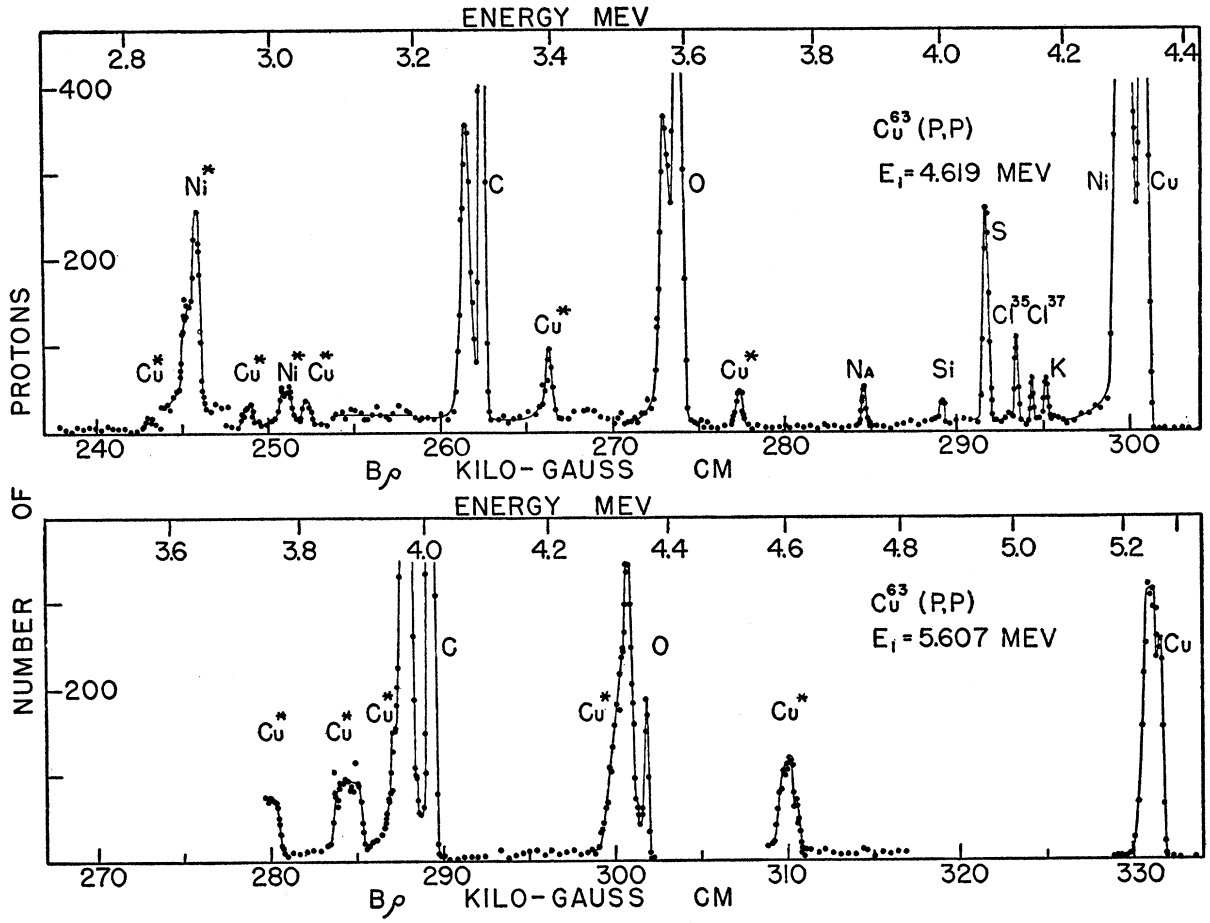

FIG. 3. Number of protons scattered from copper, enriched in Cu^{63} *versus* the magnetic rigidity $B\rho$. The target for the upper spectrum was copper, enriched in Cu^{63}, evaporated upon a Ni foil, while the lower spectrum was obtained with a copper foil, enriched in Cu^{63}. Five excited states in Cu^{63} are indentified.

to excited states in both isotopes. Thin natural nickel foils were employed, while in addition evaporated nickel oxide targets, enriched in Ni^{58} and Ni^{60} were used to establish the isotopes responsible for the observed levels. Figure 2 shows partial spectra for the scattering of protons from such targets. The desired isotope was enriched to about 98.5% with about 1.5% of the other naturally occurring isotopes present. These spectra revealed a state at 1.453 Mev in Ni^{58} and one at 1.329 Mev in Ni^{60}.

The isotopes Ni^{58} and Ni^{60} each have only one excited state below about 1.5 Mev. These levels are known from several experiments. The γ rays from the decay of Co^{60} are widely used as γ-ray energy standards. The energy of these γ rays from the first excited state of Ni^{60} has been determined with great precision as 1.3325 ± 0.0003[8] and 1.3316 ± 0.0010.[9] The value for the energy of this state, as given in Table I, is in agreement with these values to within the experimental errors. The energy of the Ni^{58} state was not previously known to such precision. A level at 1.497 Mev was reported for inelastic proton scattering from Ni,[10] with an over-all quoted accuracy of about 20 kev. This value is in fair agreement with the present value of 1.453 ± 0.005 Mev.

No states were observed below the 1.329-Mev state in Ni^{60} or the 1.453-Mev state in Ni^{58}. For the nickel isotopes with a closed shell of 28 protons, one expects the higher energy first excited state to occur in Ni^{58}, which is semimagic with 28 protons and two excess neutrons outside the 28 shell. Ni^{60}, being magic in protons, but with 4 neutrons outside the 28 shell, has a slightly lower first excited state. It is interesting to note that the energies of these first excited states are about the same as that of Fe^{54}, which is also semimagic with 26 protons and 28 neutrons.

[8] Lindstrom, Hedgran, and Alburger, Phys. Rev. **89**, 1303 (1953).
[9] Lind, Brown, and DuMond, Phys. Rev. **76**, 1838 (1949).
[10] Ely, Allen, Arthur, Bender, Hausman, and Reilly, Phys. Rev. **86**, 859 (1952).

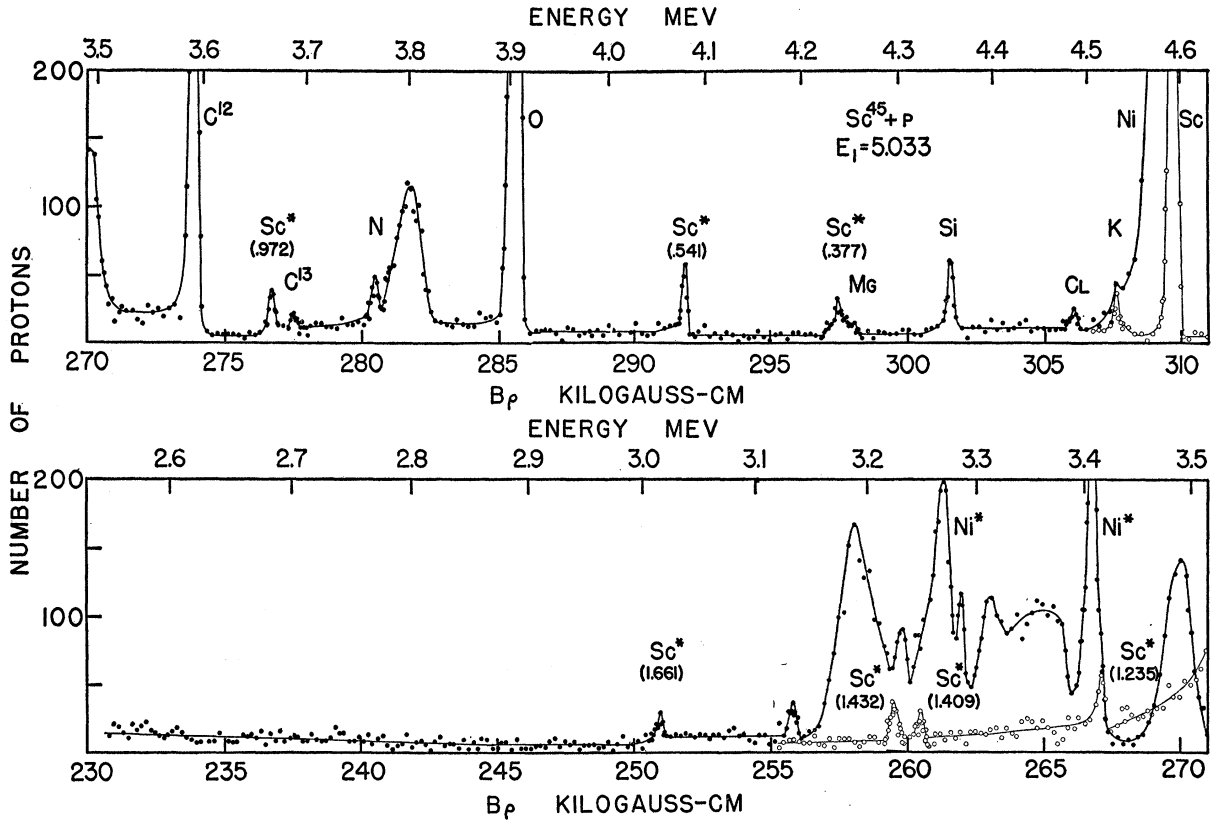

FIG. 4. Number of protons scattered from Sc^{45} *versus* the magnetic rigidity $B\rho$. The target for the spectrum with closed circles was an evaporated layer of Sc^{45} oxide upon a Ni foil and shows the elastic Ni group and the two inelastic Ni groups, the latter showing resonance structure in the relatively thick Ni foil. The open circles are for a spectrum obtained at the same bombarding energy, with a target of Sc^{45} oxide upon a C foil.

3. $Mn^{55}(p,p')Mn^{55}$

Only one complete spectrum was obtained with a manganese target, and for this experiment data were taken to about 1.4 Mev of excitation in Mn^{55} using a bombarding energy of 4.776 Mev. No levels were found; however, the contaminants on the thick carbon backing may have obscured possible states. A few plates at bombarding energies different from 4.776 Mev were exposed in the momentum region of the manganese elastic group. The manganese 0.128 Mev state appeared on these plates. Presumably the higher bombarding energies increased the yield so that the state was observable above background. The results of these experiments are given in Table I, although no spectrum is shown.

The manganese experiments are incomplete, and more work is needed to ascertain that states do not fall under contaminants. Evidence for the 0.128-Mev state, however, is fairly conclusive. This level is in agreement with that obtained by Coulomb excitation.[11]

[11] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **96**, 426 (1954); Mark, McClelland, and Goodman, Phys. Rev. **98**, 1245 (1955).

4. $Cu^{63}(p,p')Cu^{63}$

The two abundant isotopes of copper, Cu^{63} and Cu^{65}, were studied by bombarding natural copper targets. Proton groups arising from Cu^{63} were identified by the use of targets enriched to about 99% in that isotope.

The spectrum resulting from the bombardment of a copper target, enriched in Cu^{63}, is shown in the top part of Fig. 3. This target was evaporated on a foil of natural nickel so that elastic nickel groups and inelastic groups corresponding to the excited states of Ni^{58} and Ni^{60} all appear in addition to proton groups from several contaminants. The Cu^{63} elastic group is well resolved to the right of the elastic nickel groups. At lower momenta there are five proton lines attributable to Cu^{63}. These groups correspond to levels at 0.669, 0.961, 1.325, 1.411, and 1.546 Mev of excitation in Cu^{63}. The discontinuities in the background in the low momentum region of the spectrum were due to variations in the alignment of the incoming beam, resulting in more or less scattering from material in the target region. Nevertheless, the states were all clearly present above background.

TABLE I. Energy levels for the nuclides Sc^{45}, Mn^{55}, Fe^{54}, Fe^{56}, Ni^{58}, Ni^{60}, and Cu^{63} determined by inelastic scattering and approximate cross sections for inelastic scattering.

Nucleus	Mean energy of excitation (Mev)	Bombarding energy (Mev)	Cross section (mb/sterad)
Sc^{45} [a]	0.377±0.003	Observed	0.2
		at	0.2
		bombarding	0.3
	0.541±0.003	energies	0.2
		4.514,	0.4
		5.033,	0.3
	0.722±0.005	and	0.2
		5.608 Mev	...
			0.3
	0.972±0.004		0.2
			0.4
			0.4
	1.235±0.005		0.2
			0.4
			...
	1.409±0.005		...
			0.3
			0.2
	1.432±0.005		...
			0.3
			0.1
	1.661±0.005		0.1
			0.2
			0.1
Mn^{55}	0.128±0.007	4.776	...
		5.506	1.0
		5.144	...
		5.127	0.9
Fe^{54}	1.413±0.005	4.634	2.0
Fe^{56}	0.845±0.005	5.725	3.2
		5.532	1.8
		5.113	...
		4.638	2.3
		4.454	1.0
Ni^{58}	1.453±0.005	5.513	3.7
		4.765	2.9
		4.634	1.6
		4.441	3.4
Ni^{60}	1.329±0.005	5.513	2.5
		4.626	1.5
		4.441	0.8
		4.437	...
Cu^{63}	0.669±0.005	5.607	1.5
		4.619	1.0
	0.961±0.005	5.522	2.4
		4.619	1.9
	1.325±0.005	5.607	2.0
		4.619	0.7
	1.411±0.005	5.607	1.7
		4.619	0.6
	1.546±0.005	5.607	1.5
		4.619	0.4

[a] The cross sections for each excited state of Sc^{45} are listed in the same order as the bombarding energies. Where no cross section is given for Sc^{45}, the state was not observed at that bombarding energy.

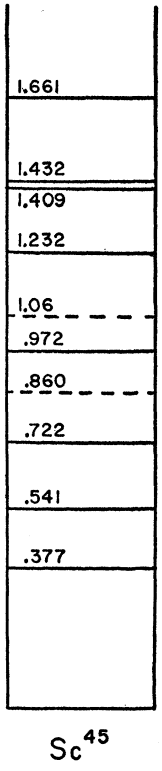

FIG. 5. An energy level diagram for Sc^{45}. The solid lines indicate states observed by inelastic scattering at two or more bombarding energies. The dotted lines indicate possible states, observed only once by inelastic scattering (see text).

The lower part of Fig. 3 shows the results of bombarding a Cu foil, enriched in Cu^{63}, that had been peeled off the aluminum foil onto which it was evaporated. The thickness of this foil was 400 $\mu g/cm^2$. These data confirmed the existence of states at 0.669, 1.411, and 1.546 Mev. They left in doubt the states at 0.961 and 1.325 Mev since these two lines fell under oxygen and carbon peaks. Since the 0.961-Mev state was well established[12] by other means only the 1.325-Mev state was somewhat questionable. However, the high points on the base of the carbon line from the back surface of the foil indicated that the copper level was probably present, and energy calculations using this group agreed with those obtained from the top spectrum of Fig. 3. No known contaminant lines could explain the proton group observed in the spectrum shown in the upper part of Fig. 3.

No levels have as yet been positively identified in Cu^{65}.

5. $Sc^{45}(p,p')Sc^{45*}$

To observe the level structure of Sc^{45} targets of ScO evaporated onto thin nickel or carbon foils were bombarded at three bombarding energies: 4.5, 5.0, and 5.6 Mev. Due to the complexity of the inelastic proton spectrum observed in the initial bombardment, these energies were chosen such that any group, obscured by elastic protons from contaminants at one bombarding energy, would be observable at the other two bombarding energies.

Figure 4 shows a typical spectrum obtained in one of the bombardments. The intense groups are due to the elastic scattering from Sc^{45} and O^{16} in the target material, a C^{12} surface contamination, and inelastic scattering from the natural nickel used as a backing foil. A number of weak groups, assigned to other surface contaminants, also appeared in each of the spectra.

Table I lists the mean values of the excitation energies of Sc^{45} determined from the lines ascribed to that

[12] Huber, Medicus, Preiswerk, and Steffen, Helv. Phys. Acta **20**, 495 (1947).

isotope in each of the three spectra. The states of Sc^{45}, thus deduced, are shown in the energy level diagram of Fig. 5. For the states shown by solid lines, the evidence is conclusive; groups yielding this Q value were observed in two or more spectra, and could not be ascribed to contaminants. The two dashed lines indicate possible states. The proton groups which could be interpreted as due to such states showed better consistency if considered as due to N^{14} and C^{13} surface contaminants.

The work of Temmer and Heydenburg[13] indicated a level in Sc^{45} at 388 kev, which is in reasonable agreement with the 377-kev level found in the present experiment. Since their work was concerned with levels below 500 kev, they did not observe the 541-kev level, which the present results indicate to be the second excited state of this nucleus.

The β^- decay of Ca^{45} has an end point of 0.254 Mev[14] and thus produces no information on the level structure of Sc^{45}. The β decay of Ti^{45} has a maximum energy of 1.02 Mev; however, various observers[15] do not agree on the presence of γ rays in this process. The only reported γ-ray energy, 0.450 Mev, does not agree with the first excited state energy found here.

[13] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **93**, 351 (1954).

[14] B. H. Ketelle, Phys. Rev. **80**, 758 (1950); Macklin, Feldman, Lidofsky, and Wu, Phys. Rev. **77**, 137 (1950); L. Marquez, Phys. Rev. **92**, 1511 (1953).

CROSS SECTIONS

Cross sections were estimated for all of the reactions studied. The values obtained are probably only accurate within a factor of two or three. For these measurements target thicknesses were determined as described previously. The yield was determined by direct count of the proton tracks that appeared in a given line on the photographic plate, while the incident beam was measured by means of a current integrator. The solid angle subtended by the spectrometer detection system was calculated from geometric considerations of the spectrometer dimensions, but was more accurately determined empirically by measuring the yield of reactions of known cross sections. The cross sections for the individual reactions are given in Table I along with the energy level information.

[15] H. E. Kubitschek, Phys. Rev. **79**, 23 (1950); Ter-Pogossian, Cook, Porter, Morganstern, and Hudis, Phys. Rev. **80**, 360 (1950); Naussbaum, Van Leishout, and Wapstra, Phys. Rev. **92**, 207 (1953).

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Total Neutron Cross Section of Thulium in the Energy Region 0.038 to 1.56 ev*

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Measurements of the total cross section of thulium as a function of neutron energy have been made with the Materials Testing Reactor crystal spectrometer. Twelve cylindrical pellets which contained a total of 2.414 grams of metallic thulium were used as a sample. The low-energy data can be described by the expression $\sigma(E)=6.5+20.1E_{ev}^{-\frac{1}{2}}$ (barns). The extrapolated value for the total cross section at 0.0253 ev is 134±3 barns.

I. INTRODUCTION

PRECISE values of the neutron cross section of thulium are of importance in the production of high specific activity thulium x-ray sources. Measurements of the resonance structure of thulium have been made by Foote, Landon, and Sailor[1] and Harvey, Hughes, Carter, and Pilcher.[2] When metallic thulium became available to the cross-section group at the Materials Testing Reactor (MTR), measurements were undertaken to increase the statistical accuracy of the data below 1 ev and to extend the measurements to 0.03 ev.

* Work carried out under contract with the U. S. Atomic Energy Commission.

[1] Foote, Landon, and Sailor, Phys. Rev. **92**, 656 (1953).

[2] Harvey, Hughes, Carter, and Pilcher, Phys. Rev. **99**, 10 (1955).

II. EXPERIMENTAL DETAILS

The cross-section measurements were made on the MTR crystal spectrometer at 5-minute increments in glancing angle with the 240 planes of a sodium chloride monochromating crystal. The over-all instrument resolution was 0.9 μsec/meter or 2.5% in energy at 1 ev.

The sample consisted of 12 cylindrical metal pellets that were sent to the MTR for irradiation. These were made available for cross-section measurements prior to irradiation. The pellets were 0.422 cm in diameter, 0.160 cm high and had a measured density of 9.00±0.05 g/cm^3. The thulium was purified and fabricated into pellets by Dr. F. H. Spedding and his colleagues at the U. S. Atomic Energy Commission's Ames Laboratory. The pellets, made by powder metallurgy techniques, contained small voids which were visible under low