Energy Levels in Magnesium, Vanadium, Chromium, and Manganese*

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(Received July 21, 1952)

Targets of Mg, V, Cr, and Mn have been bombarded by 8-Mev protons from the 47-in. cyclotron and the reaction particle observed at an angle of 150° to the incident beam. Three levels are assigned to Mg^{24}, seven to Mg^{25}, and two to Mg^{26}. Fourteen levels are reported for V^{51}, 15 for Cr, and 15 for Mn^{55}.

I. INTRODUCTION

MEASUREMENTS of the energy levels of stable nuclei in the region 10 to 30Z by means of inelastic charged particle reactions have been relatively neglected as compared to investigations on the light nuclei. Recently[1] an extensive program of instrumentation has been completed at the University of Pittsburgh for the study of nuclear reactions. This has permitted the use of an energy-analyzed beam of eight-Mev protons for precision determinations of nuclear energy levels. The present paper is a continuation of the studies of energy levels in the medium Z range as reported by Reilley *et al.*[2] and Ely *et al.*[3]

II. APPARATUS

The apparatus for the precision scattering project has been described elsewhere.[1] Briefly, the diverging beam of protons from the University of Pittsburgh 47-in. cyclotron is focused by a 14° sector magnet on a slit located in the center of an eight-foot shielding wall. The slit acts as a source for the beam-analyzing magnet which focusses the beam of particles at a point $1\frac{3}{4}$ in. in front of the target. The dispersion of the beam-analyzing magnet is 300 kev/in. for eight-Mev protons. Reaction particles are magnetically analyzed by a third magnet of high resolution. Charged particle groups are detected by a zinc sulfide fluorescent screen and an EMI 5311 photomultiplier tube. A set of remotely controlled absorption foils which can be positioned in front of the detector slit and scintillation screen are used to differentiate between charged particles of the same momentum.

Thin targets (approximately 10 kev) of magnesium, chromium, vanadium, and manganese were obtained by evaporation of the pure metals from conically shaped 30-mil tungsten filaments. Thicker targets used for general survey of the materials were evaporated from 5-mil tantalum boats except vanadium. Thin (18-microinch) gold foils were used as a backing material. No inelastic levels were observed from the gold backing.

Target thicknesses were measured by carefully weighing the target frame before and after evaporation. It is estimated that thicknesses can be measured to ±20 percent. Spectroscopic analysis of the targets showed less than $\frac{1}{10}$ percent contamination.

III. RESULTS

A. Magnesium

From the proton bombardment of aluminum, previously reported by Reilley *et al.*,[2] two unresolved alpha-particle groups were observed at an angle of 90° to the incident beam resulting from the $Al^{27}(p,\alpha)Mg^{24}$ reaction. The high energy alpha-particle group, assigned to the 1.38-Mev level in Mg^{24}, was superimposed upon an inelastic proton group from aluminum. The low energy alpha-group, assigned to the 4.14-Mev level in Mg^{24}, although of very weak intensity had indications of being complex.

A survey of the protons scattered from a thin natural magnesium target at an observation angle of 90° indicated four resolved proton groups: the magnesium elastic peak, a group corresponding to the 1.38-Mev level, and a resolved doublet at 4.14-Mev excitation. Since naturally occurring magnesium contains three isotopes, there existed the possibility that one of the proton groups assigned to the 4.14-Mev doublet in Mg^{24} could have arisen from an excited state in either Mg^{25} or Mg^{26}. It was decided to determine whether the apparent doublet exists in Mg^{24} at 4.14-Mev excitation by observing the alpha-particles from the proton bombardment of aluminum at an angle of 150° to the incident beam.

The reason for the choice of the observation angle of 150° was twofold. Calculations showed that the relative motion of the alpha-particle groups to that of neighboring proton groups from aluminum would be such as to eliminate any overlap. Also, the variation of energy of the scattered particles with angle is such as to improve the relative resolution of the alpha-groups.

With a 0.19-mg/cm² aluminum target, three resolved alpha-groups were found corresponding to the 1.38-Mev level in Mg^{24} and a doublet at 4.14 Mev. No alpha-particle group corresponding to the ground-state reaction was found. However, the momentum of the ground-

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[1] Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. 23, 542 (1952).
[2] Reilley, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. 86, 857 (1952).
[3] Ely, Allen, Arthur, Bender, Hausman, and Reilley, Phys. Rev. 86, 859 (1952).

state alpha-group was very near to that of the intense aluminum proton elastic peak. Because of the large relative difference in intensity, an upper limit was placed on that of the ground-state alpha-group. It was estimated as being no greater than 1/20 the intensity of the 1.38-Mev alpha-group.

A thick target 0.44 mg/cm^2 survey of the protons scattered from natural magnesium at the observation angle of 150° resolved 15 proton groups. Actual level assignments were made using a thin (0.1 mg/cm^2) natural magnesium target and improved resolution. A spectrum of the proton groups scattered from a thin natural magnesium target is plotted in Fig. 1. Peaks *a*, *c*, and *d* are the elastic peaks of Mg, O, and C. Three of the proton groups, peaks *e*, *n*, and *o*, were assigned to levels in Mg^{24}, positive identification being made by the $Al^{27}(p,\alpha)Mg^{24}$ measurements. Inasmuch as the ground-state alpha-group from the above (p,α) reaction was not resolved, a *Q* value of 1.594 as reported by Van Patter[4] was used to calculate the excited levels in Mg^{24}. The values determined are 1.39, 4.12, 4.22, which are in good agreement with the assignments made by inelastic proton measurements.

Seven proton groups were tentatively assigned to excited states in Mg^{25}. The assignment of these levels was made by comparison with the levels reported by Endt *et al.*[5] from the $Al^{27}(d,\alpha)Mg^{25}$ reaction and from the $Mg^{24}(d,p)Mg^{25}$ reaction. The proton group corresponding to the 2.744 level reported has indications of being complex. It is probable that this group corresponds to the 2.736- and 2.799-Mev doublet in Mg^{25} reported by Endt *et al.*[5] Two groups have been assigned to Mg^{26} by comparing their energies with the reported[6] levels.

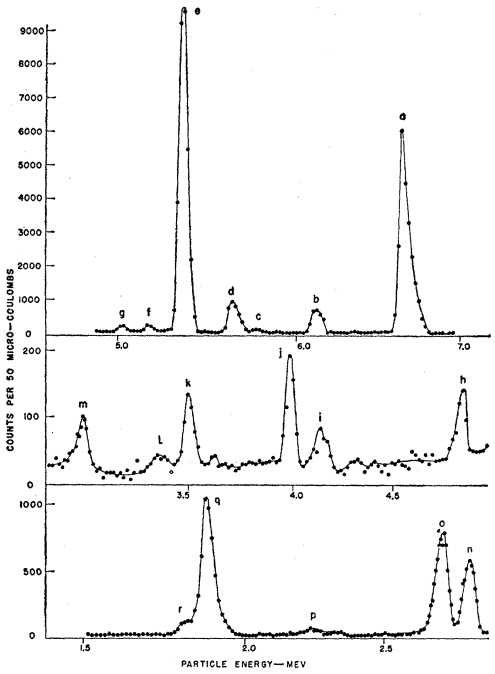

FIG. 1. Spectrum of charged particles scattered from magnesium at 150°.

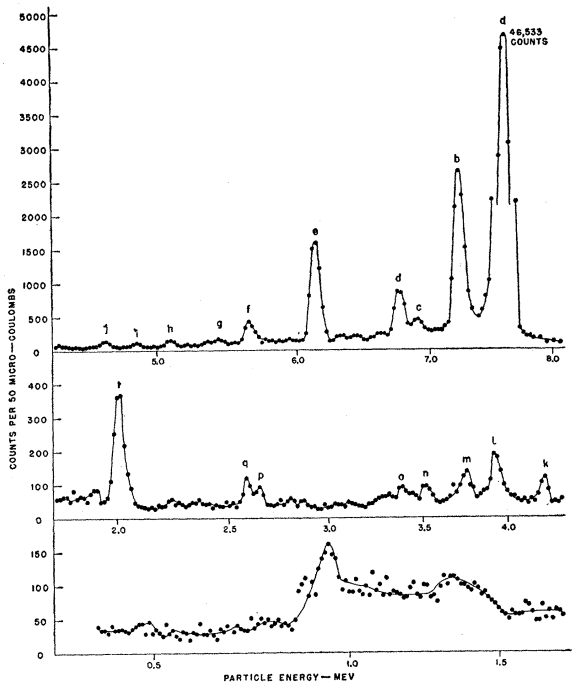

FIG. 2. Spectrum of charged particles scattered from vanadium at 150°.

B. Vanadium

A thin (less than 5 kev) target of vanadium was bombarded with 8-Mev protons and the reaction particles observed at an angle of 150° to the incident beam. Natural vanadium has two stable isotopes, V^{50} and V^{51}. The percentage of V^{50} in natural vanadium, 0.25 percent, is small enough that the likelihood of detecting inelastic proton groups from V^{50} is small. Consequently, all energy levels have been assigned to excited states in V^{51}.

Seventeen proton groups (see Fig. 2) were recorded. Calculations show peaks *a*, *b*, and *f* to be elastically scattered protons from gold, vanadium, and carbon, respectively. The proton group corresponding to peak *r* has been assigned to the 4.44-Mev level in carbon. Four energy levels have been previously recorded in V^{51}.[7] Two of the levels, 0.267 and 0.320 Mev, were determined from *K* capture in Cr^{51}; the 1.1- and 4.7-Mev levels were determined by $Ti^{48}(\alpha,p)V^{51}$ reaction. Peaks *c* and *e* can tentatively be assigned to the 0.320- and 1.1-Mev levels. There was no indication in the present experiment of the 0.267-Mev level. It is possible that the group corresponding to the 0.267-Mev level could be of such low

[4] D. M. Van Patter, Massachusetts Institute of Technology Technical Report No. 57, January (1952) (unpublished).
[5] Endt, Enge, Haffner, and Buechner (to be published).
[6] Endt, Haffner, and Van Patter, Phys. Rev. **86**, 518 (1952).
[7] Way, Fano, Scott, and Thew, *Nuclear Data*, National Bureau of Standards. Circular 499 (1950).

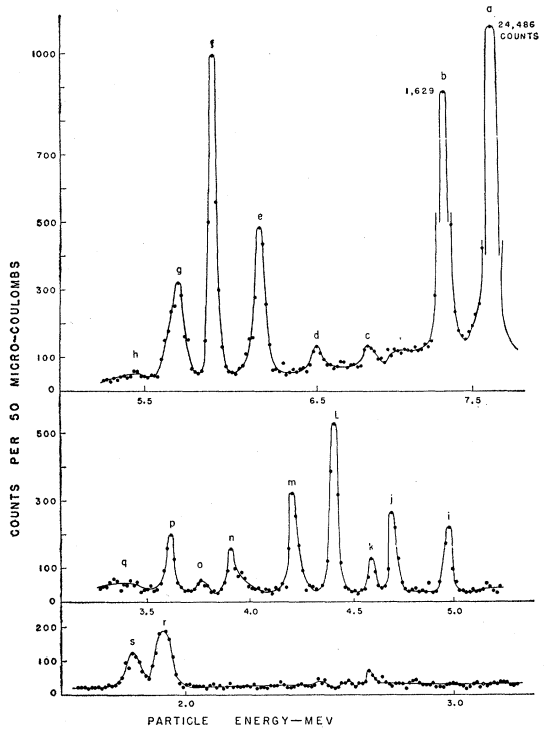

FIG. 3. Spectrum of charged particles scattered from chromium at 150°.

intensity as to be obscured by background. There is a low intensity doublet, peaks *p* and *q*, corresponding to excitation energies of 4.90 and 4.97 Mev, respectively, which can possibly be assigned to the 4.7-Mev level reported.

C. Chromium

The spectrum of scattered protons from a thin natural chromium target at an angle of 150° to the incident beam is shown in Fig. 3. Twenty-three proton groups were observed in the reaction, nineteen of which are shown from the thin target spectrum. Peaks *a*, *b*, *e*, and *g* are the elastically scattered protons from gold, chromium, oxygen, and carbon, respectively. Peaks *r* and *s* have been assigned to the 4.44-Mev level in carbon which was present on both the front and rear faces of the target. Particle groups *f*, *i*, and *l*, corresponding to excited states of 1.46, 2.43, and 3.01 Mev in Cr^{52} agree with the known levels[7] in Cr^{52} determined by the decay of Mn^{52}. There is a possible assignment of peak *d* to the 0.835-Mev level of Cr^{54} determined by Deutsch and Elliot[8] from the decay of Mn^{54} and the subsequent emission of an 0.835 gamma-ray.

Since natural chromium has five stable isotopes, absolute assignment of energy levels cannot be made at present. It is possible, however, that peaks *j*, *k*, *m*, *n*, and *p* are inelastic groups from Cr^{52}, the most abundant chromium isotope, due to their large relative intensities.

[8] M. Deutsch and L. G. Elliot, Phys. Rev. **65**, 211 (1944).

D. Manganese

Since manganese consists of only one stable isotope, the assignment of the groups shown in Fig. 4 is relatively simplified. The spectrum of manganese was obtained at an angle of 150° to the incident beam. Both thick and thin target spectrums were obtained and the energy levels quoted in Table I are an average of both runs. Peaks *a*, *b*, *e*, and *h* were determined to be the elastic groups for gold, manganese, oxygen, and carbon, respectively. Peak *t* has been assigned to the 4.44-Mev level in carbon. Peak *c* has been assigned to an excited state in Mn^{55}. The unresolved nature of the carbon elastic peak is assumed to be caused by layers of carbon deposited during successive evaporations in the preparation of the manganese target. Peak *u* has also been assigned to the 4.44-Mev level in carbon and probably arises because of the large carbon deposits on the back of the gold foil. Other than the above-mentioned groups, all peaks have been assigned to excited states in Mn^{55}. It is interesting to note that in the region of proton group energy of 2.0 to 4.0 Mev there appears to be a large number of low intensity unresolved groups. No attempt was made to resolve groups in this region as it was indicated that the experimental level widths are large compared to the level spacing.

IV. DISCUSSION

A detailed analysis of the spectral distributions of the emitted particle groups from the bombarded targets will not be discussed here. However, there are some general conclusions concerning these distributions which

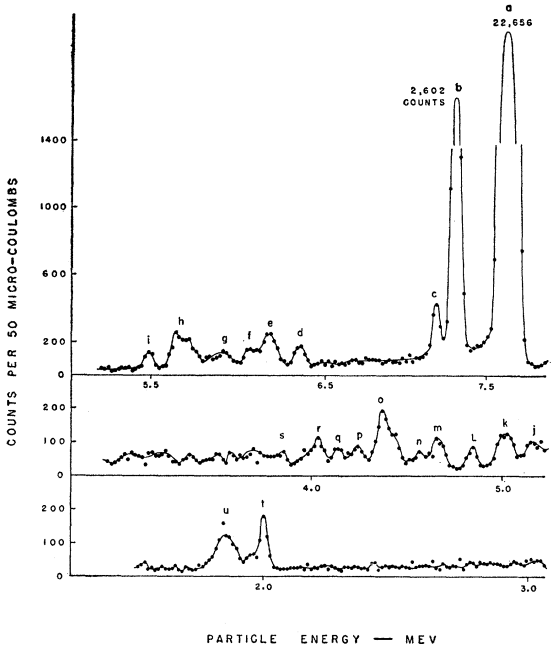

FIG. 4. Spectrum of charged particles scattered from manganese at 150°.

indicate qualitative agreement with the expected distributions predicted by the statistical models of the nucleus. The various statistical treatments for the heavier elements ($A>50$) predict a level spacing above a few Mev excitation energy which is very small compared to the natural widths of the levels.

On broad general lines it can be seen that the level densities of the residual nuclei, vanadium, chromium, and manganese, increase with increasing excitation of the residual nucleus. The general tendency of the intensity distributions of these three elements is a gradual decrease in the intensities of the groups as a function of increasing group energy. This is in qualitative agreement with the distributions predicted by Weisskopf and Ewing.[9]

TABLE I. Energy levels (probable error ±0.02 Mev).

Mg^{24}	Mg^{25}	Mg^{26}	Mg	V^{51}	Cr^{52}	Cr	Mn^{55}
1.38	0.61	1.83	3.54	0.33	1.45	0.48	0.13
4.13	1.62	2.96	4.71	0.48	2.43	0.81	1.00
4.24	1.98		5.03	1.16	2.99	2.69	1.30
	2.56			1.84		2.79	1.56
	2.76			2.22		3.20	1.91
	3.41			2.43		3.46	2.27
	3.91			2.65		3.51	2.42
				3.11		3.65	2.59
				3.41		3.80	2.77
				3.58		3.99	2.85
				3.83		4.07	3.05
				3.96		4.78	3.21
				4.90			3.31
				4.97			3.42
							3.64

The authors are indebted to Mr. L. M. Diana, Mr. K. B. Rhodes, Mr. R. F. Weise, Mr. E. M. Perkins, and Mr. R. A. Barjon for their collaboration in this project.

[9] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

PHYSICAL REVIEW VOLUME 88, NUMBER 6 DECEMBER 15, 1952

Nuclear Energy Levels in the Region of the 28-Neutron Shell*,†

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(Received August 21, 1952)

Energy levels of the titanium nuclei of mass numbers 47, 48, 49, 50, and 51 have been obtained by measuring the ranges of proton groups from the reactions Ti(d,p)Ti. With the use of enriched isotopes, it has been possible to assign thirty observed Q values to their proper reactions. Good agreement was found in most cases in which results of this study could be compared with the results of others.

The data have been analyzed in terms of the strong spin-orbit coupling shell model of nuclear structure. A study of the binding energy of each residual nucleus and the energy of its first excited state revealed definite evidence for the existence of a closed shell at 28 neutrons.

I. INTRODUCTION

OF the well-known magic numbers, the evidence for particular stability is poorest in the cases of 20 and 28. Mayer[1] did not expect the shells at 28 neutrons or protons to be strongly marked. Harvey[2] found a change in neutron binding energy of about 1 Mev, but the decrease apparently occurred between 29 and 30 neutrons, rather than between 28 and 29. Collins, Nier, and Johnson[3,4] have reported discontinuities in the binding energy surface at 20 and 28 neutrons and protons.

The known excited states of nuclei have been studied by Pollard[5] and by Scharff-Goldhaber[6] in attempts to observe regularities which might be attributed to shell structure. The most noticeable regularity which has been found is that the energy of the first excited state as a function of the number of protons or neutrons in the nucleus reaches a series of maximum values at closed shells. Figures 1 and 2 are plots of the first excited states which are known for light elements as functions of proton and neutron number. These plots show definite evidence for shell effects at 8 and 20 nucleons. Data of this sort are scare in the regions of the higher magic numbers.

The present investigation is concerned with the expected shell at 28 neutrons; a companion investigation[7] is concerned with the 28-proton shell. The element titanium is particularly suited for this problem since it has stable isotopes containing 24, 25, 26, 27, and 28 neutrons. Analysis of the proton groups from the series of reactions Ti(d,p)Ti allows the study of the binding energies and energy levels of a series of nuclei having a constant number of protons and a continuous series of neutron numbers, 25 through 29. Any effects on the

* Part of a dissertation presented to the faculty of the Graduate School of Yale University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

† Assisted by the joint program of the ONR and AEC.

‡ AEC Predoctoral Fellow.

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[2] J. A. Harvey, Phys. Rev. **81**, 353 (1951).

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[6] G. Scharff-Goldhaber, Phys. Rev. **87**, 218 (1952).

[7] D. C. Hoesterey, thesis, Yale University (1952) (unpublished).