Inelastic Scattering of Protons from Cu^{65}, Ni^{58}, Ni^{60}, and Ni^{62} †

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(Received June 17, 1957)

The Rice Institute 180° magnetic spectrometer was used in measuring the energies of inelastically scattered protons from targets of natural nickel and from targets enriched in the isotopes Ni^{58}, Ni^{60}, Ni^{62}, and Cu^{65}. Energy levels below 3.09-Mev excitation in Ni^{58}, Ni^{60}, and Ni^{62} and below 1.64-Mev excitation in Cu^{65} were determined.

INTRODUCTION

ENERGIES for the first excited states of Ni^{58} and Ni^{60} and for several low-lying states of Cu^{63} have been determined from inelastic proton scattering by Windham *et al.*[1] These authors pointed out that the first excited state of Ni^{60} at 1.330 Mev as compared with the first excited state of Ni^{58} at 1.453 Mev is qualitatively in accord with the shell structure theory for these nuclei. Similarly, the first excited state of Ni^{62} should be lower than the first excited state of Ni^{60}, and the first excited state of Cu^{65} is expected to be lower than the first excited state of Cu^{63}. In order to test the validity of these ideas and to provide a more complete picture of the energy level structure of Ni^{58}, Ni^{60}, Ni^{62}, and Cu^{65}, spectra of inelastically scattered protons from these nuclei were observed.

EXPERIMENTAL PROCEDURE

Energy levels in Ni^{58}, Ni^{60}, Ni^{62}, and Cu^{65} were determined by magnetic analysis of inelastically scattered protons. Thin natural nickel foils and evaporated targets enriched in Ni^{58}, Ni^{60}, Ni^{62}, and Cu^{65} were bombarded with protons from the 5.5-Mev Van de Graaff accelerator. The momenta of the scattered protons were determined using a 180° magnetic spectrometer. Ilford nuclear track plates were used to detect the scattered particles. The exposure for each nuclear track plate was approximately 500 microcoulombs of protons incident on the target. The energies of the scattered protons were calculated from their momenta. The bombarding energy for each spectrum was calculated from the energy of an appropriate group of elastically scattered protons. The Q values, or excitation energies, corresponding to groups of inelastically scattered protons were then obtained from the energy of the group and the bombarding energy. Isotopic assignments for the energy levels were made on the basis of the target composition. The spectrometer and related calculational techniques have been described previously.[2]

$Cu^{65}(p,p')Cu^{65}$

Figure 1 is a spectrum taken at a bombarding energy of 4.98 Mev with an enriched Cu^{65} target. In this and in succeeding figures the proton yield has been plotted *versus* the magnetic rigidity, $B\rho$. The percent of isotopic enrichment of the target material and the bombarding energy, E_1, are given in each figure. The enriched isotopes were supplied by the Isotopes Division, Oak Ridge National Laboratory. A scale of the scattered proton energy, E_2, appears at the top of each figure. In Fig. 1 a group of protons corresponding to a state at 0.768 Mev in Cu^{65} appears at a $B\rho$ value of 287 kilogauss-centimeters. Groups of protons corresponding to the state at 0.768 Mev were also observed in spectra

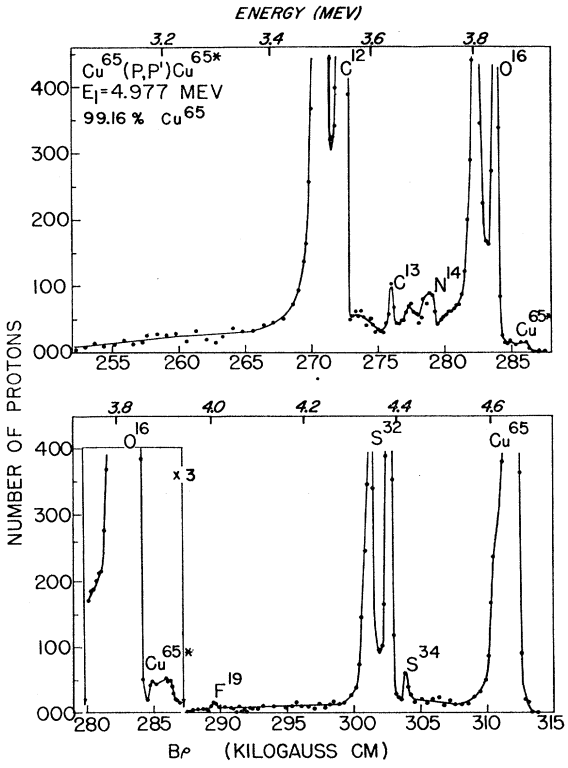

FIG. 1. Partial spectrum of protons scattered from an evaporated target enriched to 99.16% in Cu^{65} and showing the proton group from the state at 0.768 Mev of excitation in Cu^{65}. The scale at the top of each figure gives the energy E_2 of the scattered protons.

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† Supported in part by the U. S. Atomic Energy Commission.

[1] Windham, Gossett, Phillips, and Schiffer, Phys. Rev. **103**, 1321 (1956).

[2] Gossett, Phillips, and Eisinger, Phys. Rev. **98**, 724 (1955).

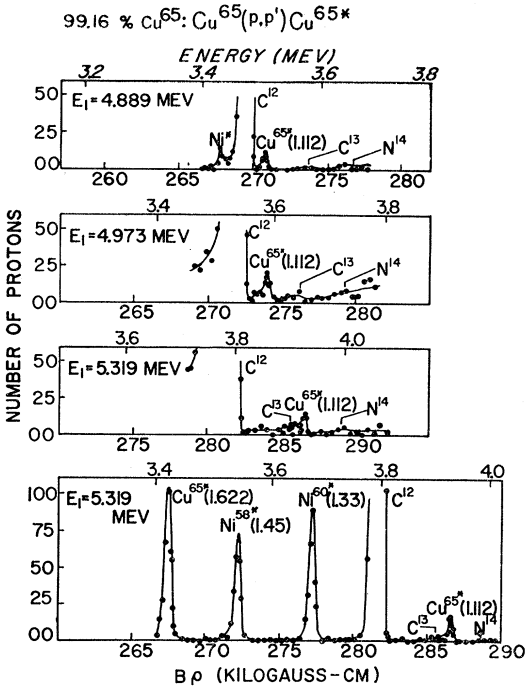

FIG. 2. Partial spectra of protons scattered from an evaporated target enriched to 99.16% in Cu^{65}. The upper three spectra are those used to identify the state at 1.112 Mev of excitation. The lower spectrum shows a proton group from the state at 1.622 Mev.

taken at 5.1-Mev and 5.39-Mev bombarding energies (not shown). Since elastic groups from contaminants of carbon, nitrogen, and oxygen obscured a large portion of the region of interest in these spectra, it was necessary to take a series of partial spectra at several slightly different bombarding energies as in Fig. 2. A group of protons corresponding to the excitation of Cu^{65} to 1.112 Mev was identified by its shift in energy due to a change in the bombarding energy. In addition, a group from a state at 1.622 Mev in Cu^{65} is quite evident in the last of the spectra of Fig. 2. Groups from the states at 1.112 Mev and 1.622 Mev also appeared in the 5.1-Mev spectrum.

Ni(p,p')Ni

In previous inelastic proton experiments[3] using natural nickel targets, a number of proton groups were observed that were determined to be due to excited states above 2-Mev excitation in isotopes of nickel. An additional proton group was observed which was presumed to correspond to the first excited state of Ni^{62} at about 1.17-Mev excitation. Subsequent experiments employing enriched isotopes have made possible specific isotopic assignments for these states. Additional states in nickel were also determined and assigned to particular isotopes.

Figure 3 shows three spectra that were taken at

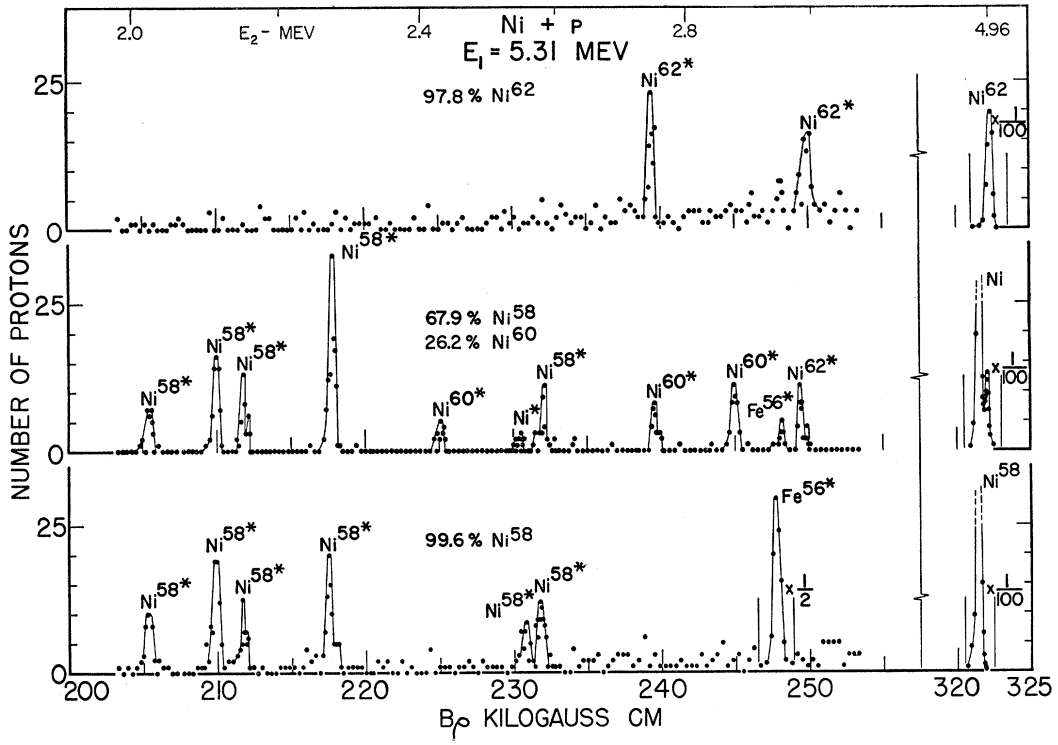

FIG. 3. Partial spectra of protons scattered from targets of nickel oxide enriched to 97.8% in Ni^{62} and nickel oxide enriched to 99.6% in Ni^{58} and evaporated on carbon foils, and a natural nickel foil. Protons from excited states above 2.0 Mev in nickel are shown. The scale at the top gives the energy E_2 of the scattered protons.

[3] Spencer, Phillips, Schiffer, and Young, Bull. Am. Phys. Soc. Ser. II, 1, 95 (1956).

5.31-Mev bombarding energy. The region of excitation in nickel explored in these spectra is from 2.0 to 3.09 Mev. Ni^{62} and Ni^{58} enriched nickel oxide were evaporated onto carbon foils and were used as targets for the upper and lower spectra, respectively, while the center spectrum was taken with a 4 micro-inch natural nickel foil. Spectra covering this same region of excitation were taken at a bombarding energy of 5.0 Mev with these targets. These spectra showed no new proton groups which could be attributed to states in nickel. The lower spectrum in Fig. 4 was taken using a target of nickel oxide with enrichment in the Ni^{60} isotope. The region of excitation covered in this spectrum is from 2.0 Mev to 2.96 Mev. Groups from four excited

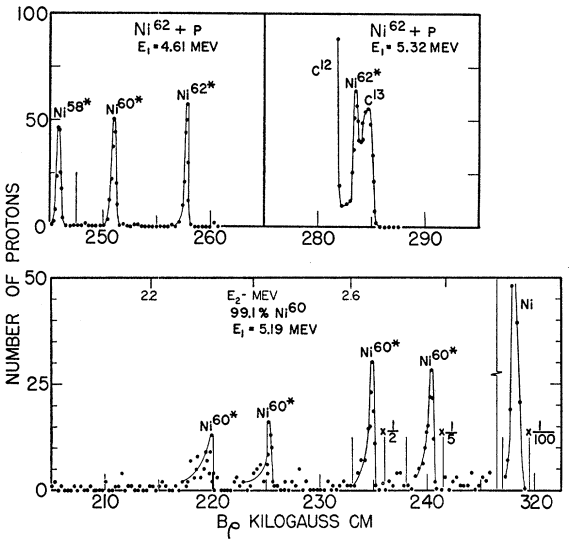

FIG. 4. Upper left: partial spectrum of protons scattered from a target of nickel oxide enriched to 97.8% in Ni^{62} and evaporated on a natural nickel foil. Protons from the first excited states of Ni^{58}, Ni^{60}, and Ni^{62} are shown. Upper right: partial spectrum of protons scattered from a target of nickel oxide enriched to 97.8% in Ni^{62} evaporated on a carbon foil. A group of protons from the first excited state in Ni^{62} is superposed on the elastic group from C^{13}, Below: partial spectrum of protons scattered from a target of nickel oxide enriched to 99.1% in Ni^{60} evaporated on a carbon foil. Protons from states above 2.0 Mev in Ni^{60} are shown.

states in Ni^{60} appear. The upper right-hand spectrum was taken with a target of enriched Ni^{62} oxide evaporated onto a carbon foil. A proton group from the first excited state of Ni^{62} is superposed on the C^{13} elastic group. The upper left-hand spectrum of Fig. 4 was taken while using a target of enriched Ni^{62} oxide evaporated onto a natural nickel foil. This spectrum shows the first excited states of Ni^{62}, Ni^{60}, and Ni^{58}. The same target was used to investigate the region of excitation from 0 to 1.17 Mev, but no proton groups were observed which could not be attributed to contaminants. Spectra have also been taken using targets enriched in Ni^{62} and

TABLE I. Observed energy levels.

Isotope	Mean energy of state and estimated error (Mev)	Number of determinations
Cu^{65}	0.768±0.004	3
	1.112±0.004	5
	1.622±0.005	2
Ni^{58}	1.453±0.004[a]	10
	2.456±0.007	5
	2.483±0.010	1
	2.779±0.004	6
	2.905±0.004	4
	2.945±0.005	2
	3.041±0.004	4
Ni^{60}	1.330±0.004[a]	7
	2.161±0.005	7
	2.287±0.004	6
	2.512±0.010	1
	2.629±0.006	5
Ni^{62}	1.172±0.004	4
	2.047±0.004	3
	2.304±0.005	2

[a] Includes the values given by Windham *et al.*

Ni^{58} covering the region of excitation from 1.46 Mev to 2.0 Mev. No proton groups were observed in these spectra.

DISCUSSION

The energy levels of Cu^{65}, Ni^{58}, Ni^{60}, and Ni^{62} that were observed in these experiments are listed in Table I. The energy values given there are an average of all the determinations made at this laboratory including the results of Windham *et al.*[1] In addition, the number of determinations for each energy level is given.

The state at 2.161 Mev in Ni^{60} is in agreement with the value reported by Wolfson[4] from analysis of γ rays following the decay of Co^{60}. Except for the 2.483-Mev state in Ni^{58}, all of the states in Ni^{58} and Ni^{60} are in agreement with a recent report of Paris and Buechner.[5] These authors did not observe a state near 2.483 Mev in Ni^{58}.

It is interesting to notice that the relative positions of the first excited states of Ni^{58}, Ni^{60}, and Ni^{62} are as expected from the shell theory whereas the relative positions of the first excited states of Cu^{63} and Cu^{65} are not as expected. Although elastic groups of protons from contaminants hampered the analysis of the data in the low-lying region of excitation in Cu^{65}, it is felt that an excited state of energy less than the 0.768-Mev state in Cu^{65} could have been observed if its cross section at the bombarding energies used were greater than 1% of the elastic cross section for proton scattering from Cu^{65}.

[4] J. L. Wolfson, Can. J. Phys. **33**, 886–888 (1955).
[5] C. H. Paris and W. W. Buechner, Bull. Am. Phys. Soc. Ser. II, **2**, 61 (1957).