PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Level Structure of Ni^{64} and Zn^{64}†

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(Received 26 November 1962)

The energy spectra of inelastically scattered protons that lead to excited levels in Ni^{64} and Zn^{64} were measured at incident proton energies of 9.6 and 11.7 MeV. The excitation energies of ten levels of Ni^{64} below 4.4 MeV and fourteen levels of Zn^{64} below 4.7 MeV were measured.

DURING the course of studying proton elastic scattering from Ni^{64} and Zn^{64}, spectra of inelastically scattered protons were also measured. These spectra showed the existence of several energy levels that have not been reported in the published information[1–15] on the level structure of these nuclei. Except for reference 15, most of this information is summarized in the compilation of Way *et al.*[16] The energies of the first excited states appear to be well established at 1.34 and 0.99 MeV, respectively, for Ni^{64} and Zn^{64}. The excitation of only one additional level (at 3.83 MeV) has been reported for Ni^{64}. Levels of Zn^{64} at 1.78, 2.29, ~3.0, 3.2, and 3.3 MeV are included in the compilation of Way *et al.*[16] Recently, additional Zn^{64} levels at 3.8, 4.15, 4.7, and 5.2 MeV have been measured in the (α,α') work of Broek *et al.*[15]

In the work reported here, excitation energies of 10 levels of Ni^{64} and 14 levels of Zn^{64} were measured in (p,p') experiments. Measurements were made at several scattering angles and two bombarding energies to provide corroboration for our conclusions.

These experiments were performed with the external proton beam of the variable-energy cyclotron of the Lawrence Radiation Laboratory at Livermore. The report of the elastic scattering data[17] contains a detailed description of the experimental arrangement. A brief description is given here.

The proton beam from the cyclotron is magnetically analyzed, focused, and collimated to a diameter of $\frac{1}{8}$ in. After traversing a 40-in.-diam scattering chamber, it is collected in a Faraday cup which monitors the beam. At the center of the scattering chamber there is an eight-position target changer that is remotely controlled. Within the scattering chamber is a rotatable table with provisions for precisely mounting a detector. The table is remotely rotated and the angular position is indicated in the control room, with a precision of ± 0.1 deg.

Adjacent to the entrance to the collimator and separated from it by 0.030 in. is another hole. Some of the beam entering this hole is scattered 90°, passes through a variable absorber, and then into a double proportional counter. An anticoincidence circuit is used to make a differential range measurement of the scattered beam with a precision of about 1%. Immediately back of the proportional counters is a scintillation detector consisting of a CsI crystal and photomultiplier tube. After the particle range has been measured, the absorber is reduced enough to allow about 1.5 MeV of proton energy to be deposited in the crystal. Pulses from the photomultiplier tube are fed into a "continuous-energy-monitor" which is a circuit that measures the average height of the input pulses and yields a continuously visible meter reading. Sensitivity checks showed that throughout the course of our runs the incident proton energy was constant within $\pm 0.15\%$.

The targets consisted of self-supporting foils. The Ni^{64} foil was prepared by E. B. Olzewski of the Isotopes Division of Oak Ridge National Laboratory. The Zn^{64} foil was prepared by F. Keresek of Argonne National

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

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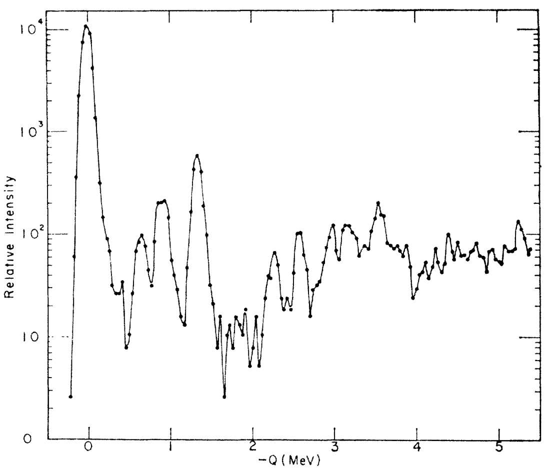

FIG. 1. Energy spectrum of scattered protons from Ni^{64}. The incident proton energy was 9.60 MeV, and the detection angle was 75°. Zero abscissa corresponds to elastically scattered protons from Ni^{64}. The peaks at $-Q\sim0.6$ and ~0.9 MeV are due to protons elastically scattered from oxygen and carbon impurities in the target foil.

Laboratory. The isotopic assay for each of the foils as given by the Isotopes Division of ORNL is as follows:

	Zn^{64}	Zn^{66}	Zn^{67}	Zn^{68}	Zn^{70}
Zn^{64} target	98.5%	1.1%	0.1%	0.3%	<0.1%
	Ni^{58}	Ni^{60}	Ni^{61}	Ni^{62}	Ni^{64}
Ni^{64} target	1.99%	1.20%	0.14%	0.77%	95.9%

The thickness of the Zn^{64} target was 4.94 mg/cm^2. The Ni^{64} target was visibly nonuniform in thickness; the thickness was about 5 mg/cm^2. The data were obtained with the targets fixed at 45° to the beam.

Scattered particles from the targets were detected by a telescope that consists of a silicon *p-n* junction diode preceded by a gas proportional counter with off-set center wire. Pulses from the gas proportional counter (dE/dx pulses) and from the silicon counter (E pulses) are fed into a pulse multiplier network. The output pulses of the latter identify the detected particle as a proton, deuteron, or alpha particle. Multiplier pulses produced by protons were used to gate a multichannel analyzer which recorded the proton spectra. The silicon counter is thick enough to stop 13-MeV protons. Although this detector is capable of yielding 1% resolution, the overall energy resolution observed in these experiments was 1.5 to 2.5%, contributed in large part by the target thickness. This meant that the most useful spectra were obtained by transmission scattering (i.e., scattering at angles forward of 90°).

A typical spectrum obtained from Ni^{64} is shown in Fig. 1 and one obtained from Zn^{64} is shown in Fig. 2. For Figs. 1 and 2 the raw pulse-height data were transformed to corrected energy spectra by the aid of a program called CONDAC[18] and an IBM 7090 computer. The abscissa of a given peak indicates the excitation energy of the corresponding level. Excitation energies for the levels of the two isobars were determined from the averages of values obtained at several angles where the respective peaks were most prominent.

The method by which the excitation energies were actually calculated is a comparison technique which was fully described in a previous report.[19] In addition to Ni^{64} and Zn^{64} data, spectra were obtained from a Mylar film target at each detection angle. These data served to identify the peaks in the Ni^{64} and Zn^{64} data that are due to oxygen and carbon in metallic foils and to provide an energy calibration of the detector.

The energies of the scattered protons that resulted from excitation of the well-known states of C^{12} and O^{16} were calculated from the kinematics of the reactions. Pulse height vs proton energy values were thus derived from data obtained from the Mylar target at several detection angles; the results were plotted to yield a calibration curve. Use of the calibration curve makes it unnecessary to correct for energy loss of the detected particle in the foil and proportional counter ahead of the solid state detector.

The excitation energies of several states in Ni^{64} and Zn^{64} were determined by use of a relation[20] that is derived from the well known Q-value equation. The energy E of the scattered proton in the laboratory system is given by

$$E^{1/2}=v+(v^2+\omega)^{1/2},$$

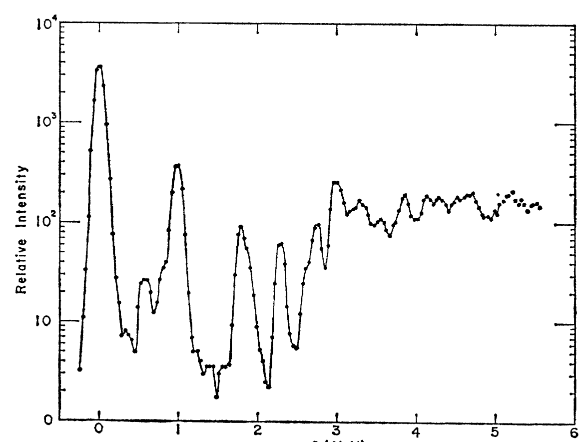

FIG. 2. Energy spectrum of scattered protons from Zn^{64}. The incident proton energy was 9.60 MeV, and the detection angle was 70°. Zero abscissa corresponds to elastically scattered protons from Zn^{64}. The peak at ~0.6 MeV is due to oxygen impurity; the hump on the low-energy side of the 1-MeV peak is due to carbon impurity in the target foil.

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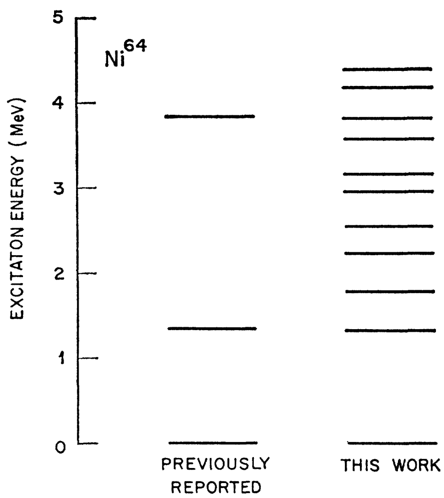

FIG. 3. Energy levels of Ni^{64}. For the compilation of K. Way *et al.* (see reference 16).

where

$$v=(E_1)^{1/2}/(1+A)\cos\theta_{\rm lab},\quad \omega=AQ+E_1(A-1)/(1+A).$$

E_1 is the bombarding energy in the laboratory system and A is the mass of the target nucleus. E is determined from the calibration curve after the pulse-height channel of the peak is obtained. At each angle a value of v is calculated and a corresponding value of ω is derived from

$$\omega=E-2vE^{1/2}.$$

Thus, an independent measurement of Q is obtained at each angle of observation.

The use of the calibration curve to determine the energies of the scattered protons is tantamount to comparing the excitation energies of the levels of Ni^{64} and Zn^{64} with the energies of the well-known states in carbon and oxygen. It is necessary, however, that corrections be made for the differences in energy loss in the Ni^{64} and Zn^{64} target foils and in the Mylar film.

The excitation energies of levels of Ni^{64} that were measured in our experiments are given in Table I for data obtained with 9.6- and 11.7-MeV bombarding energies. Similar results for Zn^{64} are given in Table II.

TABLE I. Excitation energies of Ni^{64} levels in MeV.

Level No.	9.60-MeV data	11.7-MeV data
1	1.33±0.02	1.34±0.02
2	1.79±0.03	1.88±0.10
3	2.24±0.03	2.30±0.06
4	2.56±0.02	2.60±0.04
5	2.94±0.02	2.93±0.06
6	3.13±0.02	3.15±0.04
7	3.53±0.02	3.55±0.02
8	3.79±0.03	
9	4.17±0.05	
10	4.38±0.05	

TABLE II. Excitation energies of Zn^{64} levels in MeV.

Level No.	9.60-MeV data	11.7-MeV data
1	0.98±0.02	0.99±0.02
2	1.78±0.02	1.77±0.03
3	1.92±0.24	1.91±0.04
4	2.28±0.02	2.31±0.03
5	2.59±0.03	2.62±0.05
6	2.73±0.02	2.74±0.05
7	2.98±0.02	3.03±0.05
8	3.27±0.03 (double level)	
9	3.53±0.02	
10	3.84±0.02 (double?)	
11	4.12±0.02	
12	4.27±0.03	
13	4.49±0.03	
14	4.66±0.05 (multiple)	

The values shown represent the averages of Q values obtained from data at several detection angles.

The levels reported here for Ni^{64} are compared graphically with published results in Fig. 3. The levels for Zn^{64} are compared with published results in Fig. 4. In addition, our Zn^{64} level structure results are compared in Fig. 4 with the recent (α,α') work of Broek *et al.*[15]

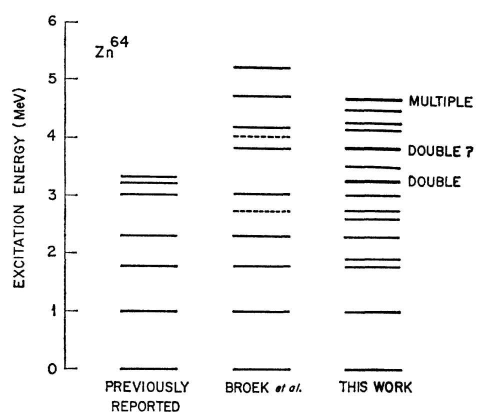

FIG. 4. Energy levels of Zn^{64}. For the compilation of K. Way *et al.* (see reference 16); for the work of H. W. Broek *et al.* (see reference 15).

The levels that we observe at about 1.90 MeV and at about 2.60 MeV in Zn^{64} are not reported by Broek *et al.* This may be attributed to the better energy resolution in the proton work reported here. Evidence for levels at 3.27 and 3.53 MeV, which are not observed in the (α,α') work, is seen in Fig. 2. We observe no evidence for the uncertain level at 4.0 MeV that was reported by Broek *et al.*

The excitation energies of only two levels have been previously reported for Ni^{64}. Our results are in good agreement with the well-established excitation energy of 1.34 MeV for the first excited level and in reasonable agreement with the previously measured excitation energy for the level near 3.8 MeV. Our data determine the excitation energies of eight additional levels in Ni^{64} below 4.4 MeV.