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# POLARIZATION STUDY FOR ISOBARIC ANALOG RESONANCES IN $^{62}$Ni (p,p) $^{62}$Ni

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## ABSTRACT

Polarization excitation functions of protons elastically scattered from $^{62}$Ni at a laboratory angle of 50° have been measured in the energies between 2.43 and 2.75 MeV by using the double-scattering techniques. Differential cross sections also have been measured at the laboratory angles of 140° and partly 160°. Four analog resonances corresponding to the ground, the first, the second, the third excited states in the parent nucleus of $^{63}$Ni were observed. The spins of $p_{1/2}$, $f_{2/5}$, $p_{3/2}$ and $p_{1/2}$ were assigned to these states, respectively.

## 1. Introduction

It is well known that isobaric analog resonances in the compound nucleus can be produced by the elastic scattering of protons from various target nuclei[1]. If the target spin is zero, the excitation functions measured at suitably chosen angles will yield the assignments of the l-values of the resonances. Also the values of the total spin j can be found by the observation of polarization excitation functions at appropriate angles and the polarization angular distribution near the resonance energy;[1,2] that is, the variation of the polarizations will clearly differentiate between $l+1/2$ and $l-1/2$, since the polarization is produced only with the interference between the resonance and some background amplitude.[3] Therefore, the polarization measurements of protons elastically scattered from spin zero target have been carried out with the polarized proton beam[4~8] and with double scattering techniques.[9~12]

The individual states of $^{63}$Ni have been observed with $^{62}$Ni (d, p) $^{63}$Ni reaction by R.H. Fulmer and A.L. McCarthy.[13] They have reported the ground, the second and the third excited states to have the (d, p) angular distribution characteristic of a $l=1$ orbital angular momentum transfer and the first excited state to have that of a $l=3$ orbital angular momentum transfer. Usually, the total angular momentum j of these states cannot be determined directly from the (d, p) reaction. However, the observation of j-dependent effects in the (d, p) stripping reactions has shown that the ground state of $^{63}$Ni has the spin $1/2^-$ and the second and the third excited states have the spin $3/2^-$.[14] From a simple shell model point of view, the first excited state may have the spin $5/2^-$.

Previously,[15] the isobaric analog states in the compound nucleus $^{63}$Cu have been studied on the cross section excitation functions for the reaction $^{62}$Ni (p, p). The analog resonances of the ground state and the second excited state of $^{63}$Ni were observed and these resonances had a $l=1$ orbital angular momentum.

Recently, differential cross section excitation functions were measured at laboratory angles of 90°, 120°, 135°, and 160° by J.C. Browne, et al.[16] They observed the fine structure of isobaric analog resonances. They reported that the isobaric analog resonances measured by C. Gaarde et al. consisted of many $T_<$-resonances and $T_>$-resonances, and the ground, the second and the third excited states of $^{63}$Ni would have the spin $p_{1/2}$, $p_{3/2}$ and $p_{1/2}$, respectively.

In the present work, the measurements of the polarization excitation functions for the reaction $^{62}$Ni (p, p) $^{62}$Ni have been done with the double-scattering techniques in the energy range from 2.43 to 2.75 MeV of incident protons and at the energies around 3.0 MeV. The level schemes and reaction routes considered here are illustrated in Fig. 1.

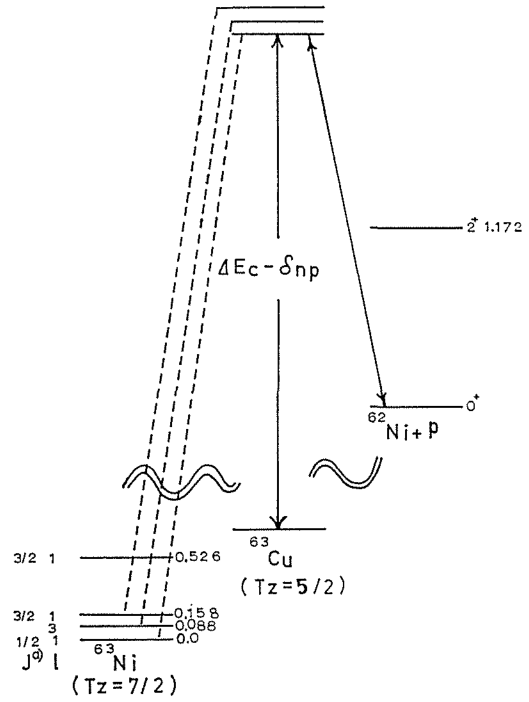


Fig. 1. Level schemes and reaction routes considered in the present experiment. The lower states in $^{63}$Ni are connected by dashed lines to their isobaric analog states in $^{63}$Cu. a) ; see Ref. 14.
$\delta_{np}$=(neutron binding energy)−(proton binding energy).

The purposes of this paper are the determination of spins and parities for 'parent states' in $^{63}$Ni, which correspond to the highly excited states in $^{63}$Cu, and to study that the state corresponding to a weak resonance in the elastic scattering excitation functions can be observed definitely by the measurements of polarization excitation functions and the polarization angular distribution.[5]

## 2. Experimental Procedure

The proton beam used in this studies was produced by the Tandem Van de Graaff accelerator at Kyoto University.[17] The beam was analyzed with 90° bending magnet and was focussed through a 3 mm-diam. collimating aperture onto a thin nickel target. After passing through the target, the beam was collected in a Faraday cup. A beam intensity of about 70 nA was maintained and an integrated beam current of 100 $\mu$c$\sim$300 $\mu$c was collected for each datum point.

The beam energy was calibrated by using the $^{27}$Al (p, n) threshold energy. The uncertainty in this calibration was about 9 keV, which was caused by changing of the beam path.

The self-supporting metalic foil target of the separated nickel isotope–62 was prepared by an electroplating method. The thickness of the target was determined by a balance and by the measurements of elastic scattering yields at the several off-resonance energies. At these energies the cross sections were assumed to arise from pure Rutherford scattering. The measured thickness of the target was $0.223 \pm 0.002$ mg/cm$^2$. This thickness corresponded to the energy loss of approximately 15 keV at the proton energy of 2.50 MeV. The target was always placed perpendicular to the incident beam. Scattered protons were detected by a 0.5 mm thick silicon surface barrier detector.

The electronic systems used in the measurements of both the cross section and the polarization were shown in Fig. 2. It might be possible to use this electronic systems as a multiinput route circuit.

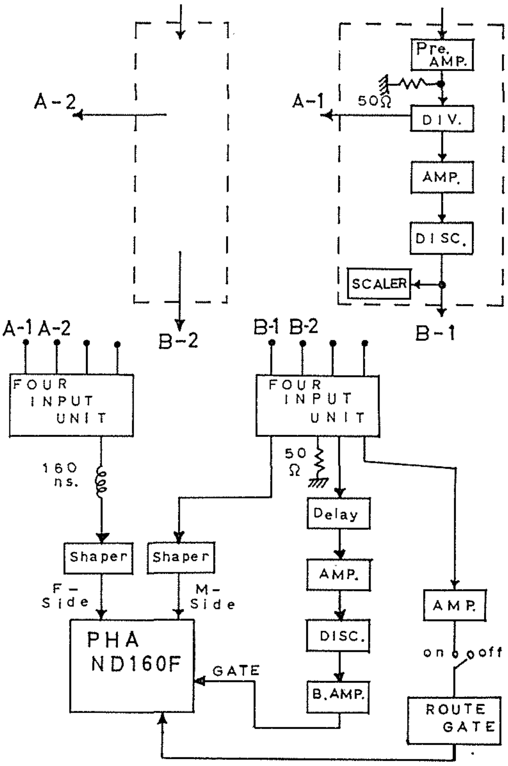


Fig. 2. Electronic systems used in the present experiment.

Excitation functions for the elastic scattering of protons from $^{62}$Ni were measured at the energy step of about 8 keV in the energy regions from 2.43 to 2.73 MeV at the laboratory angles of 140° and partly 160° and the preliminary measurements were done in the energy regions around 3.0 MeV.

The absolute cross sections were determined by lowering the beam energy and by observing the angular distribution at off-resonance energies, where the scattering would arise from the pure Rutherford scattering.

Each datum points represented $2\times10^4$ to $1\times10^5$ counts. The relative experimental errors would be caused by the inhomogenity in target, variation in solid angles when the beam would wander over the target, and small fluctuation in the beam energy as the beam path would be drifted. However, the absolute errors in cross sections would be believed to be smaller than 5%.

The polarization excitation functions were measured in the energy regions from 2.43 to 2.73 MeV at a laboratory angle of 50° by using the double-scattering techniques. The preliminary measurements were also done around 3.0 MeV. The simple calculations had shown that for the $l=3$ and $l=1$ resonances the magnitudes of the polarizations would be large at the angle of 50°. Therefore, the polarizations were measured at the laboratory angle of 50°. Polarization dependences were also measured at the energy near the center of the $l=3$ resonance. These observations were done at the laboratory angles of 50°, 60°, 80° and 130°.

The polarimeter used in the polarization measurements was described in detail in Ref. 18. The geometry of the arrangement was shown in Fig. 3. The important dimension of the system was listed in Table 1. Those were almost the same that was described in Ref. 18.

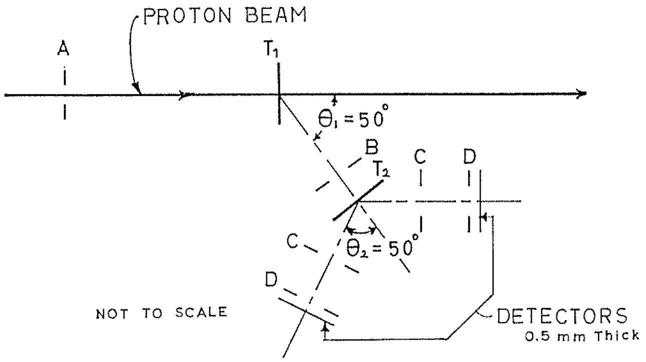


Fig. 3. Schematic drawing of the double scattering apparatus. The important dimensions are given in Table 1.

Table 1. Dimensions for the geometry used in the polarization measurements. All symbols refer to Fig. 3.

| Designation | Size (diameter or width x height) (mm) | Distance from given location (mm) |
|---|---|---|
| A | 3. | 43 from $T_1$ |
| B | $4.0\times4.0$ | 19 from $T_2$ |
| C | $5.0\times10.0$ | 44 from $T_3$ |
| D | $5.0\times10.0$ | |
| $\Delta\theta_1$ | ±2.7° | |
| $\Delta\theta_2$ | ±3.3° | |

These meant that even if there were some contaminants in the second target of the self-supporting carbon foil which was prepared with the thermal cracking method, they produced perhaps no effect on the measured polarizations, since the analyzing power of the polarimeter was the polarization of p–$^{12}$C elastic scattering due to the total contents of the same second target.

In order to cancel and check the geometrical asymmetries of the polarimeter, these measurements were often taken on both sides of the beam, that is, interchanging the roles of the two counters.

The contaminants in the first nickel 62 target would produce an error in the measured asymmetries. Fortunately, we measured the polarizations for $^{62}$Ni (p, p) $^{62}$Ni reaction at a forward angle, where the ratio of the elastic scattering protons from $^{62}$Ni to ones from $^{12}$C and $^{16}$O was very large. Therefore, the contaminants would be contributed to the polarizations only within errors.

## 3. Results and Discussions

Sample pulse height spectra of the double-scattering protons are shown in Fig. 4. As seen in this figure, double scattering protons could be completely separeted from the background of $\gamma$-rays or neutrons.

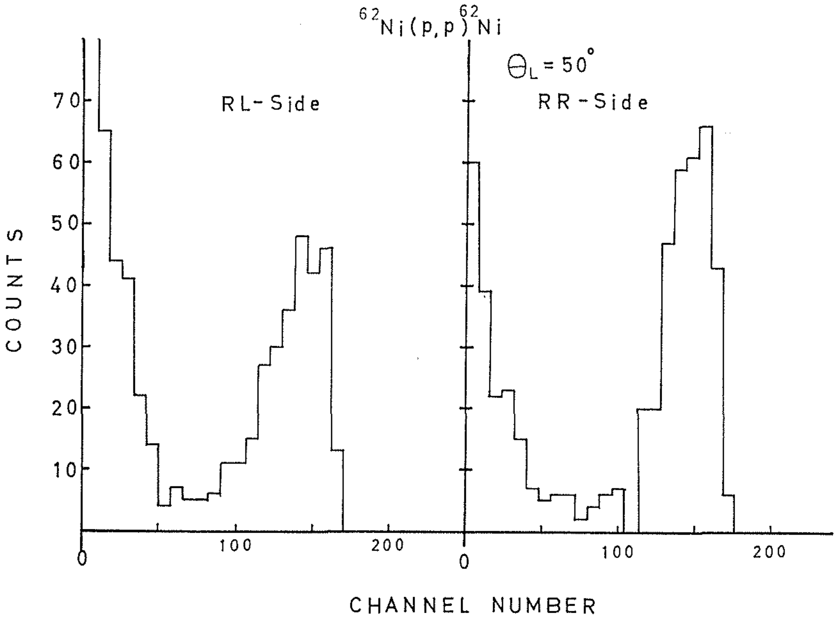
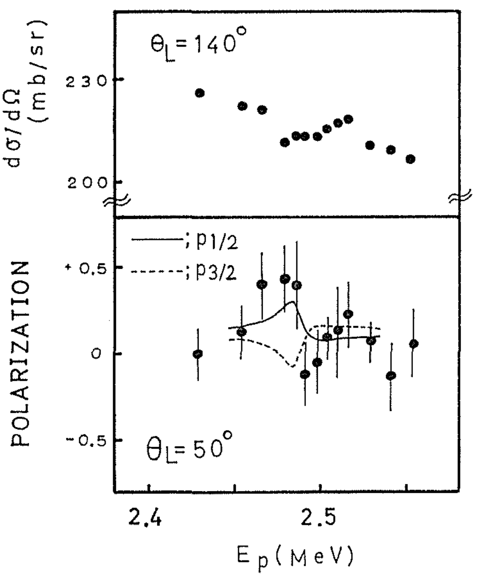


Fig. 4. Sample pulse-height spectra of protons doubly scattered from $^{62}$Ni and $^{12}$C at a laboratory angle of 50°.

In Figs. 5, 6 and 7, the differential cross-sections measured at laboratory angles of 140° and partly 160° and the polarization excitation functions are shown. The polarization angular distribution at 2.57 MeV is shown in Fig. 8. The errors indicated are statistical errors only and are not accounted for the errors arising from the instrumental asymmetries.



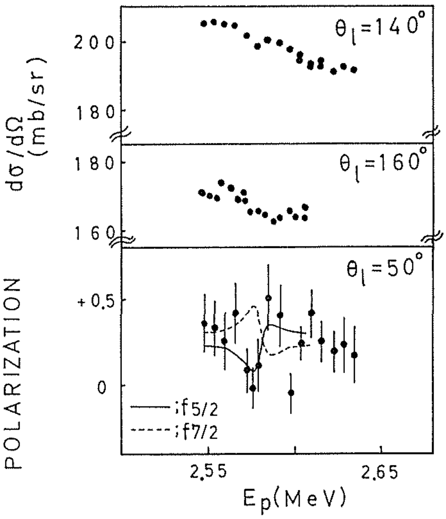
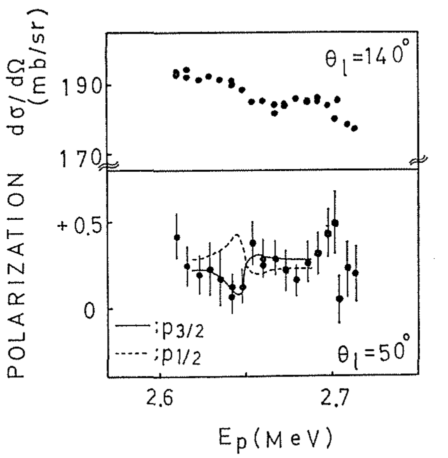


Fig. 5. Excitation functions of polarizations and differential cross sections. The solid line and the dashed line represent a preliminary calculation described in the text.

Fig. 6. Excitation functions of polarizations and differential cross sections. The curves represent a preliminary calculation.



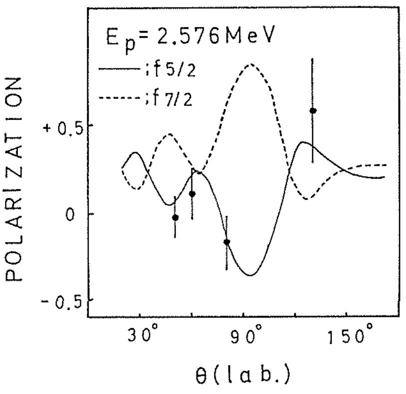


Fig. 7. Excitation functions of polarizations and differential cross sections. The lines represent a preliminary calculation.

Fig. 8. Polarization angular distribution. The solid curve and the dashed curve represent a preliminary calculation.

As seen in Figs. 5, 6 and 7, the resonance-like patterns are shown at the energies near 2.48, 2.58, 2.60, 2.65 and 2.70. At the energies near 3.0 MeV, two resonance-like patterns may be seen. These patterns would correspond to the isobaric analog resonances and $T_<$-resonances.

For the elastic scattering of protons by spin zero nuclei the differential cross sections and the polarizations can be expressed in terms of the coherent and incoherent scattering amplitudes.2),19)

To make spin assignments from the present result the preliminary calculation was done on the following conditions;

1) Neglect the optical phase and the resonance phase.
2) Not considering the contributions from the $T_<$-resonances and the effects of the fine structures for $T_>$-resonances.16)
3) Not taking in the thickness of the nickel target and the angular spread.
4) Assuming that the total width was equal to the elastic partial width15) since these resonance energies lay below the neutron threshold energy of 4.71 MeV and then the compound nucleus decay proceeded to the elastic scattering channel mainly.

The resonance energies used for the corresponding calculations were 2.442, 2.533 and 2.602 MeV for the resonances near 2.48, 2.58 and 2.65 MeV respectively.

Now the polarizations measured in this studies and/or the calculated results might be shifted only by a constant value. It, however, would not be believed that the shape of the polarization excitation functions would be changed. Therefore, the assignment of the total spin would be possible. In Figs. 6, 7 and 8, the preliminary calculations which are shown with the solid and dashed lines are shifted by a constant value of 0.26. This value corresponds to the asymmetry of 0.055.

### 3-1 On the resonances near 2.48 and 2.65 MeV.

As seen in Figs. 5 and 7, polarization excitation functions measured at the laboratory angle of 50° showed the resonance patterns at the energies near 2.48 MeV and 2.65 MeV.

These resonances were previously observed on the excitation functions of protons elastically scattered from the $^{62}$Ni target by C. Gaarde et al.,15) T. Hasegawa et al.20) and J.C. Browne et al.16) According to C. Gaarde et al. and T. Hasegawa et al., these resonances seems to have the $1=1$ orbital momenta. By using the beam with high resolution, J.B. Browne et al. indicated that many $s_{2/1}$ resonances and $p_{1/2}$ or $p_{3/2}$ resonances were included in these two analog resonances measured previously. Therefore, the resonances investigated in the present work were also interpreted in terms of the gross resonances.

The orbital angular momentum of the captured neutron was obtained by the study of the $^{62}$Ni (d, p) $^{63}$Ni stripping reaction,13) which showed that the ground and the second excited states in $^{63}$Ni had a $1=1$ orbital angular momentum. The spins of the ground and the second excited states in $^{63}$Ni have been assigned $1/2^-$ and $3/2^-$, respectively, by the (d, p) j-dependences obtained by Schiffer.14)

The polarization excitation functions are not contributed from the $s_{1/2}$-resonances. Therefore, assuming that only the $1=1$ orbital angular momentum contributed the polarization effect, the preliminary calculation was done.

As seen in Figs. 5 and 7, the shapes of polarization excitation functions have agreed with the shapes calculated for $p_{1/2}$ and $p_{3/2}$. Therefore, the resonances near 2.48 and 2.65 NeV would have the spins $p_{1/2}$ and $p_{3/2}$, respectively. These resonances would be the analog resonances of the ground and the second excited states in $^{63}$Ni.

These results have agreed with those obtained by J.C. Browne et al.16) and those of (s, p) j-dependences mentioned above.14)

### 3-2 On the resonance near 2.58 MeV

As seen in Fig. 6, the polarization excitation functions showed the resonance pattern at the energy near 2.58 MeV. The resonance near 2.48 MeV was the analog resonance of the ground state in $^{63}$Ni. Therefore, this resonance would be considered to be the analog resonance of the first excited state of 0.088 MeV in the parent nucleus of $^{63}$Ni. The $^{62}$Ni (d, p) $^{63}$Ni angular distribution[13] showed that the first excited state in $^{63}$Ni had the $l=3$ orbital angular momentum. Therefore, assuming that the only $l=3$ orbital angular momentum contributed the polarization effect, the preliminary calculation was done for this resonance.

As seen in Figs. 6 and 8, the shapes of the polarization excitation functions and the polarization angular distribution have agreed with the shape calculated for $f_{5/2}$. These indicate that the resonance near 2.58 MeV would have the spin $f_{5/2}$ and would be the analog resonance of the first excited state in $^{63}$Ni, that is, the first excited state in $^{63}$Ni would have the spin $5/2^-$.

Although the excitation functions were measured, the resonance near 2.58 MeV were not explicitely observed. In this energy region, the proton penetrabilities for $l=3$ were so small that the analog resonances could not almost be observed in the cross sections.

This fact shows that the measurements of the polarizations are a sensitive test of the total spin j-value, that is, the weak resonance and the resonance hindered from non-resonance part can be easily investigated by the measurements of the polarizations.

### 3-3 On the other resonance near 3.0 MeV

The measurements of the polarization excitation functions at the energy regions around 3.0 MeV have been done.

The excitation functions measured by T. Hasegawa et al.[20] have shown that the $l=1$ resonance lies in this energy regions. Therefore, assuming that only the $l=1$ orbital angular momentum contributed the polarization effect, the preliminary calculation has been done.

As seen in Fig. 9, the resonance near 3.0 MeV would have the spin $p_{1/2}$. The $p_{1/2}$ resonance would be an analog resonance of the third excited state of 0.526 MeV in $^{63}$Ni. Therefore, this state would have the spin 1/2 from our experimental results although the (d, p) j-dependences[14] have shown that the third excited state have the spin $3/2^-$. Our result has agreed with that obtained by J.C. Browne et al.[16]

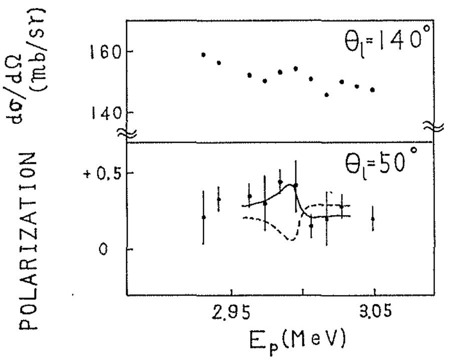


Fig. 9. Excitation functions of polarizations and differential cross sections. The solid line and the dashed line represent the curves for $p_{1/2}$ and $p_{3/2}$ patterns, respectively.

### 3-4 Coulomb displacement energies

The coulomb displacement energy $\Delta$Ec between the analog state and the parent state are given by the relation ship

$$\Delta \mathrm{Ec} = \mathrm{Ep} + \mathrm{Q}_{\mathrm{dp}} + 2.225 \text{ (MeV)},$$

where Ep is the center-of-mass proton energy at which the analog resonance in the nucleus (N, Z+1) occurs, $\mathrm{Q}_{\mathrm{dp}}$ is the (d, p) reaction Q-value, and 2.225 MeV is the deuteron binding energy.

The results are shown in Table II with other results[15),16)] and compared with $\Delta$Ec value computed using the empirical relation of Long et al.[21)]

$$\Delta \mathrm{Ec} = \mathrm{B}_1 + \mathrm{B}_2 \cdot \mathrm{Z} \cdot (\mathrm{A})^{-1/3}$$

where $\mathrm{B}_1 = -1.032$, $\mathrm{B}_2 = 1.448$, Z and A are charge and mass numbers for the parent nucleus.

Table 2. The Coulomb displacement energies $\Delta \mathrm{E}_{\mathrm{c}}$ and comparison with the other results.

| $Q_{\mathrm{dp}}$ (MeV) | $(p,n)$-Threshold (MeV) | $E_{\mathrm{pc.m.}}$ (MeV) | $l$ | $j$ | $E_{\mathrm{x}}$ (MeV) | $\Delta E_{\mathrm{c}}{}^{\mathrm{d)}}$ (MeV) | $\Delta E_{\mathrm{c}}{}^{\mathrm{a)}}$ (MeV) | $\Delta E_{\mathrm{c}}{}^{\mathrm{b)}}$ (MeV) | $\Delta E_{\mathrm{c}}{}^{\mathrm{c)}}$ (MeV) |
|---|---|---|---|---|---|---|---|---|---|
| 4.6149 | 4.71 | 2.44 | 1 | 1/2 | 0.0 | 9.28±0.012 | 9.30±0.01 | 9.28±0.01 | 9.21 |
| | | 2.53 | 3 | 5/2 | 0.088 | 9.29±0.012 | | | |
| | | 2.60 | 1 | 3/2 | 0.158 | 9.29±0.012 | 9.32±0.01 | 9.29±0.01 | |

a) See Ref. 14).
b) See Ref. 15).
c) See Ref. 20). the empirical relation of Long et al.
d) present experiment.

As seen in Table II, the measured coulomb displacement energies agree with those predicted by the relation of Long et al. and other results within errors. Errors include the thickness of the target, the uncertainty of beam energy and the resonance energy.

## 4. Conclusions

The resonances studied in this paper would be the analog resonances of the ground, the first, the second and the third excited states in the parent nucleus of $^{63}$Ni. The spins of the isobaric analog resonances near 2.48, 2.58 and 2.65 MeV would be assigned $\mathrm{p}_{1/2}$, $\mathrm{f}_{5/2}$ and $\mathrm{p}_{3/2}$, respectively. The analog resonance of the third excited state might be considered to have the spin $\mathrm{p}_{1/2}$. The spins of the ground and the second excited state would agree with the results investigated with the (d, p) j-dependences[14)] but the spin of the third excited state would not agree with those. However, the spins of these states would agree with the results obtained by J.C. Browne et al.[16)]

One of the interesting features is the result that the spin assignment via polarization excitation functions and polarization angular distributions could have been made even if the resonances had been weakly seen and hindered from nonresonance parts in the elastic channel. Therefore, by using the good polarized proton beam and the beam with high resolution, such resonance parameters as the total width, the elastic partial width and the resonance phase would be easily determined.

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