EXCITED STATES OF ^{64}Zn

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Summary

The reaction ^{63}Cu(p,n)^{63}Zn has been studied at bombarding energies between 5 and 11·5 MeV using an activation technique with good energy resolution. Previously unknown levels in ^{64}Zn at excitation energies of approximately $13\cdot3_7$, $13\cdot7_5$, $14\cdot1_2$, $14\cdot3_1$, $14\cdot9_0$, $15\cdot1_8$, $15\cdot6_1$, and $15\cdot7_7$ MeV have been found. It is shown that six of these levels, and the observed absence of levels in some energy regions, can be accounted for in terms of Nilsson's calculations for the single-particle states of a deformed nucleus. If this interpretation is correct, the deformation of ^{64}Zn must be negative, at least in its highly excited states.

I. Introduction

In previous studies of the cross section for the reaction ^{63}Cu(p,n)^{63}Zn (Blaser *et al.* 1950; Ghoshal 1950; Howe 1958) the measurements have not been made with any high degree of precision. The principal limitations on accuracy have been due to the use of targets several hundred keV thick and the lack of a suitable source of variable-energy protons. In all the previous experiments the technique of stacked foils has been used. The results obtained have shown a smooth variation of cross section with bombarding energy above 5 MeV. As a result, it was concluded that the levels of ^{64}Zn are numerous and closely spaced, as suggested by compound nucleus theory.

In the present experiment, the yield curve for the reaction has been obtained with considerably increased resolution. The results show that discrete levels in ^{64}Zn are observable at excitation energies above 13 MeV.

II. Experimental Details

It is not convenient to study the reaction by means of neutron counting, since the presence of 30% of ^{65}Cu in natural copper results in neutrons from the reaction ^{65}Cu(p,n)^{65}Zn. The number of neutrons produced by this competing reaction is comparable to the number produced by the ^{63}Cu reaction. Both ^{63}Zn and ^{65}Zn are radioactive, decaying by positron emission to ^{63}Cu and ^{65}Cu. Since the half-life of ^{63}Zn is 38·4 min while that of ^{65}Zn is 256 days, the two decays can be easily separated. In consequence, a measurement of the activity of a copper foil after proton bombardment affords a convenient method for studying the ^{63}Cu(p,n)^{63}Zn reaction. This method has been used for the present experiment.

Twenty copper foils of thickness 2·8 mg cm^{-2} were used. These foils have a half-thickness of 60 keV at 5 MeV and 35 keV at 11·5 MeV. The relative

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thickness of the targets was accurately determined by bombarding them all with protons of the same energy. This calibration was repeated for several proton energies.

The extracted proton beam of the Melbourne University Variable Energy Cyclotron (MUVEC) was used for the experiment. Any energy between 5 and $11 \cdot 5$ MeV can be obtained. The proton energy was determined by means of a magnetic analyser stabilized by a proton nuclear resonance set. The energy reproducibility and resolution of this system are better than $0 \cdot 1\%$. The absolute energy of the analyser has been determined by calibration with $5 \cdot 3$ MeV α-particles from polonium 210. Up to date no other points on the calibration curve have been obtained. Until a more complete analyser calibration is carried out, it is possible that energy estimates may be in error in the 11 MeV region. However, it is unlikely that the error could be as great as 2% at 11 MeV.

Measurements of the relative cross section for the reaction $^{63}\mathrm{Cu}(p,n)^{63}\mathrm{Zn}$ were made at intervals of 30 keV from $5 \cdot 0$ to $11 \cdot 5$ MeV proton energy. For each bombardment, the foils received a charge of 2 μC over a period of about 1 min. The charge was measured by a vibrating reed integrator having an accuracy of $\pm 0 \cdot 2\%$. The decay of the ^{63}Zn during bombardment was compensated for by using an appropriate leakage resistor across the integrating condenser.

Positrons from the decay of ^{63}Zn were counted by a Geiger tube connected to a scaler, the time for 30 000 counts being recorded. The geometry of the system was fixed, so that the relative values of cross section could easily be obtained. No attempt was made to evaluate the absolute cross section, owing to the uncertainty in determining the solid angle of the counter with respect to the source. The error due to counting statistics was $\pm 0 \cdot 6\%$ and the overall reproducibility of the results was $\pm 1\%$. The measurements were all repeated and any doubtful points were taken a third time.

III. Experimental Results

If the curve of cross section as a function of energy contains a resonance whose width is less than the energy loss of the protons in the target, the peak height will be reduced. If there are two or more peaks less than about 100 keV apart, these will not be resolved. Furthermore, a large number of close spaced peaks of equal size will be indistinguishable and will appear as a continuum. The initial data have been corrected for target thickness by considering each point as representing the mean cross section over an energy range corresponding to the thickness of the target to the particular energy of the incident protons. A histogram of all the points was then plotted and an appropriate smooth curve having the same area as the histogram was produced.

The experimental curve which was obtained for the relative cross section is shown in Figure 1. The energy scale is plotted in centre-of-mass coordinates. It can be seen that eight prominent peaks have been found at proton energies, in the centre-of-mass system, of $5 \cdot 6_6$, $6 \cdot 0_4$, $6 \cdot 4_1$, $6 \cdot 6_0$, $7 \cdot 1_9$, $7 \cdot 4_7$, $7 \cdot 9_0$, and $8 \cdot 0_6$ MeV. The addition of a proton to ^{63}Cu leads to an excitation of $7 \cdot 71$ MeV in ^{64}Zn. These peaks therefore correspond to excitations of $13 \cdot 3_7$, $13 \cdot 7_5$

$14 \cdot 1_2$, $14 \cdot 3_1$, $14 \cdot 9_0$, $15 \cdot 1_8$, $15 \cdot 6_1$, and $15 \cdot 7_7$ MeV in ^{64}Zn. For proton energies above 8·06 MeV, it was not possible to distinguish any peaks with certainty. When all the points in this energy region were plotted with their appropriate error bars, it was possible to draw a smooth curve through them. There may, however, be small peaks in this region. It must be pointed out that before an analysis for target thickness was applied, the peaks at 7·47 and 8·06 MeV were

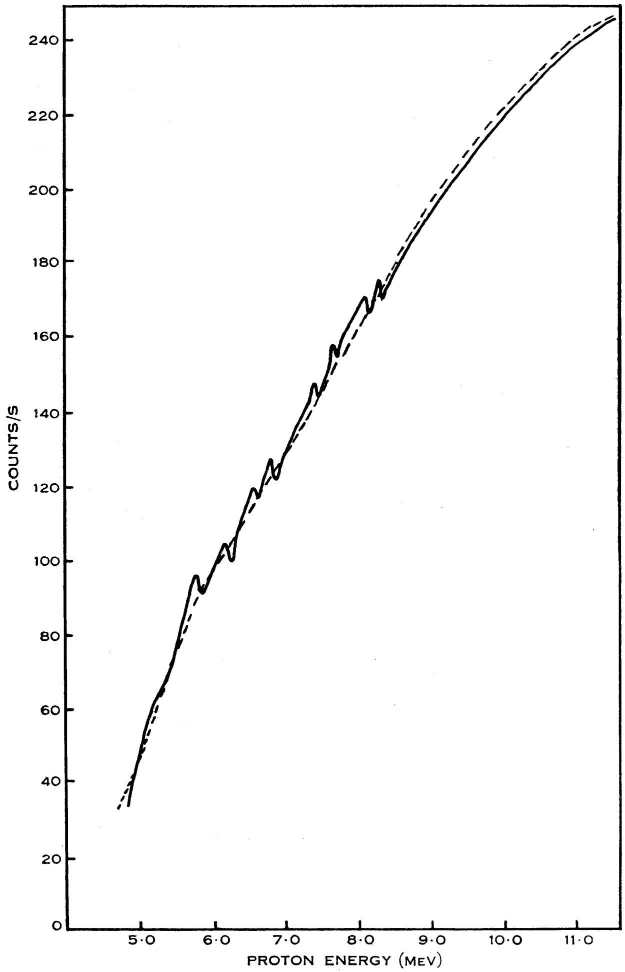

Fig. 1.—^{63}Cu(p,n)^{63}Zn relative cross section plotted in counts/s as a function of proton energy.

just barely distinguishable and in the analysis they were assumed to be genuine. A change of about $1\frac{1}{2}\%$ in two neighbouring points could have made these appear much more real or alternatively made them almost disappear. The fact that all the points were repeatable to an accuracy of 1% suggested that they were genuine. There was also some evidence for a peak at $5 \cdot 1_8$ MeV, however, it was not possible to establish its existence with certainty and so a smooth curve was drawn through this region.

In Figure 2 a smoothed out version of the results is compared with the absolute cross sections of Blaser, Ghoshal, and Howe. The results of this experiment were normalized to give best agreement with the curves of Blaser, Ghoshal, and Howe. The same normalization factor gives the agreement with the Shapiro theory indicated in Figure 1. The shape of the experimentally determined cross section is seen to agree well with the results obtained by previous workers.

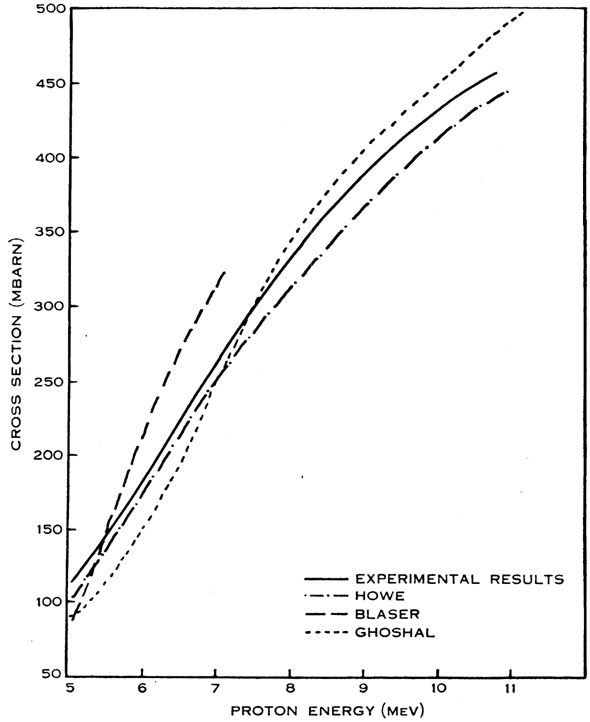

Fig. 2.—Comparison of experimental results with previous measurements. The cross section in millibarns is plotted as a function of centre-of-mass proton energy.

IV. Discussion of Results

Shapiro (1953) has calculated the expected cross section for a number of (p,n) reactions including ^{63}Cu$(p,n)^{63}$Zn. It is assumed that there are a large number of closely spaced levels and the theoretical cross section obtained is an average over many resonances. In consequence, the theory predicts a cross section which rises smoothly with increasing energy. The absolute magnitude of the theoretical cross section is somewhat arbitrary since to obtain agreement with experiment it is necessary to vary the value of the nuclear radius parameter from one nucleus to another. The theoretical cross section is sensitive to changes in the value of the nuclear radius parameter. For example, a change in its value from $1 \cdot 3$ to $1 \cdot 5$ fermi increases the theoretical cross section by 50%. Shapiro's theory has achieved a good deal of success in predicting the shape of the cross-section curve but the absolute value of the predicted cross section often differs from experimental values by a factor as large as two. The theory gives values for the total cross section which includes capture elastic and inelastic scattering as well as neutron emission. At bombarding energies above 5 MeV, the neutron emission process predominates, so that the curve of cross section versus energy as calculated by Shapiro might be expected to fit the experimental data for the (p,n) reaction.

The broken line in Figure 1 shows the theoretical cross section predicted by the Shapiro theory using a nuclear radius parameter of 1·3 fermi. The curve has been arbitrarily normalized to fit the experimental data. As is seen, the general trend of the cross section is in good agreement with the theory. However, the eight peaks appear as definite anomalies. Conventional ideas of compound nucleus formation suggest that, in the energy region involved in this experiment, the levels in ^{64}Zn would be only about 20 keV apart. Levels with this spacing would not be resolved in the present experiment and the resultant cross-section curve would be expected to resemble the theoretical curve due to Shapiro over the whole energy range. The presence of the eight peaks shows that the simple compound nucleus concept is not entirely adequate.

While it is possible to postulate that the observed peaks are due to a fortuitous grouping of a number of compound nucleus levels, a more plausible explanation of the structure may be obtained by considering a single-particle model. The addition of a proton to ^{63}Cu to form ^{64}Zn in an excited state may be considered to occur in either of two ways:

(i) by the addition of a proton to the ground state of ^{63}Cu so that the bombarding particle becomes the excited particle in ^{64}Zn, or

(ii) by the addition of a proton into the nucleus of ^{63}Cu followed by the excitation of one of the nucleons from the target nucleus.

The first process leads to a number of relatively widely spaced levels while the latter process leads to a large number of closely spaced levels. The single-particle picture therefore allows for the possibility of a number of widely spaced levels due to process (i) superimposed on a continuum due to all possible processes of type (ii). It is not impossible that type (ii) processes may also produce a limited number of resolvable levels.

While the single-particle picture gives a plausible qualitative explanation for the presence of resonances in the cross section obtained in the present experiment, it is necessary to show that the observed levels occur at the correct energies and to explain the absence of observed peaks at bombarding energies greater than 8·1 MeV.

Calculations of the binding states of individual nucleons in strongly deformed nuclei have been made by Nilsson (1955). The basis of the calculations was a model for the interaction of nucleons with a deformed nuclear field. Nilsson introduced a single-particle Hamiltonian containing a modified ellipsoidal oscillator and a spin-orbit term. From these calculations the single-particle states in ^{64}Zn may be found provided the nuclear deformation parameter η is known. Stelson and McGowan (1960) have obtained an experimental value for the deformation δ of ^{64}Zn by a Coulomb excitation technique. The value obtained is $\pm(0 \cdot 21 \pm 0 \cdot 03)$. The sign of the deformation cannot be determined by this technique.

The parameter δ, determined experimentally, and the parameter η, used in the Nilsson theory are linked by the relation

$$\delta = \varkappa \eta f(\delta).$$

The term $f(\delta)$ can be taken to be unity without affecting calculations by more than 1%. However, it is necessary to know the value of the constant $\varkappa$ before values of η and δ can be compared. Nilsson assigns a value of 0·05 to $\varkappa$. There is, however, some doubt as to its true value and it may well vary from nucleus to nucleus. It seems likely that in the region of ^{64}Zn, $\varkappa$ should be, if anything, larger than 0·05.

Using the scheme formulated by Nilsson, calculations have been made of the single-particle states of ^{64}Zn assuming values of η of $-3 \cdot 2$, $-3 \cdot 4$, $-3 \cdot 6$, $-3 \cdot 8$, $-4 \cdot 0$, $-4 \cdot 4$, and $+4 \cdot 0$. Of these values, $\eta = -3 \cdot 6$ and $\eta = -3 \cdot 8$ give good agreement with the experimental results. The remainder do not. It appears unlikely that any positive value of η will give good agreement. For $\eta = -3 \cdot 6$ and an energy step of 10·0 MeV per unit (Nilsson suggests 10·25 MeV for ^{64}Zn), it is found that the single-particle states of ^{64}Zn lie at excitations of 13·00, 13·30, 13·50, 15·02, 15·19, 15·51, 15·73, and 17·23 MeV. This is shown in Figure 3, where the parameter δ is computed on the assumption that $\varkappa = 0 \cdot 05$. These results agree within 2% with the experimentally observed values of $13 \cdot 3_7$, $13 \cdot 7_5$, $14 \cdot 9_0$, $15 \cdot 1_8$, $15 \cdot 6_1$, and $15 \cdot 7_7$ MeV. They do not explain the presence of the peaks observed at $14 \cdot 1_2$ and $14 \cdot 3_1$ MeV. The Nilsson prediction of a peak at 13·00 MeV corresponds to a proton energy of 5·30 MeV. It was pointed out earlier that there was slight evidence for a peak at a proton energy of $5 \cdot 1_8$ MeV. It would thus seem possible that this was in actual fact a weak resonance. The predictions also suggest the existence of another single-particle state at a proton energy of about 5·0 MeV. It is probable that this was not found because the proton energy was not reduced sufficiently. Considering the inaccuracy involved in the assessment of the energy of a peak superimposed on a rising curve, the agreement between the Nilsson theory and the experimental data is very good. It is possible that the two observed peaks which are not explained by the Nilsson theory are due to processes of type (ii) referred to above.

Another interesting feature of the Nilsson theory is that it predicts the absence of peaks for 1·5 MeV above an excitation of 15·7 MeV. This also is in agreement with experiment. At excitation energies above 17·23 MeV, the Nilsson theory predicts a number of relatively close spaced levels which could not be resolved in this experiment.

To check whether the value of η (and consequently δ) required to fit the experimental data is sensitive to small errors in the experimentally determined energies of the peaks, calculations have been made assuming the cyclotron energy calibration to be correct at 5 MeV and to have a linearly increasing error up to 1% at 8 MeV. These calculations show no significant changes in η, and the unit energy necessary to predict the positions of the peaks.

If Nilsson's value of $0 \cdot 05$ for the constant $\varkappa$ is correct, this experiment gives a value for δ of about $-0 \cdot 18$ or $-0 \cdot 19$ for ^{64}Zn. The magnitude of this agrees reasonably well with the value of $\pm(0 \cdot 21 \pm 0 \cdot 03)$ obtained by Coulomb excitation. However, it is not possible to draw significant conclusions from the agreement, since the value of δ depends directly on the assumed value of $\varkappa$.

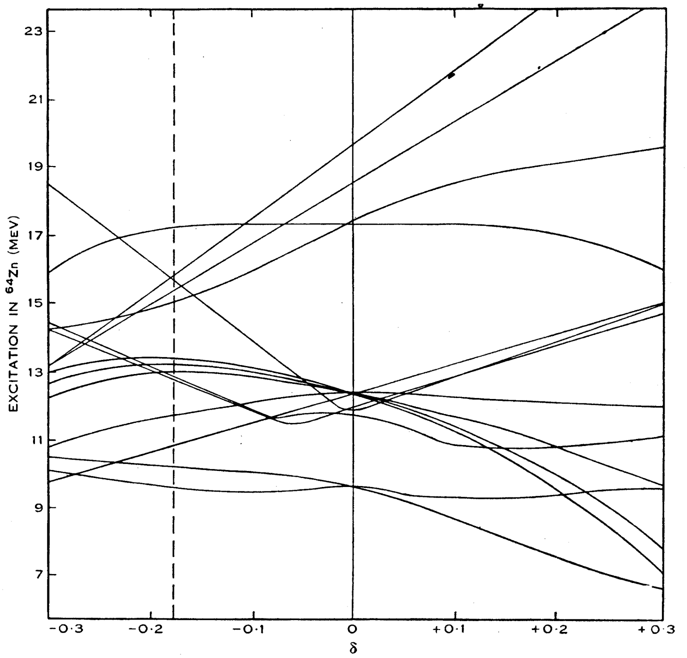

Fig. 3.—Nilsson scheme showing the locations of excited states in ^{64}Zn as a function of deformation parameter δ.

V. Conclusions

The agreement between the levels predicted by the Nilsson theory and those found experimentally appears to be quite good. This result indicates the probability of highly excited states of ^{64}Zn which are formed by the excitation of a single particle.

If this interpretation is correct, the deformation of ^{64}Zn must be negative, at least in its highly excited states, since no assumption of positive deformation leads to a fit with the experimental data.

VI. Acknowledgments

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