Zero-Spin Assignment for the 2.05-MeV State of Ni^{62} from a $(p,p'\gamma\text{-}\gamma)$ Angular Correlation Measurement*

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(Received 5 March 1963)

The γ-γ angular correlation of the 0.88–1.17-MeV cascade, following excitation of the 2.05-MeV state of Ni^{62} by the (p,p') reaction, has been measured for angular separations of 90° to 180° at an average bombarding energy of 4.71 MeV. Convincing agreement was found with the correlation expected for a $0(Q)2(Q)0$ cascade, thereby providing a unique zero-spin assignment for the second level of Ni^{62}. This assignment accounts for the measured isotropy (within $\pm 3\%$) of the 0.88-MeV cascade transition with respect to the incident beam, as well as the lack of an observed ground-state transition. While a 2+ spin would have been expected for the second level according to level systematics for neighboring even-even nuclei, a spin of zero can be accommodated by the recent theoretical predictions of Kerman and Shakin. Other evidence relating to the spin assignments and possible two-phonon character of the well-separated triplet of states in Ni^{62} is discussed. It is concluded that the measurement of a $0(Q)2(Q)0$ γ-γ angular correlation following (p,p') excitation provides a promising method for the unique identification of zero-spin states in medium-weight even-even nuclei.

1. INTRODUCTION

MANY of the systematic properties of the low-lying states of medium-weight even-even nuclei have been at least qualitatively accounted for by various collective models involving nuclear quadrupole vibrations. One predicted feature is a two-phonon ($n=2$) triplet of states (4+, 2+, 0+) at approximately twice the energy of the one-phonon first 2+ excited state.[1] Since there are still very few cases where a triplet of the required spins is well established, the question of the general existence of such a triplet continues to attract experimental interest. The location of the two-phonon 0+ state is of particular importance, since according to the predictions of several collective models,[1–3] this 0+ state is expected to lie above the 2+ and 4+ two-phonon states.

The present experiment concerns the nucleus Ni^{62}, which exhibits a well-separated triplet of levels with energies of 2.05, 2.30, and 2.34 MeV, corresponding to slightly less than twice the energy of the first 2+ level at 1.17 MeV. An earlier study of the level systematics of neighboring even-even nuclei had revealed that for nuclei with $32 \leqq N < 50$, the spin of the second excited state was always 2+ when measured.[4] However, more recently there has been evidence accumulating[5,6] which indicated a strong possibility of zero spin for the second level of Ni^{62}. In addition, the recent theoretical calculations of Kerman and Shakin[7] provide for such a possibility. It was, therefore, considered desirable to obtain a unique spin determination for this state.

It is known that prominent γ rays are emitted from Ni^{62} following excitation of low-lying states by inelastic proton scattering,[8] with sufficient intensity to permit the possibility of a γ-γ angular correlation measurement. While, in general, there are no predictions available from statistical reaction theory for a $(p,p'\gamma\text{-}\gamma)$ angular correlation, in the special case of a γ-γ cascade originating from a *zero-spin* state, the $(p,p'\gamma\text{-}\gamma)$ angular correlation would depend only the angular momenta of the γ rays and states involved in the cascade,[9] being independent of all previous processes by which the zero-spin state is reached. The expected angular correlation for a $0(Q)2(Q)0$ cascade is

$$W(\theta)=1+0.358P_2(\cos\theta)+1.143P_4(\cos\theta),$$

which has a uniquely large A_4 term which should be distinguishable from other possible $(p,p'\gamma\text{-}\gamma)$ angular correlations. If such an angular correlation could be successfully identified for $(p,p'\gamma\text{-}\gamma)$ radiations, then this should prove to be a useful method for identifying zero-spin levels in medium-weight even-even nuclei.

2. EXPERIMENTAL RESULTS AND DISCUSSION

A self-supporting foil of 97.7% enriched Ni^{62} (0.6% Ni^{58}, 1. 5% Ni^{60}) with a thickness[10] of 1.9 mg/cm² was bombarded by protons of energies ranging from 4.52 to 5.12 MeV provided by the Bartol-ONR Van de Graaff accelerator. The target was placed at an angle of 46° to the beam direction; therefore, the proton energy loss

* The study was supported by the U. S. Air Force Office of Scientific Research under Grant AF-AFOSR 62-217.

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varied from 122 to 115 keV for the incident energies chosen. Gamma-ray spectra were detected during proton bombardment using two selected 3-in.×3-in. integral-line NaI scintillation counters, placed at a distance of 14 cm from the target. Pulse-height spectra were recorded using a 400-channel RIDL transistorized pulse-height analyzer, together with a 20-channel analyzer for monitoring purposes. A conventional fast-slow coincidence circuit with a fast resolution time of $2\tau \approx 40$ nsec was used for studies of γ-γ coincidences.

For the range of bombarding energies chosen, prominent Ni^{62} $(p,p'\gamma)$ radiations of 0.88, 1.17, and 2.30 MeV are observed in singles spectra (see Fig. 1), with the excitation cross section for the 2.05-MeV level varying from 7–15% of the cross section for the 1.17-MeV level. As reported earlier,[5] no ground-state transition (<3%) is observed from the 2.05-MeV level. While this observation is consistent with a zero-spin assignment for the 2.05-MeV level, it can only be considered as confirmatory evidence, since there are well-established cases of second 2+ levels with no observed ground-state transitions (e. g., Zn^{66}, <0.8%[11]; Pt^{196}, <0.04%[12]).

On the left of Fig. 2 are shown angular distributions with respect to the incident proton beam for the 0.88-MeV cascade γ ray from the 2.05-MeV level of Ni^{62} at four different bombarding energies. These data represent an extension with improved experimental conditions to initial measurements reported earlier.[5] An average of the least-squares fits to the four distributions is represented by Legendre polynomial coefficients of $A_2=0.03\pm0.03$ and $A_4=0.01\pm0.04$. As indicated, all these data are consistent with an isotropic angular distribution to about $\pm3\%$. While such an isotropy would be expected if the 2.05-MeV level has zero spin, this observation does not rule out the possibility of a 2+ assignment, since for certain $E2/M1$ admixtures, the angular distribution of a $2+(M1,E2)2+$ transition following (p,p') excitation may be nearly isotropic according to statistical reaction theory.[13,14] However, the angular distribution of $2+(M1,E2)2+$ transitions in Ni^{60}, Zn^{64}, and Zn^{66} have been found to be distinctly anisotropic.[14]

For the angular correlation measurements, the counter detecting 1.17-MeV radiation was fixed at $\theta_2=90°$ and the second counter was moved through angles $\theta_{12}=90°$ to 180° to provide the yield of 0.88-MeV radiation in coincidence. The average proton energy of 4.71 MeV was chosen to be below the $Ni^{62}(p,n)Cu^{62}$ threshold at 4.81 MeV[15] in order to reduce γ-ray background from induced Cu^{62} activity. The coincident γ-ray spectra for $\theta_{12}=90°$ and 180° are shown in Fig. 3, and clearly indicate an increased yield of 0.88-MeV radiation at $\theta=180°$. The chance coincidence rate for these runs was appreciable, since about 94% of the intensity of the 1.17-MeV peak was estimated from auxiliary measurements to be due to chance coincidences. This chance rate was considerably larger than calculated from the observed singles rate and measured resolving time of the fast-slow coincidence circuit. This increase is attributed largely to rapid beam fluctuations occurring during normal energy stabilization of the accelerator, which was not sufficient to maintain a steady current through the 2-mm aperture of the beam-defining slits. Also, the accelerator operation was somewhat unsatisfactory during these particular observations, there being some difficulty in maintaining a steady voltage throughout the recording periods. The net result was a substantial correction for chance coincidences which had to be applied to the coincident yield of 0.88-MeV radiation, amounting to about 30% at $\theta_{12}=90°$. In addition, a distinct broadening of the γ-ray photopeaks is observed in Fig. 3, which is attributed to gain changes caused by the unstable beam conditions. This alteration of the standard spectral shapes caused an increased uncertainty in the γ-ray spectral decomposition. In order to reduce these uncertainties, the angular correlation was remeasured with improved statistics, and was found to agree within the estimated errors.

In the lower right of Fig. 2 are shown the combined results of the two separate angular correlation measurements. Although the data have substantial uncertainties, the agreement with the theoretical $0(Q)2(Q)0$ angular correlation (corrected for finite angular resolution) is convincing. Therefore, it is concluded that the spin of the 2.05-MeV level in Ni^{62} has been uniquely determined as zero.

Examination of available evidence from the decays of Co^{62} and Cu^{62}, as summarized by the Nuclear Data group,[16] led to the following best spin and parity assignments for the triplet of levels in Ni^{62}: 2.05(0,2)+, 2.30(0,2)+, and 2.34(4+) MeV. The observation of a strong $(p,p'\gamma)$ ground-state transition from the 2.30-MeV level eliminated the possibility of 0+ for this state.[8] In addition, the observed $(p,p'\gamma)$ angular distribution for 2.30-MeV radiation is in reasonable agreement with the predicted angular distribution for a $2+(E2)0+$ transition.[5]

Further information concerning spin identifications may be extracted from comparisons of the present experimental $(p,p'\gamma)$ cross sections with theoretical predictions using Hauser-Feshbach theory and optical model transmission coefficients, which will be discussed in detail in a later publication. In the case of Ni^{62}, the cross section for the 2.05-MeV level (relative to the cross section for the 1.17-MeV level) is found to be roughly 1.5 times that predicted for a 0+ level, but only 0.7

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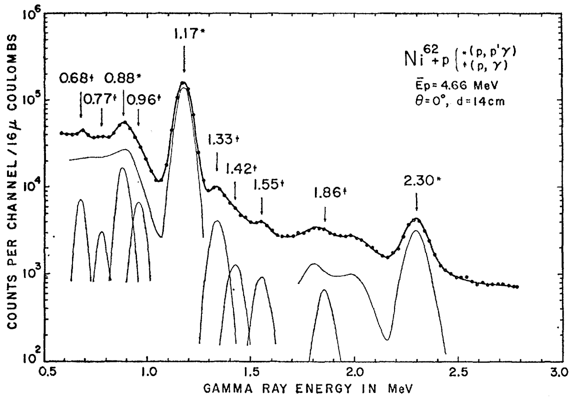

FIG. 1. Gamma-ray spectrum at $\theta=0°$ from a 97.7% enriched Ni^{62} target bombarded by 4.66-MeV protons. Prominent γ-rays assigned to the Ni^{62} $(p,p'\gamma)$ reaction are indicated by asterisks, while some of the less prominent radiations are tentatively assigned to the Ni^{62} (p,γ) reaction. Part of the 1.33-MeV γ ray can be attributed to the $(p,p'\gamma)$ reaction in the Ni^{60} (1.5%) present in the target.

times that predicted for a 2+ level. This result may be compared with the case of Ni^{60}, for which the cross section for the second 2+ level at 2.16-MeV (relative to the 1.33-MeV level cross section) is about a factor of 1.3 greater than the predicted value for similar bombarding energies.[5,8] In the case of the 2.30-MeV level of Ni^{62}, however, the relative yield of the crossover γ ray exceeds the predicted cross section ratio $\sigma_{2.30}/\sigma_{1.17}$ for a 2+ level, without adding any contribution for cascade radiation. Combining these results with the aforementioned conclusions from the decay of Cu^{62} indicates that the best choice of spins to account for the experimental $(p,p'\gamma)$ cross sections would be 0+ and 2+, respectively, for the 2.05- and 2.30-MeV states. A final piece of evidence is provided by Broek's observation of an inelastic alpha group whose center corresponds to 2.30±0.02-MeV excitation.[6] The center of gravity of the triplet of levels in Ni^{62}, assuming a spin sequence of 0+, 2+ and 4+, together with a weighting factor of $2J+1$, would be 2.31 MeV. There is now, therefore, a considerable body of evidence indicating that the spin sequence of the well-defined triplet in Ni^{62} is 0+, 2+, and 4+, as shown in Fig. 2.

It should be noted that the experimental ratio of $B(E2;2'\rightarrow2)/B(E2;2'\rightarrow0)$ of >210 listed in a compilation by Van Patter[17] was based on the lack of an observed ground-state transition from the second level of Ni^{62}.[18] Now that this level is known to have zero spin, this value of the $B(E2)$ ratio is meaningless, and should not be compared to theoretical predictions.[7] Since the branching of the 2.30-MeV level is unknown at present, no experimental value for this $B(E2)$ value is available.

3. CONCLUSIONS

On the basis of a collective model considering anharmonic quadrupole oscillations for a spherical nucleus, Kerman and Shakin[7] have achieved a surprisingly good fit to the low-lying levels of Ni^{62}, as indicated in Fig. 4. Their predictions are based on three adjustable parameters, which reduce to two, $(B')^2$ and α, when ratios of level energies to the energy E_1 of the first 2+ level are considered. For the parametric values listed in Fig. 4, the 0+ member of the two-phonon triplet lies lowest in energy. However, the choice of parameters depends critically on the spin sequence of the two-phonon triplet, since an equally good fit to the triplet in Ni^{62} (assuming a spin sequence of 2+, 0+, and 4+) is obtained for values of $(B')^2=0.035$ and $\alpha=0.5$.[7] The results of the present experiment agree with the spin sequence assumed by Kerman and Shakin on the basis of evidence previously available.[8,16]

The parameters listed by Kerman and Shakin give a good over-all fit to the triplet of levels together with the 2.89-MeV state (energy ratio=2.48) which has been given a tentative spin assignment of (2+, 3+) by Butler and Gossett,[18] on the basis of observed β- and γ-ray transitions in the decay of Cu^{62}. This choice of parameters thus associates this level with the theoretically predicted 2+ member of the three-phonon quintet. It should be noted that another choice of parameters can be found which will give a better fit to the members of the two-phonon triplet and, at the same time, alter the predicted positions of the three-phonon states.

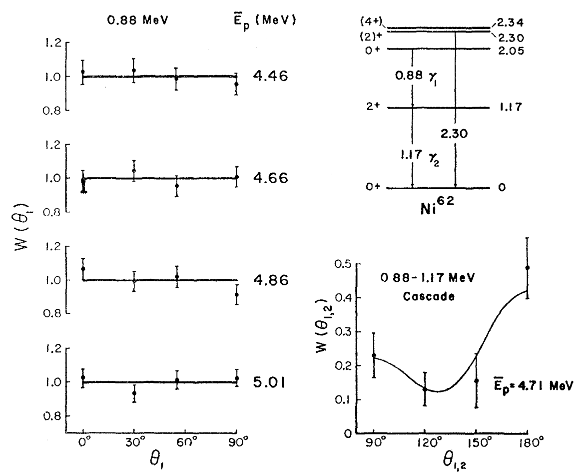

FIG. 2. The level diagram (upper right) indicates prominent $Ni^{62}(p,p'\gamma)$ transitions. On the left side are shown the angular distributions of 0.88-MeV radiation, with respect to the incident proton direction. Since its yield is averaged over an energy interval of about 120 keV due to the target thickness, average proton energies, $\bar{E}p$, are listed. In the lower right, the experimental data for the $(p,p'\gamma\text{-}\gamma)$ angular correlation for the 0.88–1.17-MeV cascade are shown, These are compared with the theoretical prediction: $W(\theta)=1+0.33P_2(\cos\theta)+0.89P_4(\cos\theta)$ for a $0(Q)2(Q)0$ cascade, corrected for the finite angular resolution of the 3-in. ×3-in. NaI detectors ($d=14$ cm).

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For example, parametric values of $(B')^2=0.05$ and $\alpha=0.01$ yield energy ratios of 1.80(0+), 1.93(2+), and 1.94(4+) for the two-phonon triplet, and 2.62 for the 2+ three-phonon state, i. e., this last state is predicted to lie 0.17 MeV higher than for the parameters given in Fig. 4. This new choice of parametric values would predict a center of gravity for the three-phonon quintet of 3.27 MeV (energy ratio 2.79), assuming a $2J+1$ weighting factor for all members.

Recent results obtained by Broek[6] from inelastic scattering of 43-MeV alpha particles are indicated on the right of Fig. 4. Broek has discussed the possibility of identifying a group corresponding to 3.24±0.04-MeV excitation (energy ratio 2.76) with members of the three-phonon quintet, which, for the parametric values listed in Fig. 4, would have a center of gravity at 3.17-MeV excitation if all members are included. It is apparent that since the best choice of parameters for fitting the Ni^{62} levels is not clearly defined, the good agreement of the position of this 3.24-MeV group with theoretical predictions may be somewhat fortuitous. Evidence for the two- or three-phonon properties of Ni^{62} levels is needed from other sources; in particular, measurements of the lifetimes of these states could reveal whether these states are primarily due to collective excitations. According to Eccleshall *et al.*,[19] there is as yet no conclusive evidence for the collective character of the 0+ member of the triplet. However, the present experimental evidence for the (0+, 2+, 4+) triplet in Ni^{62}, when combined with Broek's (α,α') results, appears to be very suggestive in view of the unusually good agreement with the predictions of Kerman and Shakin.

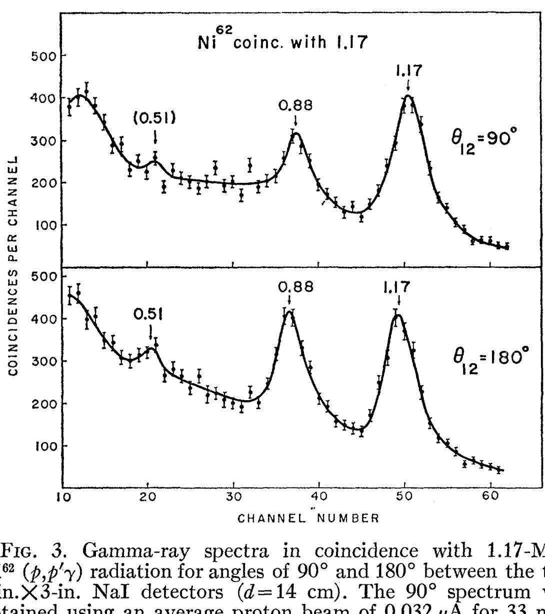

FIG. 3. Gamma-ray spectra in coincidence with 1.17-MeV Ni^{62} $(p,p'\gamma)$ radiation for angles of 90° and 180° between the two 3-in.×3-in. NaI detectors ($d=14$ cm). The 90° spectrum was obtained using an average proton beam of 0.032 μA for 33 min, yielding 1.8×10^6 counts in the single channel monitoring 1.17-MeV radiation.

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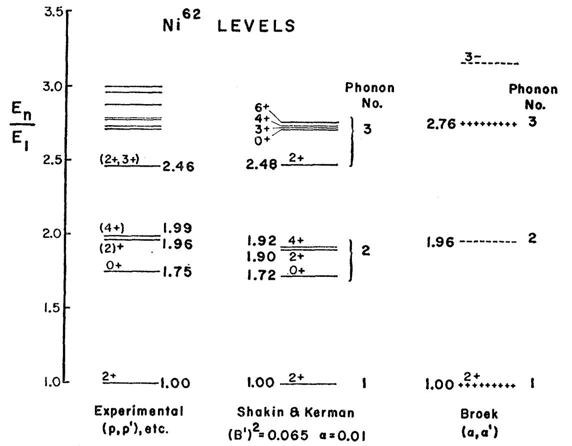

FIG. 4. Energy level diagrams for Ni^{62}, expressed as ratios of level energies to the energy of the first 2+ level at 1.172 MeV. The present experimental evidence is summarized (left), and is compared with theoretical predictions (center) of Kerman and Shakin (reference 7) for one choice of parameters $(B')^2$ and α. Recent results of Broek (reference 6) from inelastic alpha scattering are also shown (right), including signs to indicate whether a group is in phase (− − −), or out of phase (+ + +), with elastic scattering, as well as the possible phonon identification.

It is concluded that a promising method for unique identification of zero-spin states in medium-weight even-even nuclei is the measurement of the $0(Q)2(Q)0$ angular correlation for $(p,p'\gamma\gamma)$ radiations. Such measurements can be carried out for $(p,p'\gamma)$ radiations which are first found to have isotropic angular distributions with respect to the incident beam direction. After obtaining the present experimental data for Ni^{62}, the preliminary report[20] of a similar measurement of zero spin for the 2.65-MeV level of Cr^{52} came to our attention. *Note added in proof.* The earlier measurements of the Chalk River group[21] and the Osaka University group[22] should also be mentioned, since these include zero-spin assignments for nuclear levels in the $2s$-$1d$ shell on the basis of $(p,p'\gamma-\gamma)$ angular correlations.

ACKNOWLEDGMENTS

The participation of Dr. P. N. Trehan in the initial phase of this investigation is acknowledged, as well as the continuing cooperation of Dr. C. P. Swann. We wish to thank Dr. F. R. Metzger for useful advice and suggestions.

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