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Spectroscopy of the Lower Excited States of Co^{59}†

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We have investigated the low-lying states of Co^{59} by means of the (He^3,d) reaction on Fe^{58}, using an incident beam whose energy was 22 MeV. In addition to strong $l=3$ transitions to the $\frac{7}{2}^-$ ground state and a group of states centered at 2.08 MeV, strong $l=1$ transitions to the first, third, and fourth excited states were observed. From these results and the results of previous experiments, the first and third excited states can each be assigned spin and parity of $\frac{3}{2}^-$. These assignments are consistent with the results from our study of the $Ni^{60}(d, He^3)Co^{59}$ reaction. The present results are in agreement with previous assignments of either $\frac{1}{2}^-$ or $\frac{3}{2}^-$ for the fourth excited state, but cannot distinguish between these values. Spectroscopic factors for these transitions were obtained from a comparison of the experimental data with the predictions of a distorted-wave calculation.

I. INTRODUCTION

The spin and parity of the ground state of Co^{59} are well known[1] to be $\frac{7}{2}^-$, but there is considerable uncertainty about the spins of the low-lying excited states. The locations of these states have been determined by proton inelastic-scattering measurements.[2,3] Transitions to the ground state and to the first, third, and fourth excited states are observed in the β decay of Fe^{59}.[1,4,5] Most of the information on the nature of these three excited states has been obtained from the measurements of β-decay spectra, β circularly polarized γ-angular correlations, β-γ angular correlations, γ-γ angular correlations, and internal conversion of electrons.[6,7] However, the differences in some of the measured quantities obtained by different experimenters result in contradictory spin assignments to these states.

On the basis of his internal-conversion data, Metzger[4] proposed the assignments of $\frac{5}{2}^-$ to the first excited (1.10-MeV) state and $\frac{3}{2}^-$ to the third excited (1.29-MeV) state. These assignments were consistent with the results of a γ-γ angular correlation measurement.[8] More recently, Collin *et al.*[6] remeasured the internal-conversion coefficients for the decay of these two states to the ground state. From their results, they concluded that the spin and parity of the 1.10-MeV state were $\frac{5}{2}^-$. Their internal conversion data for the decay of the 1.29-MeV state did not permit a spin assignment to this state, but on the basis that the state was not observed in Coulomb excitation experiments,[9,10] Collin *et al.* suggested that it decayed to the ground state with an $M1$ γ transition, and made a $\frac{5}{2}^-$ assignment to the state. However, the more recent Coulomb-excitation data of Alkhazov *et al.*[11] indicate a strong excitation of this state.

As a result of his β-γ circular-polarization measurements, Haase[12] suggested that the two states each be assigned spin and parity of $\frac{3}{2}^-$, and showed that this assignment is consistent with the results of the γ-γ angular correlation measurement of Heath *et al.*[13] Furthermore, Mann *et al.*[7] have pointed out that when the internal-conversion data of Metzger[4] are compared with more recent theoretical calculations,[14] these data are compatible with spins of either $\frac{3}{2}$ or $\frac{5}{2}$ for each of these two states.

Largely because of the confusion in the assignment to the 1.29-MeV state, the spin of the fourth excited (1.43-MeV) state is also in doubt. Assignments of both $\frac{3}{2}^-$ [6] and $\frac{1}{2}^-$ [13,15] have been made to this state.

Because of the lack of definite spin assignments to the lower excited states of Co^{59}, it has not been possible to formulate an appropriate model for this nucleus. It was originally suggested[4] that the first, third, and fourth excited states are single-particle states, but it has also been suggested that the lower excited states can be interpreted in terms of a core-excitation model.[11,15]

We report here the results of a study of these states by means of the $Fe^{58}(He^3,d)Co^{59}$ stripping reaction.

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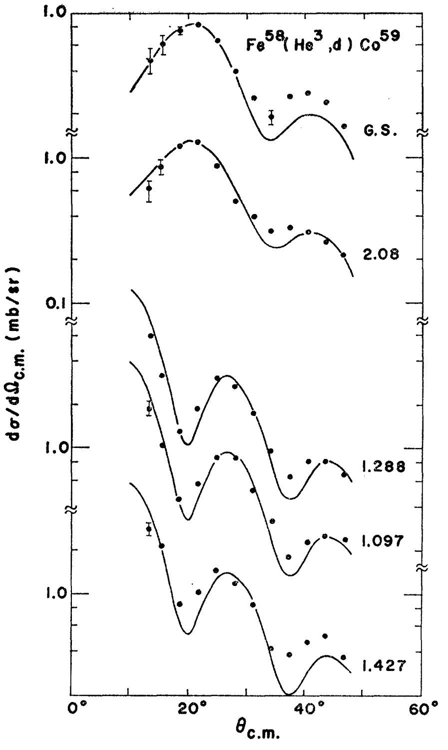

FIG. 1. Angular distributions of deuteron groups from low-lying states in Co^{59}. The curves result from a distorted-wave calculation, and are normalized to the experimental distributions at their peaks in the 20°–30° region. The calculation was performed for $l=3$ transitions for the two distributions at the top of the figure, and for $l=1$ transitions for the three distributions at the bottom of the figure. (G.S.≡ground state.)

Previous work[16,17] has shown that this reaction provides spectroscopic information on proton states equivalent to that provided on neutron states by the (d,p) reaction. We also discuss briefly some of our results from a $Ni^{60}(d,He^3)Co^{59}$ reaction study, which will be reported more fully in a later publication. This latter study employed a 22-MeV deuteron beam from the three-stage Van de Graaff accelerator at this Laboratory.

II. EXPERIMENTAL PROCEDURE

The experimental arrangement has been discussed previously.[16] Briefly, a 22-MeV He^3-ion beam from the Los Alamos variable-energy cyclotron was momentum analyzed, passed through a 0.97-mg/cm² Fe^{58} target, and stopped in a Faraday cup. The charged reaction products were detected in a ΔE-E semiconductor assembly, and the preamplified pulses were fed into a mass-identification system. Parallel circuitry provided amplification and coherent addition of the ΔE and E pulses; the summed pulses were then fed into a 400-channel pulse-height analyzer gated by the output of the mass-identification system.

The resulting spectra were analyzed by a least-squares computer program[18] which fits a skewed Gaussian distribution plus an exponential tail to each peak in a pulse-height spectrum, and computes the area of the peak.

III. RESULTS AND DISCUSSION

Because the Q's for the (He^3,d) reaction on Fe^{56} and Fe^{57} are comparable to that for Fe^{58}, it was necessary to assess the importance of these contaminant isotopes in the Fe^{58} target so that the data could be corrected appropriately. For this purpose, targets of natural Fe (91.7%) and Fe^{57} (78.0% isotopic purity)[19,20] were used. By observing the $Fe^{57}(He^3,d)Co^{58}$ reaction at several scattering angles we determined that the presence of the Fe^{57} isotope (2.0% abundance) in the Fe^{58} target[19,20] had a negligible effect on the deuteron spectra in the region of interest. From the observation of the (He^3,d) reaction on natural Fe, it was apparent that the only interfering group resulting from the Fe^{56} isotope (18.7% abundance) in the Fe^{58} target was the Co^{57} ground-state group. Since the 110-keV resolution in the present experiment was not sufficient to allow identification and separation of this group in the Co^{59} data, it was necessary to make a channel-by-channel correction in the data at each scattering angle. For this purpose, accurate values of the reaction Q's were required. The most recent determination[21] of the mass of Co^{57} yields a Q of 0.529 MeV for the $Fe^{56}(He^3,d)Co^{57}$ reaction, while the Q for the $Fe^{58}(He^3,d)Co^{59}$ reaction is given[22] as 1.873 MeV. Our measurements yielded Q's of 0.538 ± 0.020 MeV and 1.871 ± 0.020 MeV, respectively, in agreement with these values. These Q's place the Co^{57} ground-state deuteron group between the groups from the third and fourth excited states of Co^{59}. The required correction to the data was never more than 10% of the cross section of either of the affected Co^{59} angular distributions.

The most recent (p,p') reaction data,[3] which are in good agreement with earlier (p,p') data,[2] show that the first five excited states of Co^{59} appear at 1.096, 1.187, 1.288, 1.429, and 1.456 MeV. In this region of excitation, the (He^3,d) reaction yields deuteron groups from states whose energies we measure to be 1.097, 1.288, and 1.427 MeV, with a ±10-keV uncertainty in each value. These results are in manifest agreement with the (p,p') reaction values for the first, third, and fourth excited states. These three deuteron groups and the ground-state group are the only ones observed below 2.08 MeV

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of excitation, at which energy there appears a broad (150-keV) group resulting from the excitation of two or more states.

The angular distributions of these five deuteron groups are shown in Fig. 1. The $l=3$ character of the ground-state and 2.08-MeV-group distributions, and the $l=1$ character of the distributions to the 1.10-, 1.29-, and 1.43-MeV states, are apparent when one compares these distributions with known $l=1$ and $l=3$ distributions from the (He^3,d) reaction in this mass region.[16,17] Also shown in Fig. 1 are the results from a distorted-wave (DW) calculation,[23] whose application to the (He^3,d) reaction has been discussed previously.[16,17] The optical-model parameters for the incoming He^3-ion channel were obtained from optical-model fits to elastic scattering data[24]; the values used were $V=138.4$ MeV, $r_{0r}=1.08$ F, and $a=0.781$ F for the real Saxon well, and $W=23.1$ MeV, $r_{0i}=1.54$ F, and $b=0.801$ F for the imaginary Saxon well. The parameters for the outgoing deuteron channel were obtained from set B of the results of the optical-model analysis of Perey and Perey.[25] The predictions from the DW calculation are in satisfactory agreement with the experimental angular distributions for the stated l values.

The results of this experiment require that the spins and parities of the states at 1.10, 1.29, and 1.43 MeV be restricted to $\frac{1}{2}^-$ or $\frac{3}{2}^-$. Of these two values, the only assignment for the 1.10- and 1.29-MeV states allowed by the previous experiments (see Sec. I) is $\frac{3}{2}^-$. With this assignment to the 1.29-MeV state, the results of γ-γ coincidence and γ-γ angular correlation measurements favor a $\frac{1}{2}^-$ assignment to the 1.43-MeV state.[13,15,26]

The assignment of $J^\pi=\frac{3}{2}^-$ to the 1.10- and 1.29-MeV states is consistent with the results from our study of the $Ni^{60}(d,He^3)Co^{59}$ reaction. In this latter reaction, of the first four excited states only the 1.10- and 1.29-MeV states are excited with appreciable cross sections, and their angular distributions show an $l=1$ character. The appearance of low-lying $p_{3/2}$ transitions in the (d,He^3) reaction is expected on the basis of the results from the (He^3,d) reaction on Ni^{62} and Ni^{64}.[16] In this reaction a known $\frac{7}{2}^-$ state is excited in Cu^{63} and in Cu^{65}. Interpretation of this transition in terms of a simple stripping mechanism implies that the $f_{7/2}$ proton shell in the Ni nuclei is not completely closed. This in turn suggests a promotion of protons to the next highest orbital in the Ni nuclei, i.e., to the $2p_{3/2}$ orbital.

From the DW analysis, the spectroscopic factor[27] for the transition to the Co^{59} ground state is 0.17. This value is to be compared to the predicted value of 0.25 corresponding to the exhaustion of the $f_{7/2}$ proton strength in a pure $(f_{7/2})_0{}^{-2}\rightarrow(f_{7/2})^{-1}$ transition.[28] Whether this discrepancy indicates a deficiency in our application of the DW calculation or, rather, suggests additional $f_{7/2}$ transitions to higher-lying Co^{59} states cannot yet be answered decisively. In our study of the $Ni^{60}(d,He^3)$ reaction, however, a transition with a probable $f_{7/2}$ assignment was observed to a state in Co^{59} at 2.07 MeV. This may be one of the states in the 2.08-MeV group excited in the present (He^3,d) reaction study.

On the assumption that the states observed at 1.10, 1.29, and 1.43 MeV in the (He^3,d) reaction have $J^\pi=\frac{3}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$, respectively, the spectroscopic factors obtained from the DW analysis are, in the same order, $C^2S=0.11$, 0.34, and 0.37. Although the 2.08-MeV group may include a $\frac{7}{2}^-$ state, as suggested above, it is likely that its main components are $\frac{5}{2}^-$ states. Under the limiting assumption of a $\frac{5}{2}^-$ assignment to each state of the group, the DW calculation yields a spectroscopic factor $C^2S=0.38$ for the group. Since values close to unity are required to exhaust the sum rule for the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ proton single-particle states, the results indicate that large fractions of these single-particle states lie higher than 2.1 MeV of excitation. Indeed, many deuteron groups are observed at higher excitation energies. The poor quality of the Fe^{58} target (relatively great thickness and the presence of isotopic impurities) makes the analysis of these states rather difficult, however, and we do not include the results in the present report.

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