Electromagnetic Transition Rates in ^{56}Ni

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The lifetimes of the first two excited states in ^{56}Ni have been investigated using the reaction ^{54}Fe(^{3}He,$n\gamma$)^{56}Ni and the Doppler-shift attenuation method. Pulse-shape discrimination was employed for the neutron-γ-ray coincidence measurements. These measurements lead to the following mean lives: $\tau(2699\text{ keV}) = 76^{+49}_{-24}$ fsec and $\tau(3924\text{ keV}) > 1$ psec. The $E2$ transition strength for the $2^+ \to 0^+$ transition is compared to shell-model predictions.

I. INTRODUCTION

Different schemes assuming either a closed $f_{7/2}$ subshell for the ground state or allowing for admixtures of up to four holes and four particles have been proposed to describe the ^{56}Ni nucleus.[1] Until now the reported information[2-8] is based on the two-particle-transfer reactions ^{54}Fe(^{3}He, n), ^{54}Fe(^{16}O, ^{14}C), and ^{58}Ni(p, t) and on the ^{54}Fe(^{3}He, $n\gamma$) reaction. In these articles, excitation energies, spin assignments, and γ transitions are given. However, because of the limited amount of experimental data, it has not been possible to draw definite conclusions about the dynamical structure of ^{56}Ni. In the present work, Doppler-shift attenuation measurements were performed on transitions from two excited ^{56}Ni levels in an attempt to get a sensitive test for predicted wave functions.

II. EXPERIMENTAL PROCEDURE

Levels in ^{56}Ni were excited through the ^{54}Fe(^{3}He, n)^{56}Ni reaction. The target consisted of 1.3 mg/cm^2 of iron, enriched to 95% in ^{54}Fe, deposited by electrolysis on a silver backing. The target, which was inclined 45° to the beam direction, was bombarded with a 10-MeV ^{3}He beam. Neutrons were detected with a 4-cm-thick by 25-cm-diam NE213 detector placed at 80° to the beam axis with its front face at 34 cm from the beam spot. The γ-ray flux in the neutron detector was reduced by a 1-cm-thick lead shield and the detected γ rays were rejected by a crossover time discriminator method. In order to reduce feeding of the first excited state via γ rays issuing from higher states, a threshold was set on the neutron energy so as to reject neutrons with energies less than about 6 MeV. γ rays were detected in an 84-cm^3 Ge(Li) counter placed with its front face 5.8 cm from the target and γ-ray spectra were recorded at three angles. Under actual running conditions, the resolution width of the Ge(Li) detector was 6 keV for a 2.6-MeV γ-ray line. To check the stability of the system gain, γ-γ coincidences from a ^{56}Co source placed between the Ge(Li) detector and an Na(I) crystal shielded from the target were continuously recorded.

In addition to the 2.70-MeV γ ray from the first excited state, only a line at 1.22 MeV was found to be in coincidence with the neutrons. According to Schneider *et al.*,[8] it corresponds to the transition between a $J^\pi = 0^+$, 3.92-MeV level and the first excited state. In order to get a more precise value for the attenuation factor of this transition, another set of runs was performed. The 84-cm^3 Ge(Li) detector was replaced by a 54-cm^3 Ge(Li) detector having a 2.8-keV resolution at 1.3 MeV. In this case, a ^{60}Co source was used to check the gain stability of the system. No transitions from higher excited states in ^{56}Ni to the 3.92-MeV state having been seen in previous ^{54}Fe(^{3}He, $n\gamma$) work,[8] the neutron threshold level was lowered to 2 MeV.

III. DATA ANALYSIS AND RESULTS

Figure 1 displays γ-ray energies versus $Q_1 \cos\theta$, where Q_1 is the finite solid-angle correction factor for the Ge(Li) counter and θ the angle between the

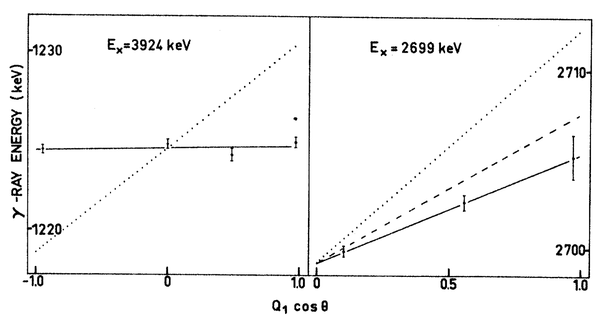

FIG. 1. The attenuated centroid shifts of the 1225- and 2699-keV γ rays resulting from the decay of the 3924- and 2699-keV levels in ^{56}Ni. The solid lines are least-squares fits to the measured points and the dotted lines are the full-energy shifts calculated from the kinematics. The attenuated Doppler shift of the 2699-keV γ rays, corrected for the 1225-keV cascade transition, is shown by the dashed line.

detected γ rays and the recoiling ions. Experimental Doppler shifts were determined by least-squares fits to the observed peak centroids. γ-transition energies were also derived from these fits and the precision on these energies takes into account the differential nonlinearity of the system gain. The γ-ray full-energy shifts were calculated from the kinematics. The uncertainty on the full shifts is estimated to be ±7% from consideration of the anisotropy of experimental neutron angular distributions.[9] An attenuated Doppler shift of 0.12 ± 0.18 keV was obtained for the 1225 ± 1-keV γ transition. Thus, by adding 2 standard deviations to the calculated Doppler shift, an upper limit of 0.09 could be set on the attenuation factor of this transition.

The experimental Doppler shift for the 2699 ± 3-keV γ transition observed with the 6-MeV neutron threshold results from a direct neutron feeding of the first excited state and a feeding by γ rays from the second excited state. The ratio of the yields of the 1225- and 2699-keV γ rays was found to be constant within the errors at the different detection angles and equal to 0.37 ± 0.07. The corrected attenuation factor, $F = 0.64 \pm 0.07$, was obtained by taking into account the fact that the observed γ rays had shifted and unshifted components. From consideration of the limit of the attenuation factor for the 1225-keV γ transition, the accuracy on the centroid of the unshifted component was taken to be 9% of the full-energy shift of the 2699-keV γ transition.

The $F(\tau)$ curve was calculated using the formulas of Blaugrund[10] based on the theory of Lindhard, Scharff, and Schiøtt (LSS).[11] Corrections f_e and f_n were applied to the LSS theoretical electronic and nuclear stopping powers. The correction factor f_e, the ratio of the electronic stopping power deduced from Northcliffe and Schilling's table[12] to the LSS one, was found to be 0.83. Northcliffe and Schilling's range value could be reproduced by multiplying the theoretical nuclear stopping power by the factor $f_n = 0.95$. Uncertainties of 20% were assigned to both f_e and f_n. The present analysis yields a mean life $\tau = 76^{+49}_{-24}$ fsec for the first excited state in ^{56}Ni and a lower limit of $\tau > 1$ psec for the level at 3924 keV.

IV. DISCUSSION

From the present experiment, an $E2$ transition rate between the 2^+ state and 0^+ ground state of 77 ± 32 e^2 fm^4 can be deduced. This $B(E2)$ value is compared to the results of two shell-model calculations.

The shell-model treatment of Oberlechner and Richert[13] predicts the first 2^+ state to be at 2.37 MeV. The basis states used in these calculations include 0h-0p, 1h-1p, 2h-2p, and 4h-4p states. The single-particle energies are derived from the ^{41}Ca spectrum, and furthermore the $1f_{5/2}$ single-particle energy is lowered by an amount of 2.5 MeV in order to get a good agreement for the level energies. This reduction of the $1f_{5/2}$-$1f_{7/2}$ separation leads to a strong mixing of 2h-2p (40%) and 4h-4p (40%) configurations into the ground-state wave function. Using effective charges calculated to the first order in a perturbation expansion[13] and Oberlechner and Richert's wave functions, a $B(E2, 2^+ \rightarrow 0^+)$ rate equal to 42 e^2fm^4 is obtained, 33% of its strength arising from the 4h-4p components of both states. This calculated $B(E2)$ value appears to be in fair agreement with the experimental value.

Recently, Pasquini and Zuker[14] performed shell-model calculations for ^{56}Ni including configurations up to 3h-3p. The matrix elements used for the two-body interaction are those calculated by Kuo and Brown[15] and the single-particle energies used are those derived from the ^{41}Ca spectrum. These calculations indicate that it is possible to describe low-lying ^{56}Ni states without the need of 4h-4p configurations, the 3h-3p configurations lowering the energies of the 2h-2p states. They lead for instance to a ground-state wave function which is mostly 0h-0p and to an energy of 3.21 MeV for the first 2^+ state. The computed $B(E2, 2^+ \rightarrow 0^+)$, 113 e^2fm^4, is about as close to the experimental value as the one from the former shell-model treatment. Thus it appears that the knowledge of the precise nature of the 0^+ and 2^+ states in ^{56}Ni requires further experimental investigations.

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