5.534 MeV level in ^{23}Na

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(Received 14 April 1975)

The ^{12}C(^{12}C, $p\gamma$)^{23}Na reaction has been used at an incident energy of 28.2 MeV to populate the 5.534 MeV level in ^{23}Na. A particle γ-ray linear polarization measurement carried out simultaneously with a particle γ-ray angular correlation measurement for the 3.457 MeV transition between the 5.534 MeV and 2.077 MeV ($\frac{7}{2}^+$) levels allows an unambiguous $J^\pi=\frac{11}{2}^+$ assignment to be made to the 5.534 MeV level. The multipole mixing ratio of the 2.829 MeV transition between the 5.534 MeV and 2.705 MeV ($\frac{9}{2}^+$) levels has been obtained and confirms previous measurements, as does the measured branching ratio for the two observed decay modes from the 5.534 MeV level.

[NUCLEAR REACTIONS ^{12}C(^{12}C,$p\gamma$), E=28.2 MeV; 5.534 MeV level, measured $P(E_\gamma, 90°)$, angular correlations, branching ratio, deduced J and Λ for transitions.]

I. INTRODUCTION

The Nilsson model[1] has proved successful in describing many of the levels and decay modes of ^{23}Na and other neighboring nuclei in the $2s$-$1d$ shell.[2-5] Recently it has also been shown that many of the levels in the $2s$-$1d$ shell which have been successfully interpreted as rotational states can also be reproduced by large-basis shell model calculations which can duplicate rotational model features.[6]

It has been proposed, using the rotational model,[4,5] that the $J^\pi=\frac{11}{2}^+$ member of the ground state ($K^\pi=\frac{3}{2}^+$) rotational band in ^{23}Na should be the experimentally observed level at 5.534 MeV. Good circumstantial evidence has been found for this proposal, since previous γ-ray angular correlation measurements[4,5] have restricted J^π for the 5.534 MeV level to ($\frac{7}{2}$, $\frac{9}{2}$, or $\frac{11}{2}$),$^+$ and enhanced $E2$ transition strengths result for the decays to the 2.705 MeV ($\frac{9}{2}^+$) and 2.077 MeV ($\frac{7}{2}^+$) levels if the 5.534 MeV level is assumed to be $\frac{11}{2}^+$. Also, Lindgren *et al.*[4] calculated the branching fraction for the decay of the 5.534 MeV level (assuming it to be the $\frac{11}{2}^+$ member of the $K^\pi=\frac{3}{2}^+$ ground state band) following Alaga *et al.*,[7] who have shown that for in-band transitions the branching fraction of the crossover to cascade transitions can be determined simply from vector coupling coefficients. The branching ratio for the decay to the 2.077 MeV ($\frac{7}{2}^+$) level calculated in this manner was 20%, in good agreement with the past[4,5] and the present work. The multipole mixing ratio for the 5.534 MeV to 2.705 MeV ($\frac{9}{2}^+$) level was also calculated by Lindgren *et al.*[5] following Preston[8] and again assuming $J^\pi=\frac{11}{2}^+$ for the 5.534 MeV level. This method yields a value of $\delta(E2/M1)=-0.20$ again, in good agreement with the past[4,5] and the present work.

Since candidates have also recently been proposed for the $\frac{13}{2}^+$ to $\frac{21}{2}^+$ members of the ground state rotational band[5,9,10] in ^{23}Na which should cascade through the $\frac{11}{2}^+$ member, it is therefore important to determine definitively the spin of the 5.534 MeV level.

In view of the well separated γ-ray transitions observed, in coincidence with protons deexciting the 5.534 MeV level in ^{23}Na, in a previous investigation of the ^{12}C(^{12}C, $p\gamma$) ^{23}Na reaction at 28.2 MeV incident energy[5] it is apparent that the primary 3.457 MeV transition from the 5.534 MeV level to the 2.077 MeV ($\frac{7}{2}^+$) level is amenable to γ-ray linear polarization and angular correlation measurements utilizing the γ-ray detection efficiency of large NaI(Tl) crystals. Accordingly, using these techniques the ^{12}C(^{12}C, $p\gamma$)^{23}Na reaction has been studied in the present work at 28.2 MeV incident energy to determine the spin of the 5.534 MeV level.

II. EXPERIMENTAL METHOD

An 80 μg cm^{-2} carbon target evaporated onto a 0.125 mm gold backing was bombarded with a 28.2 MeV ^{12}C beam. Due to the ≈400 keV energy loss in the carbon target, the average energy was ≈28.0 MeV. The outgoing protons were detected in a cooled 1 mm annular surface barrier detector placed at 180° with respect to the beam direction. With the counter surface 3.8 cm from the target the angular range of particle detection was 160 to 170° and allowed good coincidence counting rates while maintaining reasonable geometry. α particles from the ^{12}C(^{12}C, α)^{20}Ne reaction were

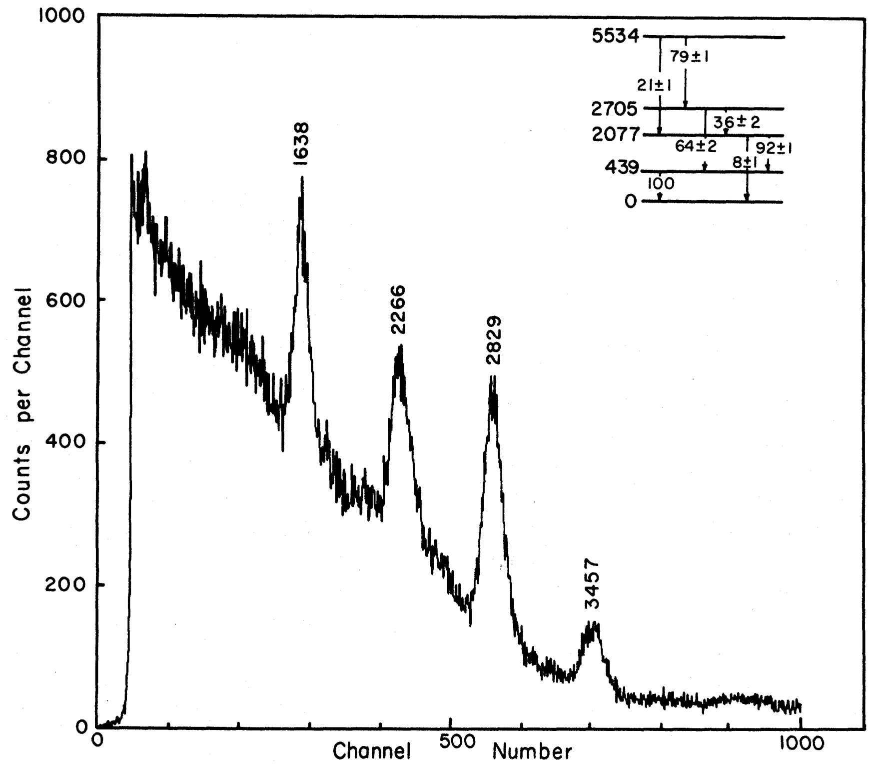

FIG. 1. Spectrum of γ rays observed in one of the 12.7×15.3 cm NaI(Tl) crystals in coincidence with protons deexciting the 5.534 MeV level in ^{23}Na. It may be noted that the approximately 5 cm thickness of lead absorber placed in front of the crystal to reduce the counting rate (for reasons explained in the text) completely absorbs two lower energy γ rays seen previously with this reaction (see Fig. 4, Ref. 5).

stopped from entering the particle detector by a 0.089 mm thick aluminum foil placed in front of the detectors, while a tantalum tube of inner diameter 2 mm passing through the center hole protected the detector from the direct beam.

The Compton polarimeter used in the present experiment consisted of a 5.1 cm ×5.1 cm NaI(Tl) crystal as the scattering crystal placed at 90° with respect to the beam direction with two 7.6 cm ×7.6 cm NaI(Tl) crystals touching the scattering crystal and positioned horizontally and vertically to it to absorb the γ rays Compton-scattered from the center crystal. The vertical and horizontal absorber crystals were shielded from each other by 1 cm of lead and from direct radiation by approximately 10 cm of lead. A 2.5 cm diameter hole in 7.5 cm thick lead was used to collimate the γ radiation from the target into the 5.1 cm ×5.1 cm scatterer crystal whose front face was 16.5 cm from the target center. A 3 mm thick lead absorber was placed inside the collimation hole to enhance the relative efficiency for higher energies.

Various radioactive sources were used to obtain the relative efficiencies of the vertical and horizontal absorber crystals to unpolarized γ rays scattered from the center crystal. The polarization sensitivity of the system to ~3.5 MeV γ rays was calculated theoretically following the procedure of Taras and Matas[11] and determined experimentally from measurements of the asymmetries of 3.003 +3.162 MeV transitions in ^{35}Cl following the ^{32}S(α, p)^{35}Cl reaction at 8 and 10 MeV bombarding energies.[12]

In order to measure the angular correlation of γ rays in coincidence with protons, observed close to 180°, deexciting the 5.534 MeV level (Method II of Litherland and Ferguson[13]), three 12.7 cm×15.3 cm NaI(Tl) crystals were positioned around the target. Since the beam current on target (~400 nA) was determined primarily by the particle γ-ray coincidence counting rates for the polarization measurement (120 h running time produced >1000 counts in vertical and horizontal absorber crystals), the counting rates in the three 12.7 cm ×15.3 cm NaI(Tl) crystals were reduced to acceptable limits by positioning the faces of the crystals 35 cm from the center of the target with 5 cm thick lead placed in front of each crystal. This had the effect of completely absorbing all

TABLE I. Attenuation corrected Legendre polynomial coefficients for the primary decays observed in the present work from the 5.534 MeV level.

Transition	a_2/a_0	a_4/a_0	Branching ratio (%)
5534 → 2077	0.43 ± 0.02	−0.20 ± 0.03	21 ± 1
5534 → 2705	0.14 ± 0.02	0.05 ± 0.02	79 ± 1

but the four highest energy γ rays in the spectra obtained as shown in Fig. 1.

Standard related-address data collection was carried out using a PDP-9 computer, random events being subtracted during later off-line analysis. At intervals during the polarization measurement the angular positions of two of the three 12.7 cm×15.3 cm NaI(Tl) crystals were changed.

The branching ratio for the decay of the 5.534 MeV level was calculated from the normalization factors A_0 corrected for relative efficiency which were obtained by linear least squares fits to the angular distributions:

$$W(\theta)=\sum_k A_k Q_k P_k(\cos\theta),$$

where the solid angle correction factors Q_2 and Q_4 were taken as 0.98 and 0.93, respectively.

The definition of γ-ray linear polarization used was

$$P(\theta)=\frac{W(\theta,\phi=0°)-W(\theta,\phi=90°)}{W(\theta,\phi=0°)+W(\theta,\phi=90°)},$$

and the phase convention of Rose and Brink[14] was adopted in the analysis. The correlation data were fitted allowing only population of the lowest substate since the reduced χ^2 for the best fits was very close to unity and it was found that allowing population of other substates showed only slightly better fits. The normalized Legendre polynomial coefficients and branching ratio are given in Table I.

III. RESULTS

Figure 2 shows the fits to the γ-ray angular correlation data for the 5.534 MeV → 2.077 MeV ($\frac{7}{2}^+$) transition for spin hypotheses $\frac{7}{2}$, $\frac{9}{2}$, and $\frac{11}{2}$ for the initial level. It may be noted from the reduced χ^2 vs arctanδ plot that the $\frac{9}{2}$ hypothesis may be ruled out at the 0.1% confidence level.

The measured asymmetry due to the polarization of 3.457 MeV γ rays was 0.14 ± 0.02 after correction for the relative efficiencies of the vertical and horizontal crystals. The polarization sensitivity of the present system was found to be 0.17 ± 0.03, thus yielding a polarization measurement of 0.82 ± 0.19 for the 3.457 MeV transition.

The polarization measurement together with

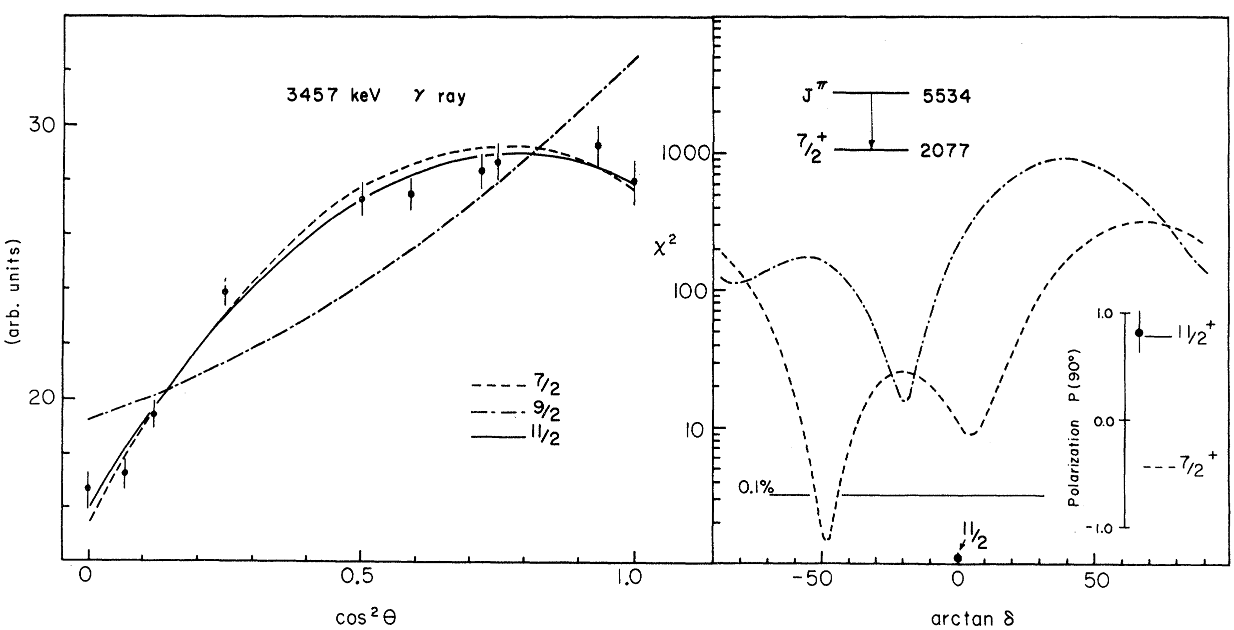

FIG. 2. Fits and χ^2 vs arctanδ plots for the angular correlation data obtained for the 3457 keV transition with spin hypotheses $J=\frac{7}{2}$, $\frac{9}{2}$, $\frac{11}{2}$. Also shown as an inset to the χ^2 plot is the result of the polarization measurement together with predicted polarizations for $J^\pi=\frac{7}{2}^+$ and $\frac{11}{2}^+$ hypotheses.

the predicted polarization for $J^\pi = \frac{11}{2}^+$ and for $J^\pi = \frac{7}{2}^+$ (using a multipole mixing ratio of −1.11, i.e., the minimum of the χ^2 vs arctanδ plot for $J = \frac{7}{2}$) are shown as an inset in Fig. 2.

The calculated polarizations were also obtained assuming population of the lowest substate alone since this had proved adequate for fitting the angular correlation data. Negative parity was not considered since this was ruled out by lifetime considerations.[5] Since the calculated polarization assuming $J^\pi = \frac{7}{2}^+$ is more than six standard deviations away from the mean of the measured polarization while the $J^\pi = \frac{11}{2}^+$ calculated polarization lies within the experimental errors of the measured polarization, one can assign $J^\pi = \frac{11}{2}^+$ to the 5.534 MeV level.

The multipole mixing ratio obtained from the γ-ray angular correlation of the 5.534 MeV ($\frac{11}{2}^+$) → 2.705 MeV ($\frac{9}{2}^+$) transition in the present experiment was -0.23 ± 0.01. The error on the multipole mixing ratio being calculated following the standard $\chi^2_{\min}+1$ rule.[15]

This multipole mixing ratio agrees within experimental errors with that obtained by Frank *et al.*,[5] as does the branching ratio for the decay modes of the 5.534 MeV level as given in Table I. As noted in the Introduction, these measurements are also in good agreement with theoretical predictions.

IV. CONCLUSIONS

Simultaneous particle γ-ray angular correlation and linear polarization measurements for the 3.457 MeV transition from the 5.534 MeV to the 2.077 MeV ($\frac{7}{2}^+$) level in ^{23}Na show conclusively that $J^\pi = \frac{11}{2}^+$ for the 5.534 MeV level. This result positively confirms earlier tentative $J^\pi = \frac{11}{2}^+$ assignments[4,5] to the 5.534 MeV level and indicates that decay modes for proposed higher members[8,9] of the $K^\pi = \frac{3}{2}^+$ ground state rotational band should cascade through the 5.534 MeV level.

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