Application of Polarized Deuterons in $(d,p\gamma)$ Angular Correlation Measurements*

C. R. Gould, R. O. Nelson, J. R. Williams, and D. R. Tilley
North Carolina State University, Raleigh, North Carolina 27607, and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

and

J. D. Hutton and N. R. Roberson
Duke University, Durham, North Carolina 27706, and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

and

C. E. Busch and T. B. Clegg
University of North Carolina, Chapel Hill, North Carolina 27514, and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706
(Received 14 December 1972)

The application and use of tensor polarized beams of deuterons in $(d,p\gamma)$ angular correlation experiments with spin-0 targets is described in connection with the measurement of mixing ratios of decays from spin-$\frac{3}{2}$ states in ^{13}C and ^{31}Si.

The angular distribution of γ rays emitted from an excited nuclear level populated in a nuclear reaction is a function of the initial and final level spins, the multipole mixing ratio for the γ-ray transition, and the population ratios for the magnetic substates of the initial state. These population ratios are not, in general, accurately predicted by reaction theories, and for this reason the technique[1] of detecting the outgoing particle along the direction of the beam axis has been widely used as a reaction-mechanism–independent method of extracting spectroscopic information from angular correlation experiments. In this collinear geometry, the maximum substate populated in the residual nucleus is limited to a value equal to the sum of the intrinsic spins of the incident particle, target, and emitted particle. A reaction such as (^{3}He, α) on spin-0 targets then populates only $|m|=\frac{1}{2}$ substates $[P(\frac{1}{2})=1]$, and there is no unknown population ratio. On the other hand, the (d,p) reaction on spin-0 targets populates both $|m|=\frac{1}{2}$ and $\frac{3}{2}$ substates, and the mixing ratio x can be extracted only if the experimental angular correlation provides enough information to determine both x and the unknown population parameter, $P(\frac{3}{2})/P(\frac{1}{2})$. This requirement is not always fulfilled and has often limited the usefulness of $(d,p\gamma)$ angular correlation measurements in the past, especially in studies of decays from spin-$\frac{3}{2}$ states.

The present work describes the utilization of tensor polarized deuteron beams in measuring $(d,p\gamma)$ angular correlations with spin-0 targets and illustrates the first application of a slight variation of a method proposed by McCullen and Seyler[2] for circumventing the difficulty associated with the unknown population parameter. The technique requires measuring correlations at different known values of the beam polarization, and then forming a combination of the correlations which is not dependent on the population of the $|m|=\frac{3}{2}$ substates in the residual nucleus. The method, as described below, was tested in a measurement of the mixing ratio of the $3.68\to0.0$ $(\frac{3}{2}^-\to\frac{1}{2}^-)$ transition in ^{13}C. We have obtained a mixing ratio of -0.154 ± 0.054, in agreement with a previous value of $-0.096^{+0.030}_{-0.021}$ obtained by Poletti, Olness, and Warburton from γ-γ correlation studies.[3] The method is applied here to a measurement of the unknown mixing ratios of the $2.32\to0.0$ $(\frac{3}{2}^+\to\frac{3}{2}^+)$ and the $3.54\to0.76$ $(\frac{3}{2}^-\to\frac{1}{2}^+)$ transitions in ^{31}Si.

The experiments consisted of angular correlation studies of the reaction ^{30}Si$(dp\gamma)^{31}$Si initiated by ~15-nA beams of polarized deuterons from the Triangle Universities Nuclear Laboratory Lamb-shift, polarized ion source.[4] The protons were detected at ~180° in a 500-μm silicon surface-barrier detector and the coincident γ rays were detected at angles between 25° and 90° in an array of four 3.7×5.1-cm^2 integral NaI(Tl) detectors. The experiments were performed at a bombarding energy of 4.15 MeV with a 200 μg/cm^2 target of silicon enriched to 98% ^{30}Si.

Measurements were first made with polarized deuterons in the $m_I=+1$ magnetic substate (p_z

$=p_{zz}=0.71$) and then made with deuterons in the $m_I=0$ substate ($p_z\sim 0$, $p_{zz}=-1.42$). Here p_z and p_{zz} are the vector and tensor polarizations, respectively, of the incident deuteron beam. The experimental values quoted are 71% of the theoretical maximum beam polarizations and were measured to an accuracy of ±3% by means of the quench ratio method.[5] The spin quantization axis of the polarized beam was always along the beam direction at the target and the correlations measured then depend only on the tensor polarization of the beam—not on the vector polarization. The decay of the spin-$\frac{1}{2}$ state of 0.76 MeV in ^{31}Si was found to be isotropic in each of the experiments and served as a check on the procedures.

The experimental results for the 2.32→0.0 angular correlation in ^{31}Si are summarized in Fig. 1. On the left are shown the data obtained with deuteron beams of tensor polarizations $p_{zz}=-1.42$ and $p_{zz}=0.71$. The two sets of data have been normalized to the same amount of total incident beam on target. Both correlations still depend on an unknown population parameter although the correlation with $p_{zz}=-1.42$ corresponds to a population of mainly $|m|=\frac{1}{2}$ substates in ^{31}Si. The contribution of the $|m|=\frac{3}{2}$ substates to this correlation can be unambiguously eliminated, however, by combining the results of the two measurements. Extending method I of Ref. 2 one can form the weighted difference

$$W(\theta)=W_\alpha(\theta)-\frac{2+p_{zz}{}^{\alpha}}{2+p_{zz}{}^{\beta}}W_\beta(\theta),$$

where $W_\alpha(\theta)$ and $W_\beta(\theta)$ are the experimental correlations associated with the incident beam tensor polarizations $p_{zz}{}^{\alpha}$ and $p_{zz}{}^{\beta}$. The correlation $W(\theta)$ corresponds to a population of only the $|m|=\frac{1}{2}$ substates and can therefore be analyzed without invoking any unknown population parameter in the fitting procedure. The result of a least-squares fit of $W(\theta)$ to the theoretical correlation formula in this case is shown in the solid line on the plot of χ^2 versus $\arctan x$ in Fig. 1(b). The fitting procedure used in this laboratory is described elsewhere.[6] The phase convention for the mixing ratio is that of Rose and Brink.[7] Two solutions for the mixing ratio are seen to be possible on the basis of the correlation data. These correspond to $\arctan x\sim-22°$ and $-53°$, yielding mixing ratios of $x=-0.41\pm0.22$ or $-1.34^{+0.44}_{-0.77}$. The theoretical fit to the data in these cases is shown in Fig. 1(c).

A priori, both solutions are equally acceptable and an independent experiment such as a mea-

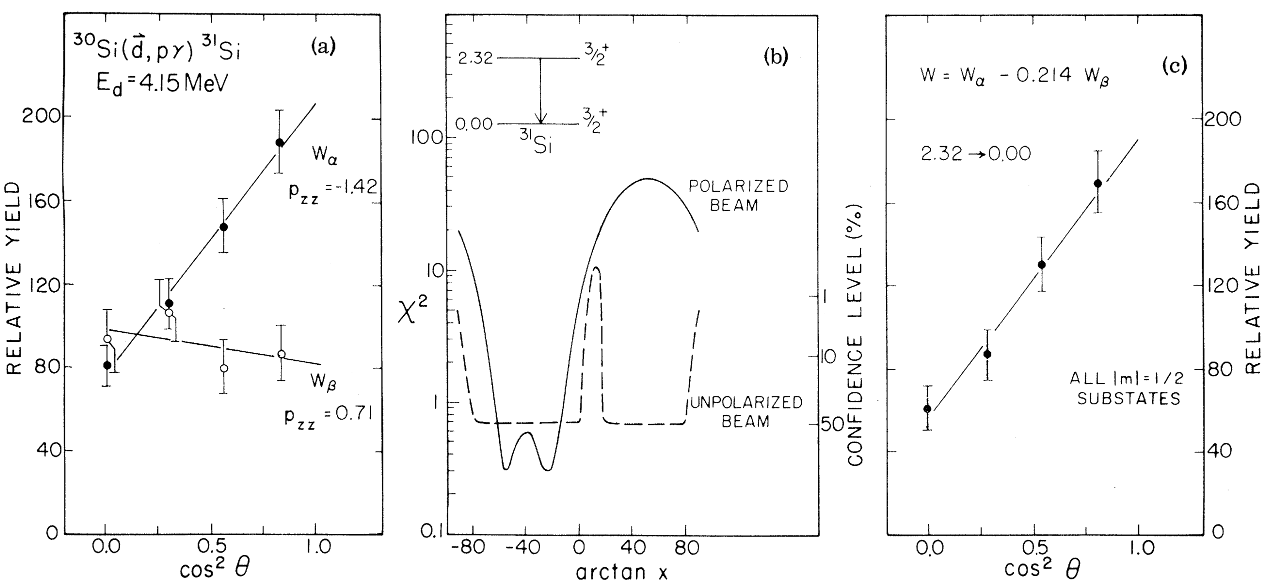

FIG. 1. Summary of data for the angular correlation of the 2.32→0.0 transition in ^{31}Si. (a) The correlations W_α and W_β, obtained with deuteron beams of the tensor polarizations −1.42 and 0.71, respectively. (b) Plots of χ^2 versus the arc tangent of the mixing ratio. The solid line is the result of a fit of the derived correlation W to the theoretical correlation formula, assuming a population of only the $|m|=\frac{1}{2}$ substates in ^{31}Si (see text). The dotted line is from Ref. 9 and is the result of the fit to data for the 2.32→0.0 transition obtained with an unpolarized beam where both $|m|=\frac{1}{2}$ and $\frac{3}{2}$ substates are populated. (c) The derived correlation W and the theoretical fit corresponding to the two minima of χ^2 in the solid line of (b).

surement of the γ-ray linear polarization would be required to rule out one or the other. However, the smaller value seems more likely in this case as the decay is an interband $K=\frac{1}{2}\rightarrow\frac{3}{2}$ transition for which one does not expect any great $E2$ enhancement. On the basis of the lifetime[8] of 55 fsec, the larger value of the mixing ratio would predict an $E2$ strength of 18 Weisskopf units (W.u.) for the $2.32\rightarrow 0.0$ transition. This would be anomalously high for such a cross-band transition in this region. The smaller value of the mixing ratio predicts an $M1$ enhancement of 0.029 W.u. and an $E2$ enhancement of 3.9 W.u.

The dotted line in the χ^2 plot of Fig. 1 is from Webb *et al.*[9] and shows the result of a least-squares fit to correlation data for the $2.32\rightarrow 0.0$ transition obtained with an unpolarized beam. Both $|m|=\frac{1}{2}$ and $\frac{3}{2}$ substates are then considered to be populated. The resulting broad range of minima in the values of χ^2 indicate that virtually no mixing-ratio information can be extracted under such circumstances, and therefore serve to illustrate the utility of the present method using polarized deuteron beams.

An equivalent analysis of the correlations for the $3.54\rightarrow 0.76$ transition leads to possible mixing ratios of $x=-0.015\pm 0.040$ and 1.8 ± 0.2. The large value can be ruled out from the knowledge of the lifetime[8] of this level (<15 fsec) as it implies an unacceptably large $M2$ enhancement of $>10^3$ W.u. The correct solution is as expected, $x\sim 0.0$, implying the transition is pure $E1$.

Many-particle shell-model calculations of electromagnetic transition strengths among the positive parity states in this mass region have been performed by Glaudemans, Endt, and Dieperink.[10] Their predictions have employed effective charges for the $E2$ transitions and both effective g factors and effective reduced matrix elements for the $M1$ transitions. In particular, the use of effective reduced matrix elements for the $M1$ decays has been extremely successful in ^{31}Si where all available experimental information to date has, within errors, agreed with the theoretical predictions. The utility of this approach would seem to be further supported by the results of the present work. The measured mixing ratio of -0.41 ± 0.22 for the $2.32\rightarrow 0.0$ transitions is in agreement in sign and magnitude with the predicted value of -0.19 (sign corrected for the phase convention of Ref. 6), although the $E2$ matrix element may be somewhat underestimated.

In conclusion then, we have shown that the use of tensor polarized beams of deuterons can eliminate the difficulties associated with the unknown population parameter in $(d,p\gamma)$ angular correlation experiments with spin-0 targets. As such the technique may be advantageous in the study of decays from any half-integral spin state, except $j=\frac{1}{2}$. The main benefit would, however, lie in the study of decays from low spin states, in particular $j=\frac{3}{2}$. In such cases, the method allows the extraction of multipole mixing ratios which are often not readily available by any other means, and which constitute a valuable experimental test of nuclear structure calculations.

---

*Work supported in part by the U. S. Atomic Energy Commission.

[1]A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39, 788 (1961).

[2]J. D. McCullen and R. G. Seyler, Nucl. Phys. A139, 203 (1969).

[3]A. R. Poletti, J. W. Olness, and E. K. Warburton, Phys. Rev. 151, 812 (1966).

[4]T. B. Clegg, C. A. Bissinger, W. Haeberli, and P. A. Quin, in *Proceedings of the Third International Conference on Polarization Phenomena in Nuclear Reactions,* edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970), p. 835.

[5]G. G. Ohlsen, J. L. McKibben, G. P. Lawrence, P. W. Keaton, Jr., and D. D. Armstrong, Phys. Rev. Lett. 27, 599 (1971).

[6]G. P. Lamaze, C. R. Gould, C. E. Moss, N. R. Roberson, and D. R. Tilley, Nucl. Phys. A158, 43 (1970).

[7]H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).

[8]H. D. Graber, P. W. M. Glaudemans, and P. M. Endt, Nucl. Phys. A149, 1 (1970).

[9]V. H. Webb, N. R. Roberson, R. V. Poore, and D. R. Tilley, Phys. Rev. 170, 979 (1968).

[10]P. W. M. Glaudemans, P. M. Endt, and A. E. L. Dieperink, Ann. Phys. (New York) 63, 134 (1971).