INCONSISTENCIES IN ANGULAR MOMENTUM ASSIGNMENTS TO NUCLEAR ENERGY LEVELS IN ^{41}Ca *

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The reaction ^{40}Ca$(d,p)^{41}$Ca has been studied with vector-polarized deuterons of an energy of 11 MeV. The measured vector analyzing power was used to make angular momentum assignments to states in ^{41}Ca at E_x=3.62, 4.62, and 4.77 MeV. Two of the present j assignments are in disagreement with results obtained by other methods. Further experiments are needed to investigate the reliability of different methods of determining angular momenta of nuclear energy levels.

Deuteron stripping reactions are often used to obtain information on the angular momenta of excited states of nuclei. The angular dependence of the (d,p) stripping cross section determines the orbital angular momentum l_n of the transferred neutron, but even for spin-zero target nuclei more complicated experiments are needed to distinguish between the two possible values of the total angular momentum of the final state, $j = l_n + \frac{1}{2}$ and $j = l_n - \frac{1}{2}$. One method to determine the total angular momentum involves a measurement of the directional correlation between the outgoing protons and the γ rays from the decay of the final state in the residual nucleus.[1] This method has been used most frequently for $l_n = 1$ transitions where the correlation is generally not isotropic for $j^\pi = \frac{3}{2}^-$ states but must be isotropic for $\frac{1}{2}^-$ states. Another method consists of observing the circular polarization of primary γ rays following the capture of polarized thermal neutrons.[2] The advantage of these methods is that the j assignments are independent of any assumptions about the reaction mechanism, but they have the disadvantage that they require relatively difficult and time-consuming experiments.

It has been noted by Lee and Schiffer[3-5] that the (d,p) stripping cross section at large angles shows a systematic j dependence, particularly for $l_n = 1$ transitions. This observation provides a relatively simple method of determining j values, but the effect is primarily empirical and has the disadvantage that it may not be valid for weak transitions where compound-nucleus processes could affect the cross section at large angles.

It has recently been shown that the j value in a (d,p) stripping reaction can be determined by inducing the reaction with vector-polarized deuterons.[6] The cross section for a given transition is measured with the deuteron polarization both parallel and antiparallel to the normal to the reaction plane, $\vec{k}_{in} \times \vec{k}_{out}$. The difference between these cross sections divided by their sum is proportional to the vector analyzing power, $iT_{11}(\theta)$, of the reaction. Yule and Haeberli[6] observed that for $l_n = 1$ transitions the vector analyzing power is strikingly different for $\frac{1}{2}^-$ and $\frac{3}{2}^-$ final states. The effect is illustrated in Fig. 1(a), which shows the present measurements for $l_n = 1$

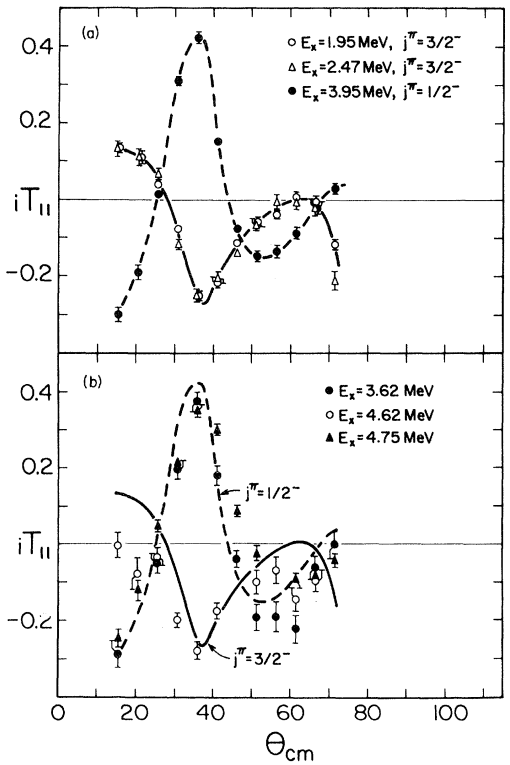

FIG. 1. (a) Measured vector analyzing powers for the reaction ^{40}Ca$(d,p)^{41}$Ca at 11 MeV bombarding energy leading to states in ^{41}Ca at E_x=1.95, 2.47, and 3.95 MeV having $j^\pi = \frac{3}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$, respectively. The solid and dashed curves show the trend of the data for the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ transitions, respectively. (b) Measured vector analyzing powers for the reaction ^{40}Ca$(d,p)^{41}$Ca at 11 MeV bombarding energy leading to states in ^{41}Ca at E_x=3.62, 4.62, and 4.77 MeV. The solid and dashed curves are identical to those in (a).

transitions to the strongly populated states in ^{41}Ca at $E_x = 1.95$, 2.47, and 3.95 MeV, having $j^\pi = \frac{3}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$, respectively.[7] The solid and dashed lines are smooth curves drawn through the data points for the two j values. The measurements were made with the purely vector-polarized deuteron beam obtained from the improved Lamb-shift polarized ion source[8-10] installed on the Wisconsin tandem accelerator. The deuteron bombarding energy was 11 MeV. The energy resolution in the proton spectra was about 50 keV.

Since the original observation of this j-dependent effect, many $l_n = 1$ transitions have been investigated,[11-17] including target nuclei as light as ^{6}Li and as heavy as ^{207}Pb, and including transitions with spectroscopic factors as low as $S = 0.02$. The experimental results are all clearly characteristic of either $\frac{1}{2}^-$ or $\frac{3}{2}^-$ final states. The observed j dependence was found to agree with distorted-wave calculations,[6] but the effect is sufficiently insensitive to bombarding energy, Q value, and target mass that one need not depend on calculations to assign j values.[13] The insensitivity to Q value is shown by the data for $j^\pi = \frac{3}{2}^-$ transitions on ^{40}Ca in Fig. 1(a).

The purpose of this Letter is to report discrepancies between j assignments in ^{41}Ca obtained with the polarized-beam method and j assignments from other methods.

Besides the strong $l_n = 1$ transitions mentioned above, weaker $l_n = 1$ transitions in ^{40}Ca(d,p) leading to known excited states[18] in ^{41}Ca at $E_x = 3.62$, 4.62, and 4.77 MeV were studied in the present experiment. The results are shown in Fig. 1(b). The smooth curves are identical to those in Fig. 1(a). Data could not be obtained at some angles because of unresolved contaminant peaks from ^{12}C$(d,p)^{13}$C and ^{16}O$(d,p)^{17}$O. Comparison of the measured vector analyzing powers with the curves in Fig. 1(b) indicates that $j^\pi = \frac{3}{2}^-$ for the state at $E_x = 4.62$ MeV and $j^\pi = \frac{1}{2}^-$ for the states at $E_x = 3.62$ and 4.77 MeV. The same j assignments were also indicated by comparison of the data with DWBA calculations.

$E_x = 3.62$ MeV. The present j assignment is in disagreement with the results of $(d,p\gamma)$ experiments.[19-21] The angular correlation between the protons and the γ rays from the decay of this state to the ground state of ^{41}Ca was reported to be anisotropic.[19,20] Therefore, the spin of the decaying state cannot be $\frac{1}{2}^-$, which contradicts the present j assignment. Regardless of the result of the angular correlation measurement, the observation of a γ decay[21] to the $\frac{7}{2}^-$ ground state strongly supports a $\frac{3}{2}^-$ assignment, since a $\frac{1}{2}^-$ state should decay to lower excited states having $j = \frac{1}{2}$ or $\frac{3}{2}$. The ground-state γ transition was not reported in the spectrum of γ rays following thermal neutron capture in natural calcium,[22] but this transition was possibly obscured by other γ rays.

Spin assignments based on the observation of the j dependence of the cross section at 7[18] and 12 MeV[23] deuteron energies are contradictory.

$E_x = 4.62$ MeV. Cross-section measurements at 7[18] and 9 MeV[24] suggested a $\frac{1}{2}^-$ assignment, as opposed to the $\frac{3}{2}^-$ assignment indicated by the present results. However, this transition is so weak[18] ($S = 0.05$) that the j dependence of the cross section may not be a valid method. No other j assignments for this state have been reported.

$E_x = 4.77$ MeV. The present $\frac{1}{2}^-$ assignment is in agreement with a measurement of the circular polarization of the γ rays populating this state following the capture of polarized thermal neutrons.[25] The j value from this experiment was only tentative, however, because of large experimental uncertainties. Cross-section measurements at 7[18] and 9 MeV[2] also suggested a $\frac{1}{2}^-$ assignment.

The discrepancy in j assignment between the $(d,p\gamma)$ measurements and the polarized-beam method for the state in ^{41}Ca at $E_x = 3.62$ MeV is particularly disturbing. Besides this state, $(d,p\gamma)$ experiments have given j assignments contradictory to the polarized-beam method for strong $l_n = 1$ transitions on ^{52}Cr and ^{54}Fe (Ref. 6; Bjorkholm and Schiffer[26]). Lee and Schiffer[27] suggested that the presence of unresolved contaminant γ rays might have caused an apparent anisotropy in the $p-\gamma$ angular correlation on ^{54}Fe and thus an incorrect j assignment. It is not clear whether this explanation is tenable in the other cases, particularly since the strong ground-state decay of the state in ^{41}Ca at $E_x = 3.62$ MeV observed with a high-resolution γ detector[21] seems to exclude a $j^\pi = \frac{1}{2}^-$ assignment to this level. On the other hand, the polarized-beam method yields such a clear distinction between $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states that neither poor counting statistics nor relatively weak, unresolved levels can affect the j assignments. Contributions to the reaction ^{40}Ca$(d,p)^{41}$Ca from compound-nucleus formation appear to be insignificant at 11 MeV.[23] The possibility that nuclear structure effects peculiar to a given final state could result in incorrect assignments from the polarized beam

method seems remote but cannot be entirely excluded.

Further measurements are needed to locate the source of the discrepancies in j assignments. Both $p-\gamma$ angular-correlation and γ-ray circular-polarization measurements using high-resolution γ detectors would seem appropriate for the transitions in question since these experiments provide independent checks on j assignments. For the state in ^{41}Ca at $E_x = 3.62$ MeV we suggest the possibility that there exist two unresolved states whose relative population in the (d,p) reaction is different at 4 MeV deuteron energy where the $(d,p\gamma)$ measurements[19-21] were made than at 11 MeV where the polarized-beam method was employed.

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[1]L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. 25, 729 (1951).
[2]L. C. Biedenharn, M. E. Rose, and G. B. Arfken, Phys. Rev. 83, 683 (1951).
[3]L. L. Lee, Jr. and J. P. Schiffer, Phys. Rev. 136, B405 (1964).
[4]J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and C. Mayer-Böricke, Phys. Rev. 147, 829 (1966).
[5]L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 154, 1097 (1966).
[6]T. J. Yule and W. Haeberli, Nucl. Phys. A117, 1 (1968).
[7]P. M. Endt and C. van der Leun, Nucl. Phys. A105, 1 (1967).
[8]T. B. Clegg, G. R. Plattner, L. G. Keller, and W. Haeberli, Nucl. Instrum. Methods 57, 167 (1967).
[9]T. B. Clegg, G. R. Plattner, and W. Haeberli, Nucl. Instrum. Methods 62, 343 (1968).
[10]T. B. Clegg, P. A. Quin, and W. Haeberli, private communication.
[11]A. M. Baxter, J. A. R. Griffith, and S. Roman, Phys. Rev. Lett. 20, 1114 (1968).
[12]W. Duerr, G. Clausnitzer, D. Fick, R. Fleischmann, H. M. Hofmann, and K. Kilian, Nucl. Phys. A122, 153 (1968).
[13]D. C. Kocher and W. Haeberli, Phys. Rev. Lett. 23, 315 (1969).
[14]S. Roman, in Proceedings of the Symposium on Nuclear Reaction Mechanisms and Polarization Phenomena, Université Laval, Quebec, Canada, 1-2 September 1969 (to be published).
[15]P. J. Bjorkholm and W. Haeberli, to be published.
[16]D. C. Kocher and W. Haeberli, to be published.
[17]H.-H. Cuno, G. Clausnitzer, and R. Fleischmann, Nucl. Phys. A139, 657 (1969).
[18]T. A. Belote, A. Sperduto, and W. W. Buechner, Phys. Rev. 139, B80 (1965).
[19]J. P. Schapira, G. Johnson, and R. Blake, Compt. Rend. Acad. Sci. Paris 267, 832 (1968).
[20]G. Johnson, R. S. Blake, H. Laurent, F. Picard, and J. P. Schapira, to be published.
[21]H. Laurent, S. Fortier, and J. P. Schapira, to be published.
[22]H. Gruppelaar and P. Spilling, Nucl. Phys. A102, 226 (1967).
[23]K. K. Seth, J. Picard, and G. R. Satchler, to be published.
[24]B. H. Wildenthal and D. H. Youngblood, Bull. Amer. Phys. Soc. 10, 377 (1965).
[25]K. Abrahams and W. Ratyński, Nucl. Phys. A124, 34 (1969).
[26]P. J. Bjorkholm and W. Haeberli, Bull. Amer. Phys. Soc. 13, 723 (1968).
[27]L. L. Lee, Jr. and J. P. Schiffer, private communication.

EXPERIMENTAL INFORMATION CONCERNING DEFORMATION OF NEUTRON RICH NUCLEI IN THE $A \sim 100$ REGION*

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We present experimental results on the ground-state bands of light even-even nuclei produced in the primary fission of ^{252}Cf. The systematics of the energy spacings and lifetimes are similar to those of deformed nuclei in the rare earth and actinide regions.

In this Letter we report experimental evidence for rotational-like behavior in very neutron-rich even-even $_{40}$Zr, $_{42}$Mo, $_{44}$Ru, and $_{46}$Pd isotopes. These results support recent theoretical studies by Ragnarsson and Nilsson[1] and by Arseniev, Sobieczewski, and Soloviev[2] which have predicted a new region of stable deformation which includes these nuclei. Fission fragments from spontaneous fission of ^{252}Cf provided experimental access to this region. We have obtained systematic information on the ground-state bands of all the light even-even fission products having calculated independent yields[3] of greater than approximately 1% per fission.

Prompt K x rays and/or γ rays in coincidence with pairs of fission fragments were measured