Direct Excitation of Rotational Levels of ^{152}Sm with Low-Energy Neutrons*

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(Received 3 May 1976)

Inelastic neutron scattering data presented for 2.5-MeV neutrons bombarding ^{152}Sm evince the direct excitation of rotational 2^+, 4^+, 6^+, and 8^+ levels of this deformed nucleus. The measured scattering cross sections for these levels are very much larger than can be ascribed to a statistical model mechanism. Coupled-channels calculations of the inelastic scattering cross sections also fall well below the observed enhancements for the 4^+ and 6^+ levels.

In this Letter, we present what we believe to be the first direct and unambiguous evidence for strong collective enhancement of neutron inelastic scattering at low bombarding energy. The evidence shows strong direct excitation of several members of the ground-state rotational band, including 4^+, 6^+, and 8^+ levels, of the deformed nuclide ^{152}Sm at an incident neutron energy of 2.5 MeV. Transfer of six units of angular momentum has rarely been observed in neutron inelastic scattering and collective enhancements for such levels have not been reported.[1] That nuclear deformations directly affect neutron scattering had been suggested by the total-cross-section survey of Glasgow and Foster[2] in 1971 and clearly established in 1973 in high-precision studies of total cross sections for the transitional samarium nuclei.[3] A recent elastic scattering study in this laboratory at 6.25 MeV incident energy was successfully analyzed by LaGrange *et al.*[4] in terms of the deformation effects on elastic scattering, but no inelastic scattering measurements were obtained.

In the meantime, and over a 15-yr period, numerous studies of low-energy inelastic scattering from spherical nuclei were shown to yield a much different picture of neutron scattering. Only the size of the nucleus, strength of the average scattering potential, and spins and parities of initial and final levels were needed to specify the scattering. Thus an early review of Day[5] emphasized the power of neutron inelastic scattering studies for spin determinations, a point extensively confirmed and amplified in subsequent reviews, in which statistical model analyses are shown to provide good fits to scattering cross sections[6] and to γ-ray angular distributions from $(n,n'\gamma)$ reactions.[7] Studies show strong excitation of levels excited with 3 units of angular momentum transfer or less.[8] Higher spin transfers are weakly excited.[1]

Several earlier experiments had shown evidence for direct excitation at energies above 7 MeV. In particular, this category includes the work of Cranberg and co-workers[9] on Pb isotopes and the early work of Stelson *et al.*[10] on light nuclei; but these studies did not relate scattering to stable nuclear deformations.

The measurements reported in this Letter explored especially the differences in scattering from spherical ^{148}Sm and deformed ^{152}Sm for an incident neutron energy of 2.5 MeV, where Shamu *et al.*[3] had reported large deformation effects. Both neutron and γ-ray detection were utilized to enable the study of several excited levels.

For both neutron and γ-ray detection the University of Kentucky compressed beam-pulse time-of-flight (TOF) facility was used.[11] The scatterers were separated-isotope samples of $^{148}Sm_2O_3$ and $^{152}Sm_2O_3$. Neutron inelastic differential scattering cross sections are presented here for thirteen angles from 20 to 157 deg. The measured oxygen scattering yields, by comparison to the known cross section for oxygen,[12] were used for normalization. Geometric effects, multiple scattering, and neutron attenuation have been properly accounted for.

Figure 1 displays the inelastic cross sections for scattering from the first excited states (2^+) of ^{148}Sm and ^{152}Sm. The solid curves are Legendre polynomial fits to the data. The manifestation of a direct reaction mechanism in the ^{152}Sm inelastic cross section is obvious in these data. Namely, the structure in the angular distribution for the rotational nucleus ^{152}Sm is marked compared with that for the spherical nucleus ^{148}Sm. Since there are many more inelastic channels open at 2.5 MeV in ^{152}Sm than in ^{148}Sm (approximately 70 as compared to 17), compound-system (CS) decay via the 2^+ exit channel should be reduced by a factor of ~ 3 in ^{152}Sm relative to ^{148}Sm. However, as seen in Fig. 1, the scattering cross sections are larger for ^{152}Sm than for ^{148}Sm.

We have estimated the CS contribution to the in-

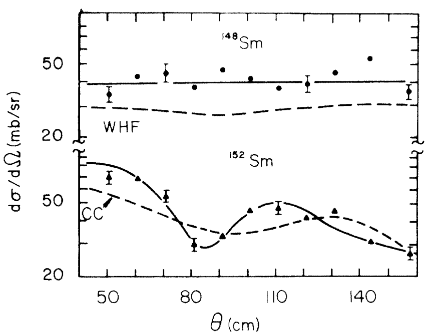

FIG. 1. Inelastic scattering cross sections from the first 2^+ states of ^{148}Sm and ^{152}Sm for an incident neutron energy of 2.47 MeV. The cross sections are plotted in center-of-mass coordinates. Solid lines are Legendre polynomial fits to these data; dashed curves represent theoretical calculations described in the text.

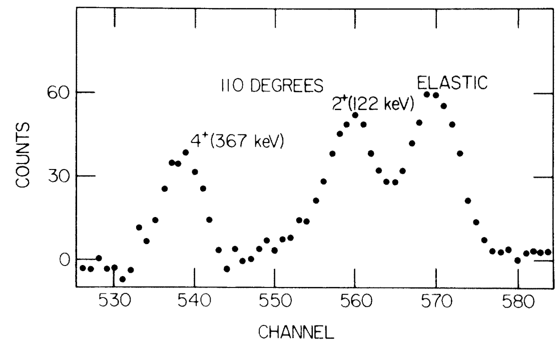

FIG. 2. ^{152}Sm + n time-of-flight spectrum for 2.47-MeV incident neutrons. Background contributions are subtracted. The three peaks are identified with the elastic scattering and scattering from the first two excited levels of ^{152}Sm.

elastic scattering cross sections using the Wolfenstein-Hauser-Feshbach (WHF) model.[13] The transmission coefficients needed in the WHF calculations were calculated with a scattering potential determined by fitting elastic differential scattering cross sections for these isotopes. A detailed description of those measurements and analyses will be published later.[14] The WHF calculations for the 2^+ levels ascribe about 28 mb/sr for ^{148}Sm, as indicated by the upper dashed curve in Fig. 1, and 10 mb/sr for ^{152}Sm. That is, only around 20% of the ^{152}Sm inelastic scattering to the 2^+ level is due to CS formation.

An updated version of the coupled-channel (CC) code of Tamura[15] was employed for estimating the direct inelastic scattering. The coupled-channel model is essentially an optical model which couples states through the deformation of the nuclear surface, parametrized as $R = R_0[1 + \sum \beta_l Y_{l0}(\theta)]$. The deformation parameters β_l represent collective modes. The CC model used for the calculations presented here is the one extensively developed and tested by Lagrange *et al.*[4] It includes coupling of the ground and first 2^+ levels. The potential and the coupling parameter, $\beta_2 = 0.22$, were determined to fit low-energy s- and p-wave strength functions and total cross sections over the incident neutron energy range from 0.8 to 14 MeV.[4] Our two-channel CC calculation for the ^{152}Sm 2^+ level is shown as the lower dashed curve in Fig. 1. The calculation fits the average magnitude of the inelastic cross sections, as seen in Fig. 1, but provides too little structure in the inelastic scattering angular distribution. Our calculations indicate that coupling additional channels and including β_4 can enhance the structure in the 2^+ calculation, but cannot provide a fit to all of the inelastic data.

That other higher-spin channels are strongly enhanced is the most remarkable new result of this study, as is evident in Figs. 2 and 3. A scattered neutron TOF spectrum is shown in Fig. 2 for ^{152}Sm, where it is evident that the 4^+ excitation strength is quite comparable to the strongly enhanced 2^+ and to the elastic scattering. The measured cross section to the 4^+ level is 250 ± 30 mb, enhanced by more than a factor of 3 over a conventional statistical model calculation (Table I).

The ^{152}Sm$(n, n'\gamma)$ differential cross sections have been measured; and a γ-ray spectrum obtained at 140 deg is shown in Fig. 3, where one

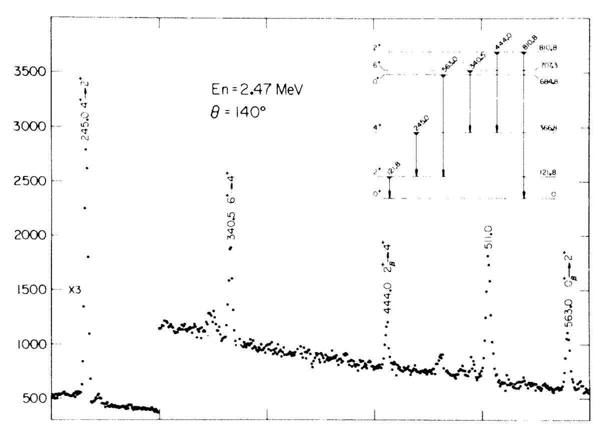

FIG. 3. $(n, n'\gamma)$ photon spectra for the rotational nucleus ^{152}Sm. The peaks in the spectrum can be identified with rotational and vibrational transitions in the level scheme shown.

TABLE I. Measured inelastic scattering cross sections for ^{152}Sm compared with CC and WHF calculations. Calculations are described in the text.

Level	Measured (n,n')	Measured $(n,n'\gamma)$	Theory CC	Theory WHF	CC + WHF
2^+	600 ± 40	$\cdots$	450	140	590
4^+	250 ± 30	272 ± 30	70	90	160
6^+	$\cdots$	50 ± 10	12	21	33
8^+	$\cdots$	7 ± 4	$\cdots$	1	$\cdots$

sees strong excitation of the 4^+ and 6^+ members of the ground-state rotational band. The $6^+ \rightarrow 4^+$ transition is one of the strong transitions, stronger than those from nearby lower spin states. The unusual character of this excitation is also indicated by noting that at 2.5 MeV the value of kR, the angular momentum parameter for the incident neutrons, is ~ 2. A recent Coulomb excitation experiment[16] confirms the identification of the 4^+ and 6^+ levels. Our γ-ray energies correspond to those of Ref. 16 to within 0.3 keV.

The measured $(n,n'\gamma)$ and (n,n') cross sections are presented in Table I. They are compared there with results of our CC and WHF model calculations. The comparison shows that scattering from the 2^+, 4^+, 6^+, and 8^+ levels is 3 or 4 times larger than predicted by the statistical model and that even an incoherent combination of CC and WHF models falls far below the measured values for the 4^+ and 6^+ states. These coupled-channels results include both β_2 and β_4. Significant variations of these parameters ranging from realistic[17] to extreme values and variations of potential depths and form factors do not improve the fit to the cross sections of the 0^+, 2^+, 4^+, and 6^+ levels.

In conclusion, the principal purpose of this Letter is to point out the dramatic collective enhancements of inelastic neutron scattering cross sections at low incident energy, not just to the 2^+ level, but apparently to the whole ground-state rotational band. These enhancements are observed at incident neutron energies where all previous studies have indicated the dominance of the statistical model.

We gratefully acknowledge the assistance of Professor J. L. Weil in a data-taking phase of this work.

*Work supported in part by the National Science Foundation.

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