Title

OBSERVATION OF STRIKING SHAPE DIFFERENCES BETWEEN 21+ ANGULAR DISTRIBUTIONS FOR HEAVY-ION-INDUCED TWO-NEUTRON STRIPPING AND PICKUP REACTIONS IN TRANSITIONAL SAMARIUM NUCLEI

Author

Maguire, C.F.

Publication Date

1977-09-01

Published in Physical Review Letters,
Vol. 40, No. 6, 358 - 361 (February 6, 1978)

LBL-7187

OBSERVATION OF STRIKING SHAPE DIFFERENCES BETWEEN 2_1^+ ANGULAR DISTRIBUTIONS FOR HEAVY-ION-INDUCED TWO-NEUTRON STRIPPING AND PICKUP REACTIONS IN TRANSITIONAL SAMARIUM NUCLEI

C. F. Maguire, D. L. Hendrie, U. Jab
J. Mahoney, D. K. Scott, J. S. Vaa
R. J. Ascuitto, and K. Kuma

September 23, 1977

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

Observation of Striking Shape Differences between 2_1^+ Angular Distributions for Heavy-Ion-Induced Two-Neutron Stripping and Pickup Reactions in Transitional Samarium Nuclei

C. F. Maguire,[a] D. L. Hendrie, U. Jahnke,[b] J. Mahoney, and D. K. Scott
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

J. S. Vaagen[c] and R. J. Ascuitto
Yale University, New Haven, Connecticut 06520

and

K. Kumar[d]
Vanderbilt University, Nashville, Tennessee 37235

(Received 23 September 1977)

The reactions $^{148}\text{Sm}(^{18}\text{O} \leftrightarrow {}^{16}\text{O})^{150}\text{Sm}$ and $^{150}\text{Sm}(^{12}\text{C}, {}^{14}\text{C})^{148}\text{Sm}$ have been performed as part of a heavy-ion study of the transitional samarium region. The angular distributions for the ground-state transitions have a typical bell shape. While the 2_1^+ angular distribution is bell shaped in the stripping reaction, it is flat with an interference minimum in both pickup reactions. The striking difference between the 2_1^+ angular distributions is not explained satisfactorily by current theories.

The even-even samarium isotopes are characterized by a rapid change of the nuclear structure with neutron number ($^{144}_{62}\text{Sm}_{82}$ is semiclosed while $^{154}_{62}\text{Sm}_{92}$ is a good rotor). Energy levels and electromagnetic moments of many of these isotopes have been explained (and in some cases predicted) on the basis of different nuclear structure theories—two of the most prominent being the boson expansion method[1] (called BEM below) and the dynamic deformation method[2] (called DDM below). The BEM structure theory has previously been combined with the coupled-channel Born-approximation (CCBA) reaction theory[3] by Sørensen[4] who analyzed an earlier version of our data on heavy-ion (^{16,18}O) induced two-neutron transfer in ^{148}Sm $\leftrightarrow$ ^{150}Sm. In this Letter, we present our data on ^{150}Sm(^{16}O, ^{18}O)^{148}Sm and ^{148}Sm(^{18}O ^{16}O)^{150}Sm as well as additional data on ^{150}Sm(^{12}C, ^{14}C)^{148}Sm. We also present the first results of a theoretical analysis where the DDM structure theory[2] is combined with the CCBA reaction theory.[3] We argue that earlier explanations[4] of the striking shape difference between 2_1^+ angular distributions in stripping and pickup reactions, based on the BEM method, are not convincing, and that this problem is not explained satisfactorily as yet.

The present heavy-ion–induced reactions were performed to explore further the role of the multistep two-neutron transfer routes[4-6] and, if possible, to relate the observed angular distribution patterns to the structure aspects. Our work represents the first heavy-ion study of transitional nuclei. That heavy-ion reactions provide a useful tool for such a purpose has been pointed out by several authors.[5,6] A direct (one-step) transfer, at energies not too high above the Coulomb barrier, typically results in a predominantly bell-shaped angular distribution while the angular distribution for a two-step process (transfer coupled with inelastic excitation) is much broader with a more pronounced diffraction pattern at forward angles.

The inverse reactions ^{148}Sm(^{18}O $\leftrightarrow$ ^{16}O)^{150}Sm were performed at bombarding energies of $E_{\rm lab}(^{18}{\rm O}) = 98.4$ MeV and $E_{\rm lab}(^{16}{\rm O}) = 104$ MeV using the Lawrence Berkeley Laboratory (LBL) 88-in. cyclotron. The reaction products were analyzed with the LBL QSD magnetic spectrometer system.[7] Angular distributions for the population of the 0_g^+ and 2_1^+ states are shown in Figs. 1(a) and 1(b).

The experimental angular distributions show that, whereas the $0_g^+ \to 0_g^+$ transitions for the inverse reactions are bell shaped,[8] the $0_g^+ \to 2_1^+$ angular distributions are strikingly different. The flat pickup angular distribution with an indication of a dip in the grazing-angle region has features similar to those found in studies of spherical,[6] as well as permanently deformed, rare-earth nuclei[9,10] in which it was shown that a significant part of the transfer takes place through routes involving inelastic excitations. To explore this transition further, the pickup reaction ^{150}Sm(^{12}C, ^{14}C)^{148}Sm was performed at a bombarding energy $E_{\rm lab}(^{12}{\rm C}) = 78$ MeV, corresponding approximately to the same energy above the barrier as the ^{16}O-induced reaction. The angular distributions shown in Fig. 1(c) have essentially the same features as those of the ^{16}O reaction; the distributions are, however, considerably wider and the interference features in the 2_1^+ angular distribution are more pronounced. The 2_1^+ cross section peaks at ~50° and the peak value is about 5% of the 0_g^+ peak value in both reactions.

The curves shown in Figs. 1(a)–1(c) are the

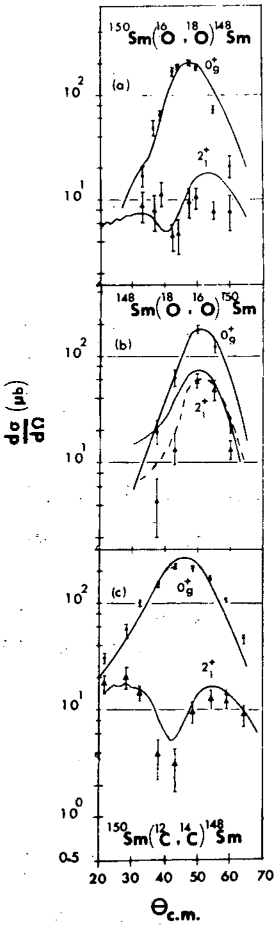

FIG. 1. Angular distributions for the three reactions discussed in the text. All reactions are fairly well matched with Q values equal to (a) -1.64 MeV, (b) 1.64 MeV, and (c) -0.71 MeV. Curves corresponding to CCBA calculations are also shown. The dashed curve in (b) illustrates the effect of including the first excited 0^+ state in the CCBA diagram as discussed in the text.

first results of a theoretical analysis where the DDM structure theory is combined with the CCBA reaction theory. The main difference from the alternative approach employed by Sørensen[4] is that, while in the BEM structure theory the nuclear deformation effects arise as a result of a complex mixing of a large number of spherical bosons, nuclear deformations are introduced in the single-particle basis itself in the DDM structure theory. Furthermore, in contrast to the rotational model employed previously in transfer-reaction calculations,[9,10] nuclear deformation is not considered to be a fixed quantity for each nucleus. Instead, nuclear deformations (the magnitude β as well as the asymmetry angle γ) are treated as dynamic variables for each state of the nucleus. Thus, the overlap amplitude for the transfer of two nucleons coupled to angular momentum J from the I state of nucleus A to the I' state of nucleus B is written as

$$O_{II'}{}^{J} = \int \Psi_{I'}{}^{B}(\beta_2)(CC)_J \Psi_I{}^{A}(\beta_2)\, d\beta_2 , \qquad (1)$$

where C is a nucleon annihilation operator. Note that the integral in Eq. (1) is a five-dimensional integral over the five components of the quadrupole deformation tensor β_2. Details of this method are given by Vaagen, Ascuitto, and Kumar.[11] We point out here that this method is valid for spherical nuclei [where the wave functions Ψ of Eq. (1) represent vibrations around the spherical shape] as well as well-deformed nuclei (where the wave functions Ψ are approximately δ functions, and one gets the usual prescription of one fixed deformation for the target nucleus and a second fixed deformation for the final nucleus).

The theoretical predictions are given in Figs. 1(a)–1(c). Although the general shapes and relative magnitudes of the angular distributions are well reproduced, the absolute magnitudes differ slightly from the experimental yields. In order to facilitate comparison with the shapes of the experimental angular distributions, we have normalized all the calculated cross sections to the experimental ones.

The agreement obtained by Sørensen[4] for ^{16,18}O reactions is quite impressive. Both the correct shapes of the angular distributions and also the correct magnitudes of the cross sections were obtained. However, our experience suggests that part of this impressive agreement may be due to the neglect of some important multistep contributions to the various cross sections. For instance, we find that the two-step route $0_g{}^+(A) \rightarrow 0'^+(B) \rightarrow 2_1{}^+(B)$ makes extremely important contributions to the $2_1{}^+$ cross sections. Our finding is in agreement with the previously available (p,t) and (t,p) data[12] on Sm nuclei where it was found that the $0_g{}^+ \rightarrow 0'^+$ cross sections are comparable to the ground-ground transitions. In the reaction ^{150}Sm$(p,t)^{148}$Sm, the $0_g{}^+ \rightarrow 0'^+$ cross section is 3 times as large as the $0_g{}^+ \rightarrow 2_1{}^+$ cross section! When we neglect this contribution our results are in better agreement with those of Ref. 4.

In fact, we find that while the route $0_g{}^+ \rightarrow 0'^+ \rightarrow 2_1{}^+$ interferes constructively with the direct route $0_g{}^+ \rightarrow 2_1{}^+$ in the stripping reaction ^{148}Sm $\rightarrow {}^{150}$Sm, the corresponding interference is destructive in the pickup reaction ^{150}Sm $\rightarrow {}^{148}$Sm. However, we must regard this "explanation" of the striking shape difference between the observed angular distributions as tentative, since the calculated magnitudes of the cross sections are not reproduced satisfactorily. Attempts are in progress[13] to improve the DDM structure theory by employing a larger configuration space where major shell mixing of type $\Delta N = 2$ is included exactly (which was neglected in the calculations presented here).

The explanation given[6] for a similar (but opposite) difference in the stripping and pickup reactions, ^{120}Sn + ^{18}O $\rightleftharpoons$ ^{122}Sn + ^{16}O, observed previously[6] is that the two-step processes $0_g{}^+ \rightarrow 2_1{}^+ \rightarrow 2_1{}^+$ and $0_g{}^+ \rightarrow 0_g{}^+ \rightarrow 2_1{}^+$ interfere with the one-step process $0_g{}^+ \rightarrow 2_1{}^+$ destructively (constructively) in the stripping (pickup) reactions. This explanation is not valid for the Sm nuclei where the pairing effects are much larger and the backward-going random-phase-approximation (RPA) amplitudes are comparable to the forward-going RPA amplitudes. A second possibility is the interference between the two multistep processes—one in which the inelastic scattering (followed or preceded by a two-nucleon transfer) occurs via nuclear interaction and one where it occurs via Coulomb interaction. However, this Coulomb-nuclear interference is destructive for *both* pickup and stripping.

Furthermore, we question the explanation proposed[4] for the shape difference observed by us in the Sm nuclei, which assumes that the one-step transfer is comparatively weak in the $2_1{}^+$ pickup reaction (and, hence, the Coulomb-nuclear interference dominates). However, no physical reason is given for such a striking difference in the amplitudes $0_g{}^+(148) \rightarrow 2_1{}^+(150)$ and $0_g{}^+(150) \rightarrow 2_1{}^+(148)$ between two nearly spherical or weakly deformed nuclei. Also, as mentioned above, the necessary two-step routes through $0'^+$ states are not included in the BEM calculations.

Our results show that heavy-ion–induced two-nucleon–transfer reactions provide rather sensitive tests of nuclear structure theories. The multistep processes involving excited 0^+ states make important contributions to the transfer reactions. The striking shape differences between $2_1{}^+$ angular distributions in stripping and pickup reactions on transitional Sm nuclei are not explained satisfactorily by current theoretical models.

(a) Present address: Vanderbilt University, Nashville, Tennessee 37235.

(b) On leave from Hahn-Meitner Institute, Berlin, Germany.

(c) Present address: NORDITA, Copenhagen, Denmark.

(d) Part of this author's work was performed while he was a summer visitor at Yale University.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720