HEAVY ION TRANSFER STUDIES USING DETECTOR ARRAYS*

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(Received October 20, 1993)

Two applications of heavy-ion induced transfer reactions are discussed here. The structure of the collective bands built upon two quasi-particle excitations excited in the ^{161}Dy(^{61}Ni,^{62}Ni)^{160}Dy; ^{161}Dy(^{61}Ni,^{60}Ni)^{162}Dy reactions was explored using the EUROGAM array at the Daresbury Laboratory. The ability of transfer reactions to populate superdeformed states was investigated by attempting to detect the decay of fission isomers populated by the ^{239}Pu(^{117}Sn, ^{118}Sn)^{238}Pu reaction, using a particle detector system within the Oak Ridge Spin Spectrometer.

PACS numbers: 25.70. Hi

1. Introduction

The study of direct transfer of nucleons between colliding nuclei has played an important role in the understanding of single particle shell structure, whereas Coulomb excitation studies using heavy ions have allowed similar insight to be gained in the nature of collective properties of nuclei. These two mechanisms are in principle combined in Heavy Ion induced Transfer Reactions (HITR) in which on the one hand the gross dynamical features of the reaction process (*e.g.* near classical orbits) make the transfer reaction an ideal mechanism for preparing the residual nuclei with suitable

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* Presented at the XXIII Mazurian Lakes Summer School on Nuclear Physics, Piaski, Poland, August 18–18, 1993.

configurations of the final nuclear states (determined by the nuclear form factor), and on the other hand the appreciable Coulomb excitation which accompanies the reaction should enable the collective properties of these states to be investigated, or at least probe the structure to high spin.

In this lecture two examples of the application of HITR will be described. In the first example gamma-ray spectroscopy is used in a study of the single neutron transfer reaction for the system $^{61}Ni+^{161}Dy$, in order to probe the structure of the two quasi-particle (q-p) states populated in the residual nuclei. In the second example the results of an experiment designed to investigate the suitability of HITR to populate superdeformed states, in which fission isomer decay is used to identify the final states of interest, are presented.

2. Study of 1 neutron transfer for the $^{61}Ni+^{161}Dy$ system

Heavy-ion transfer reactions offer the possibility of studying collective bands built upon intrinsic excitations in deformed nuclei. Fig. 1 shows a

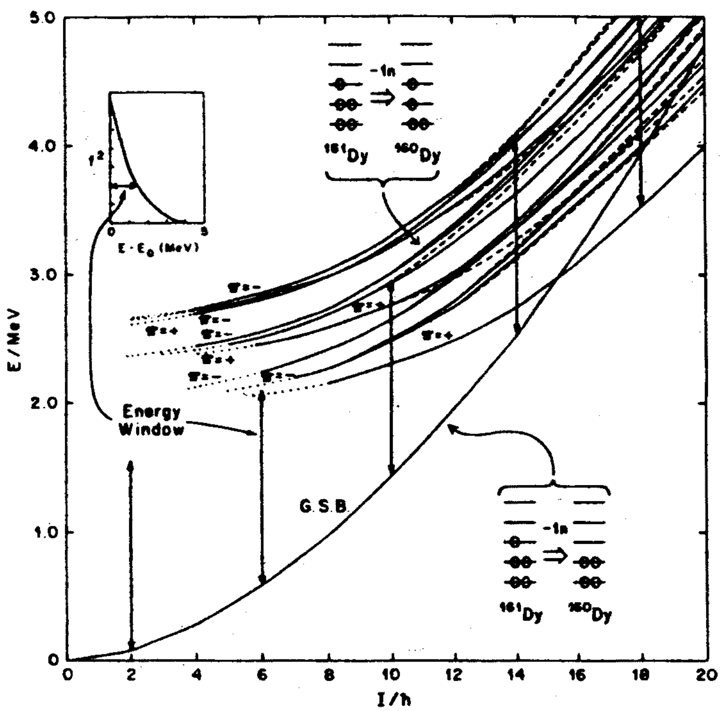

Fig. 1. Low-lying bands in ^{160}Dy calculated using the cranked shell model. (Taken from Ref. [1]).

Cranked Shell Model calculation [1] for low-lying bands in ^{160}Dy including the ground band and 2 q-p bands for which one of the q-p's is in the $\Omega = \frac{5}{2}^+$, $i_{13/2}$ neutron orbit (the unpaired neutron orbit in the ground state of ^{161}Dy). These bands should be easily formed by removing a neutron from ^{161}Dy. Experimental studies [2] of the 1 neutron pick-up process between Ni and Dy suggest that the reaction mechanism favours creation of a particle-hole state in ^{160}Dy with simultaneous Coulomb excitation to spins of around 10-12 $\hbar$.

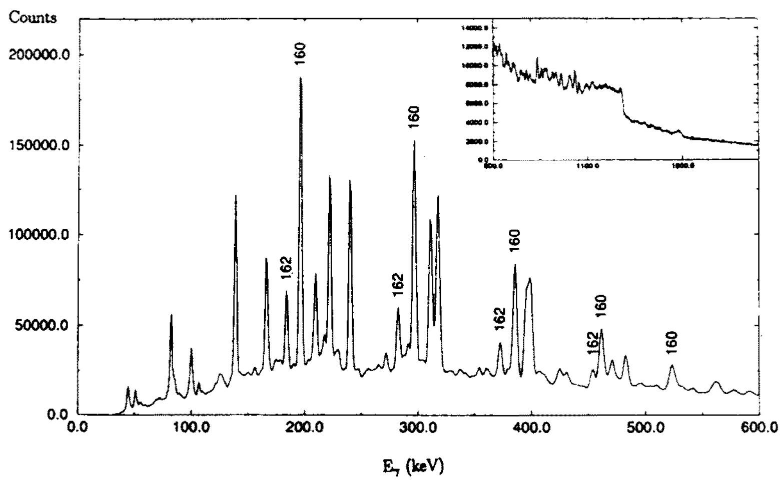

Fig. 2. Total projection of events in one Ge detector for particle-gamma-gamma coincidences following the reaction 270 MeV ^{61}Ni+^{161}Dy. Doppler shift corrections are made assuming that the γ-rays are emitted from the Dy recoil. Peaks labelled "160" arise from transitions in ^{160}Dy, those labelled '162' are in ^{162}Dy, and other prominent peaks are in ^{161}Dy.

In order to investigate the nature of the transfer process, the gamma de-excitation following the reaction 270 MeV ^{61}Ni + ^{161}Dy was measured using the EUROGAM phase I array consisting of 45 escape-supressed Ge spectrometers. The Ni beam was provided by the Nuclear Structure Facility, Daresbury. Doppler shift corrections to the emitted γ-rays were made by determining both polar and azimuthal angle of the backscattered Ni fragment detected in coincidence with an annular parallel plate avalanche counter subtending the angular range 108° to 140°. In the experiment approximately 10^7 particle-gamma-gamma events were collected. Fig. 2 shows the total projection of these events, in which the Doppler shift corrections are made assuming that the γ-ray is emitted from the target-like nucleus.

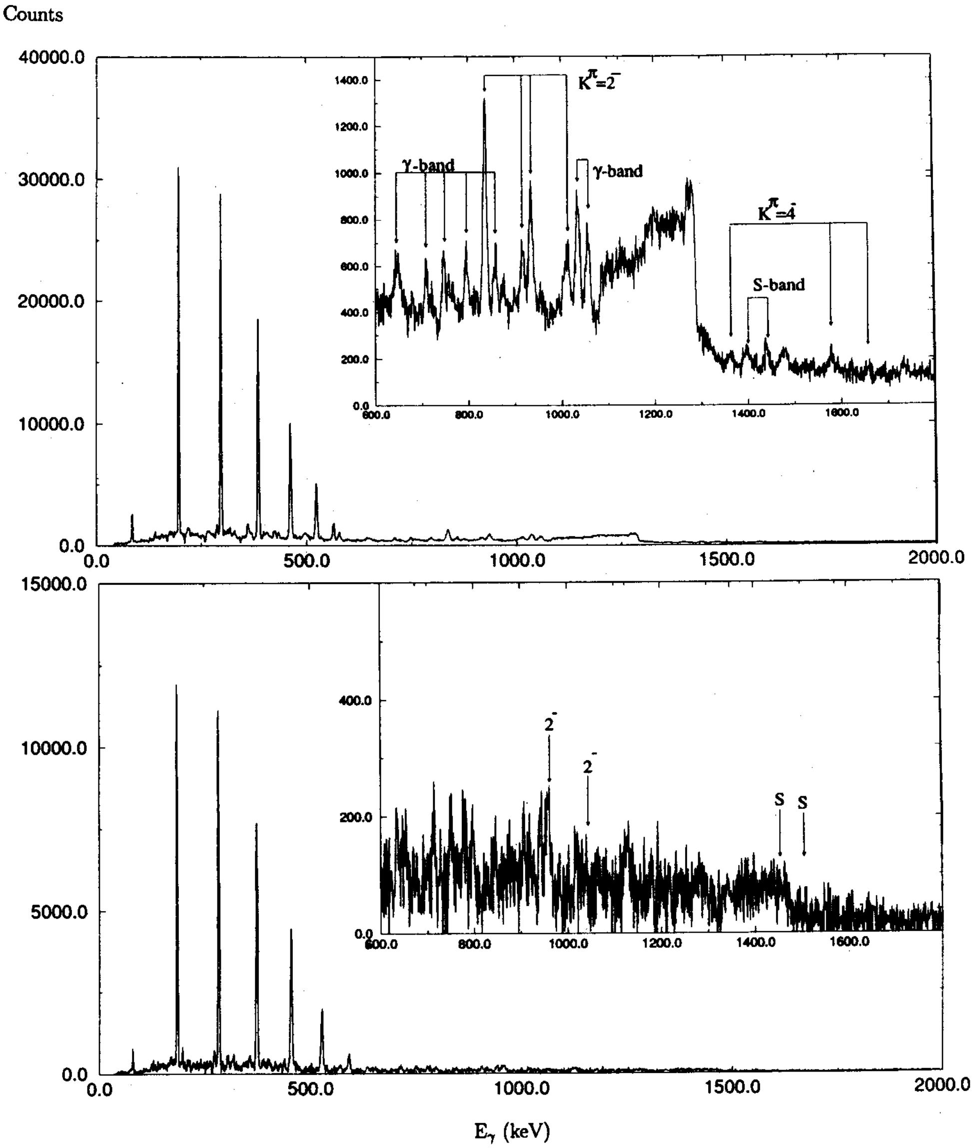

Fig. 3. Spectra of events in any second Ge detector where the energy deposited in the first Ge detector corresponds to known yrast transitions in ^{160}Dy (upper) and ^{162}Dy (lower). In these spectra the Doppler shift corrections are made assuming that the γ-rays are emitted from the Dy recoil. Transitions from previously identified low-lying collective bands are indicated.

The advantage of using a ^{61}Ni beam can clearly be seen, for the ground state Q-values for both the pick-up reaction ^{161}Dy(^{61}Ni,^{62}Ni)^{160}Dy (Q_{gg} = 4.15 MeV) and the stripping reaction ^{161}Dy(^{61}Ni,^{60}Ni)^{162}Dy (Q_{gg}=0.38 MeV) allow both reactions to proceed with considerable intensity. Each channel can be enhanced by requiring that at least one gamma-ray has to be one of the more intense yrast transitions in each nucleus. The resulting coincidence γ-ray spectra for ^{160}Dy and for ^{162}Dy are shown in Fig. 3. The spectra show significant differences between the two reactions. For the pick-up reaction, both γ-band and the $K^\pi = 2^-$ band are strongly excited and a $K^\pi = 4^-$ and the non-yrast members of the S-band, built upon the $[\nu i_{13/2}]^2$ configuration, can be seen also. These transitions are identified from the results of γ-ray spectroscopic measurements using the ^{158}Gd(α,2nγ) reaction [3], the non-yrast S-band states being previously identified using particle spectroscopy following the (^{3}He,α) reaction [4]. Such structure is not evident in the stripping reaction, where positions of non-yrast bands are also known [5]. One explanation in the difference could lie in the difficulty of matching particle-hole states in Ni with particle-particle states in Dy, as would be the case in the stripping reaction, compared with matching particle-particle states in Ni with particle-hole states in Dy, as is the case with the pick-up reaction. The effect could also arise from the different values of Q_{gg} values for the two reactions, although the similarity of the observed feeding pattern of the yrast states, suggests that this is unlikely. Further analysis of the data is in progress: to determine the angular momentum distribution of each reaction; to check whether there are contributions from non-direct processes to the population of the non-yrast structure in ^{160}Dy (otherwise these must have $i_{13/2}$ components in their configuration); and to determine whether the population of these states have any sensitivity to scattered particle angle.

3. Population of the $T_{1/2} = 0.5$ns fission isomeric state in ^{238}Pu

The existence of a second minimum in the nuclear potential energy surface with 2:1 axis ratio has been experimentally well documented [6] for nuclei with $Z = 92 - 97$ and $N = 141 - 151$. The properties of these states, whose bandheads mostly prefer to decay by fission rather than to the first minimum, have been investigated in some instances although such measurements are hampered by the small cross-section for their population, typically 1μb for light ion induced reactions.

The key to improving the experimental situation for studying these states lies in increasing their yield. An attempt to do this is described here, whereby the properties of HITR are exploited, particularly its ability to populate directly states of moderate angular momentum lying close to the yrast line. This should be an ideal situation for populating the superdeformed states which become yrast at $I \approx 35\hbar$. In the experiment described here the yield of the 0.5 ns fission isomer in ^{238}Pu following the reaction 630 MeV ^{239}Pu(^{117}Sn,^{118}Sn)^{238}Pu (Q_{gg} = 3.7MeV) was measured. The Sn beam was provided by the HHIRF of the Oak Ridge National Laboratory. In the experimental arrangement the backscattered Sn ions were detected in an annular PPAC subtending the polar angular range 118° to 156°, with six 50° sections in ϕ. The fission fragments were detected in a 6-segment PPAC covering 80% of the azimuth for a θ range of 15° to 76°. The gas detectors, which were position sensitive in both θ and ϕ were placed within the Spin Spectrometer configured to accept 18 escape-suppressed Ge detectors. The target consisted of 300μg cm^{-2} of $^{239}PuO_2$ electrodeposited onto 3.4 mg cm^{-2} Ni. The results of the investigation into the structure of the first minima in ^{238,239}Pu, carried out at the same time as the fission measurement, is reported elsewhere [7].

Two types of measurement of the fission process were carried out. In the first experiment, the prompt fission yield was measured by counting the three-body events recorded in the annular detector and two of the forward detectors. After corrections for the slowing down of the fission fragments in the Ni foil and rejection of non-coplanar events, the mass of each fragment, total mass, total energy in the centre of mass, and scattering angle between the fragments in the c. of m. could be reconstructed for each event. The spectra for these events are shown in Fig. 4, which give the expected energy and mass distribution for prompt fission. To determine the origin of the prompt fission events, the coincident γ-ray spectrum measured using the Ge detectors was constructed, in which the Doppler correction was made assuming the γ-emission was from the Sn-like scattered nucleus. This spectrum is shown in Fig. 5 where it is compared with the corresponding spectra in coincidence with transitions in ^{238}Pu and ^{239}Pu. Examination of these spectra suggests that most of the fission events are associated with excitation of ^{118}Sn rather than inelastic scattering, as expected from the known systematics of Coulomb and transfer-induced fission [8, 9].

In the second experiment a steel disc with a 3.6 mm aperture was placed 5 mm downstream of the target. The combination of the masking disc and the thick Ni backing effectively eliminated the possibility of detecting prompt fission events. In this experiment, with an integrated beam current similar to the previous experiment, a few three-body events were observed in the particle detectors. These events were analysed in a similar manner as before, except that now the energy of the Pu recoil has to be corrected for energy loss in the Ni foil. Only one event had the characteristics of a fission event, which are also shown in figure 4. The ratio of isomeric to prompt fission is estimated, assuming that both originate from the decay of

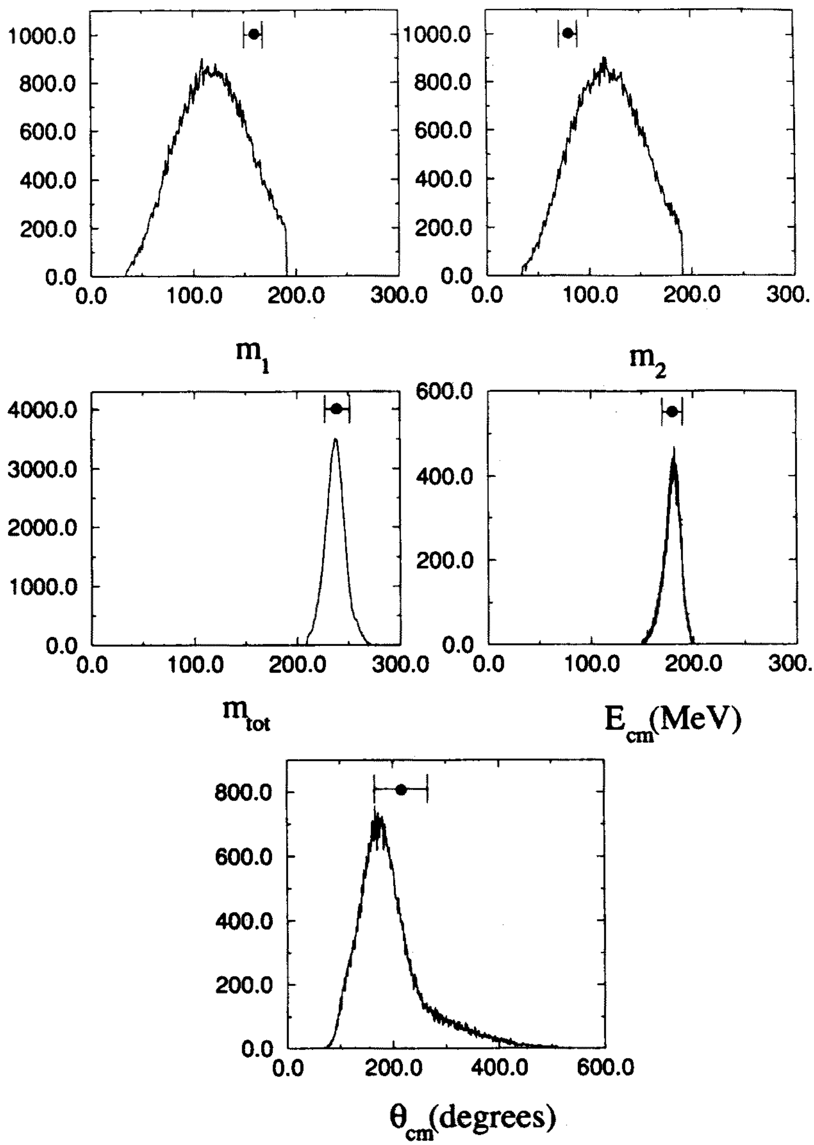

Fig. 4. Reconstructed values of fission fragment mass ($m_{1,2}$), total mass (m_{tot}), total energy in the centre of mass (E_{cm}), and scattering angle between the fragments in the c. of m. (θ_{cm}) following the reaction 630 MeV $^{117}Sn+^{239}Pu$. The spectra shown correspond to prompt fission with the mask removed. The single datum point in each spectrum corresponds to an isomeric fission event detected with the mask in place. The width of the error bar for these points corresponds to the uncertainty in the position and timing recorded by the detectors.

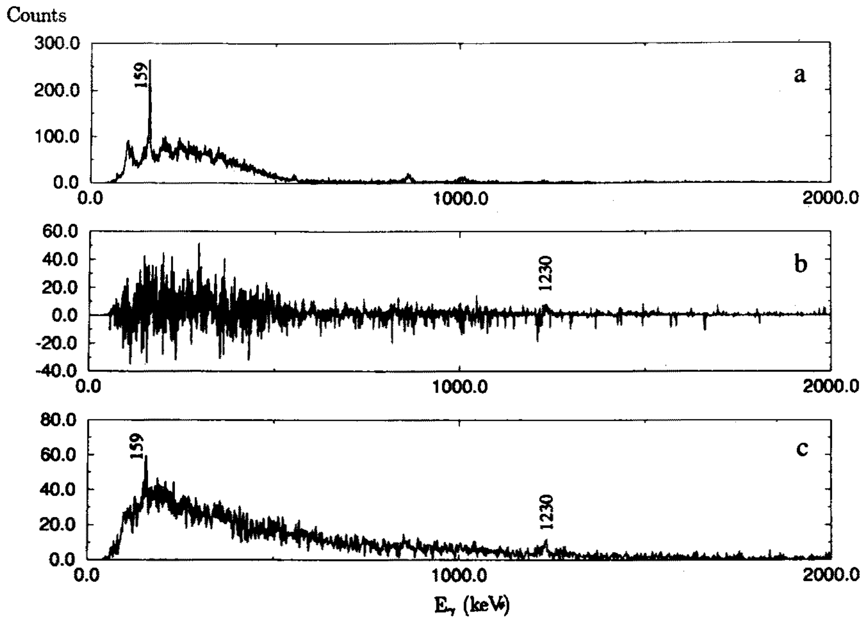

Fig. 5. (a), (b): Background subtracted spectra of events in any second Ge detector where the energy deposited in the first Ge detector corresponds to known yrast transitions in ^{239}Pu (a) and ^{238}Pu (b). (c): Spectrum of events in any Ge detector corresponding to detected prompt fission events. In these spectra the Doppler shift corrections are made assuming that the γ-rays are emitted from the Sn partner. The peaks labelled correspond to the transition from the first excited state to the ground state in either ^{117}Sn (159 keV) or ^{118}Sn (1230 keV).

^{238}Pu, to be $\approx 10^{-5}$, although the possibility exists that the isomeric event belongs to the decay of the $T_{1/2}$ = 3ns excited state in the second minimum of ^{239}Pu, corresponding to a ratio of about 10^{-4}. Discounting the latter possibility, the observed value of the fission decay ratio is similar to that observed following the ^{236}U(α,2n) reaction [10], so that no enhancement of the population of the fission isomer is observed. This suggests that either the entry states to the second minimum at high spin, which presumably lie several MeV above the minimum itself, are unstable with respect to decay through the outer barrier, or that the 2 quasi-particle states which are predominantly populated by the reaction do not readily couple to the superdeformed state.

This work was supported by grants from the U.K. Science and Engineering Research Council, the U.S. National Science Foundation, the U.S. Department of Energy (Contract Nos. W-7405-ENG-48 and DE-AC03-76SF00098) and N.A.T.O.

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