POPULATION OF HIGH SPIN STATES IN TRANSFER REACTIONS WITH VERY HEAVY IONS

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Population of states in $^{160}$Dy to $I \sim 20$ has been observed for the reaction $^{151}$Dy($^{58}$Ni,$^{59}$Ni)$^{160}$Dy. The reaction selectively excites high spin states near the yrast sequence, and the reaction mechanism is consistent with a direct process for the transfer. Thus it appears that heavy-ion induced transfer reactions can be a powerful probe of high-spin nuclear structure.

Transfer reactions with very heavy ions ($A \geq 40$) hold considerable promise as a tool for studying nuclear structure [1,2]. Resolution of the closely spaced collective states excited by heavy ions is achieved most easily using high resolution Ge $\gamma$-ray detectors to observe the $\gamma$-rays in coincidence with the scattered ions. Such coincident $\gamma$-ray spectra measure the deexcitation of the transfer products rather than the primary population pattern. To reconstruct the initial distribution one needs the $\gamma$-ray feeding pattern. Separation of the yrast and non-yrast components of the feeding requires both total energy and angular momentum information for the states populated.

We report here on the use of the ORNL spin spectrometer [3] to measure total $\gamma$-ray energies and multiplicities for the reaction $^{160}$Dy($^{58}$Ni,$^{59}$Ni)$^{160}$Dy. The targets were 600 $\mu$g/cm$^2$ self-supporting foils enriched to 97% $^{161}$Dy, with < 2% $^{160}$Dy contamination. The $E_{\text{lab}} = 270$ MeV $^{58}$Ni beams were produced by the Holifield Heavy Ion Research Facility (HHIRF). Relating the total $\gamma$-ray energies and multiplicities to the energy and angular momentum of the states populated allowed separation of the direct population of the $^{160}$Dy yrast line from that feeding the yrast line by quasizyotropic transitions. In this paper we report on the general features of the total $\gamma$-ray energy and multiplicity distribution. The cross sections for population of discrete states in the transfer reaction will be presented separately.

Population of states up to $I \sim 12$ has been discussed before for transfer with light heavy ions such as oxygen [4,5]. However, the mechanism for the reactions discussed here is expected to be qualitatively different, with collective excitation playing a dominant role in the angular momentum transfer [1]. Related work for two-neutron transfer
with Xe beams has recently been reported by Macchiaveli et al. [6] but the spin states observed are not as high as in the present work, and the lack of total energy or multiplicity information makes quantitative interpretation of the data difficult.

The experimental procedure involves detection of $\gamma$-rays by Ge detectors in coincidence with scattered target-like and projectile-like fragments which are observed using four large solid angle position-sensitive parallel-plate avalanche detectors converging laboratory angular ranges of $\pm (8^\circ - 76^\circ)$ and $\pm (104 - 162^\circ)$. The transfer is observed to have a bell-shaped distribution centered at a Ni scattering angle of $\sim 130^\circ$ (lab) with a width of $\sim 20^\circ$. The data presented here are integrated over this grazing distribution. Each particle–particle–$\gamma$ coincidence initiates the storage of spin spectrometer information, which is subsequently analyzed to determine the energy and fold of the resulting $\gamma$-ray cascade. This energy-fold spectrum was then unfolded [3] with the measured spin-spectrometer response to yield the total-energy multiplicity distribution for the reaction products.

Fig. 1 shows a $\gamma$-ray spectrum integrated over the grazing distribution. The Ge peak-to-background ratio is comparable to that for sub-barrier reactions, and inelastic and one-neutron pickup reactions dominate the spectrum. More careful analysis exhibits the presence of various multiparticle channels, which will be discussed in future work. Here we will concentrate on the one-neutron pickup reaction. Discrete lines up to the $18^+ \rightarrow 16^+$ yrast transition are seen for the reaction product $^{160}$Dy. In addition, several transitions from high-spin negative parity bands and the $\gamma$-band of $^{160}$Dy, and transitions from the first three excited states of $^{59}$Ni are observed. Fig. 2 shows the total energy-multiplicity ($E, M$) spectrum gated on the transitions deexciting the $4^+ - 12^+$ states in $^{160}$Dy. The multiplicity and total energy displayed is that of the spin spectrometer and does not include the contribution from the gating $\gamma$-ray in the Ge detector. In addition, we show as a dashed line the 0.1 contour only for the corresponding inelastic excitation of $^{161}$Dy. The ($E, M$) distribution is quite different for the two reactions, and both differ considerably from ($E, M$) distributions characteristic of heavy-ion $\alpha n$ reactions, and from related measurements reported for two-neutron transfer with light-heavy ions [5]. The distribution of fig. 2 is relatively insensitive to variation of the scattering angle across the grazing region.

For reference, the heavy dashed line in fig. 2 indicates the mean total energy and multiplicity expected if the yrast line of $^{160}$Dy and the ground state of $^{59}$Ni are populated in the transfer. The angular momentum scale ($J/\hbar$) below the multiplicity scale is strictly valid only for this line. Events lying below the dashed line reflect the finite resolution of the spin spectrometer (about 40% in $E$ and $M$). The dashed line is deduced from the known energies in the $^{160}$Dy yrast band by assuming that the transitions near the yrast line are stretched $E2$'s, and that the observed multiplicity and total energy are corrected to account for the trigger $\gamma$-ray, and the mostly internally converted $2^+ \rightarrow 0^+$ transition. This prescription gives the expected results when checked against the Coulomb excitation reaction.
heavy-ion transfer also is assumed small. Based on
the known level structure in $^{59}$Ni below $\sim 3$ MeV we estimate that the average multiplicities for
deexcitation of the $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ levels in
$^{59}$Ni are 1, 1, and 2.5, respectively.

With these estimates the results of fig. 2 can be
understood using a simple model for transfer
reactions [1] and the cranked shell model [4]. The
$(E, M)$ distribution appears to be a superposition of
two distributions: one narrow in energy peaked
at $M \sim 3$, and a stronger distribution broader in
energy and peaked at $M \sim 6$. That there are two
distinct peaks in the distribution of fig. 1 is even
more obvious in the gates on individual transitions
which were summed to produce fig. 1. The
lower-multiplicity distribution represents direct
population of the $^{160}$Dy ground band by the
pickup of the unpaired $\Omega = 5/2$, $i_{13/2}$ neutron of
the $^{161}$Dy target while the $^{59}$Ni is populated in the
ground or first two excited states (see fig. 3 and
insets). The range of angular momentum popu-
lated ($< 12h$) is comparable to that for inelastic
scattering of $^{58}$Ni + $^{160}$Dy or $^{162}$Dy, although the
detailed population distribution as measured in
the Ge detectors is different.

The upper peak in fig. 2 receives a contribution
from pickup of a paired neutron in $^{161}$Dy, leaving
the residual $^{160}$Dy nucleus in an excited two-quasi-
particle configuration and the $^{59}$Ni in one of the
states at less than 500 KeV (inset to fig. 3). Note
that the angular momentum of the Dy state finally
populated is the vector sum of the collective
angular momentum of the core and the two
quasiparticles. A second possible contribution to
the higher multiplicity peak corresponds to excita-
tion of the ground band or quasiparticle states of
$^{160}$Dy and the $g_{9/2}(3.06$ MeV) state of $^{59}$Ni, with
the Ni expected to contribute $\sim 3$ MeV and $\sim 2.5$
multiplicity units to fig. 2. However, the absence
of transitions in the $\gamma$-ray spectrum deexciting the
g_{9/2} state indicates that it is weakly excited. We
assume the majority of the higher multiplicity peak
in fig. 2 to represent two-quasiparticle Dy excita-
tion.

Fig. 3 shows a cranked shell model calculation
[8] for bands near the yrast line in $^{160}$Dy. If $^{59}$Ni
is populated in its lowest three states, Q-windows
and binding energies of the transferred particles

\[ \text{Fig. 2. The total energy-multiplicity (E, M) distribution for the}
\text{transfer reaction $^{160}$Dy($^{58,59}$Ni,$^{58,59}$Ni)$^{160}$Dy (solid lines) and the}
\text{inelastic reaction $^{161}$Dy($^{58,59}$Ni,$^{58,59}$Ni)$^{161}$Dy (dashed line,}
\text{0.1 contour only). The distributions are} \text{gated on the strong}
\text{ground band transitions in $^{160}$Dy and $^{161}$Dy respectively, as}
\text{observed by the Ge detectors. The heavy dashed line}
\text{represents the $^{160}$Dy yrast line. Events below it reflect finite}
\text{resolution. The estimated resolution in E and M is about 40%}
\text{The angular momentum scale (J/\hbar) is valid only for the Dy}
\text{yrast line, with no Ni excitation.} \]

$^{162}$Dy($^{58,59}$Ni,$^{58,59}$Ni)$^{162}$Dy. To relate fig. 2 to nuclear
structure information, it is necessary to deduce the
division of energy and angular momentum be-
tween the Ni and Dy, and to relate the observed
multiplicity to the angular momentum of states
populated.

A preliminary semiclassical analysis incorporat-
ing (d, p) spectroscopic factors and heavy-ion
kinematics indicates that the $p_{3/2}$(g.s.), $f_{5/2}(0.339$
MeV), $p_{1/2}(0.465$ MeV), and $g_{9/2}(3.06$ MeV)
states in $^{59}$Ni should dominate the transfer cross
section when states near the yrast line in $^{160}$Dy are
populated [7]. Coulomb excitation of the vibra-
tional states of the $^{58}$Ni core is calculated to have
only a $\sim 20\%$ probability, so excitation of
particle-vibration coupling states in $^{59}$Ni by the
conspire in the reaction $^{161}$Dy($^{58}$Ni, $^{59}$Ni)$^{160}$Dy to limit strong transfer to a band of states lying within 1–2 MeV of the Dy yrast line (inset to fig. 3). The dominant factor in this particular case is that excitation above the yrast line requires removal of more tightly bound particles from $^{161}$Dy, which strongly suppresses the form factor for transfer greater than 1–2 MeV above the Dy yrast line unless particles are transferred between excited nuclei with particles promoted before transfer to less tightly bound orbits [7]. The population pattern seen in fig. 1 provides direct evidence for a cold mechanism giving large cross sections for high-spin transfer between very heavy ions if ground-state Q-values are matched properly. This cold high spin transfer process obviously is significant for using these reactions as a spectroscopic tool, and for a general understanding of heavy-ion reaction mechanisms. In addition, it raises interesting possibilities for populating states and nuclei inaccessible to other reactions. For example, this mechanism would be useful for high spin population in the actinides where fission severely limits the use of heavy-ion, xn reactions.

The qualitative and even quantitative features of the $(E, M)$ population distribution of fig. 2 can
be understood in terms of fig. 3. Because of the
pairing gap, at low angular momenta ($I < 10$) only
the Dy ground band, and possibly a few vibra-
tional bands, lie in the energy window. The
population in the lower maximum of fig. 2
primarily represents direct population of the Dy
ground band and the lowest three states of $^{59}$Ni.
As the angular momentum is increased the Dy
two-quasiparticle states come down relative to the
yrast line. Above $I \sim 10$ the two-quasiparticle
bands begin to fall within the kinematic window,
and the sudden broadening of the total energy
distribution represents the kinematic accessibility
of those non-yrast bands. Our qualitative discus-
sion neglects the differences among spectroscopic
factors for different two-quasiparticle bands,
which should be included to provide more string-
ent tests of high spin models. The present
analysis also assumes that the amount of collective
angular momentum is the same for transfer to the
ground and aligned bands. This is not generally
expected to be true, but it should be a good
assumption for the average properties of a group
of bands.

With these simple considerations all the basic
features of the ($E, M$) distribution of fig. 2 may
be accounted for in a natural way. This implies
that the data of fig. 1 are related directly to the
density of Dy ground band and two-quasiparticle
states as a function of energy and angular
momentum, and provides clear support for a gap
between the ground and excited two-quasiparticle
states which decreases with angular momentum.

In conclusion we have demonstrated that
transfer reactions using very heavy ions can
populate high spin states near the yrast sequence
both in the discrete state and quasicontinuum
region by a direct reaction process with large cross
section. The general features of the yrast and
quasicontinuum population find ready interpreta-
tion in terms of simple theoretical models. We find
strong support for the general features of the
standard models of quasiparticles coupled to
rotors, and specific indications for an angular-
momentum induced decrease of the gap between
the yrast and excited two-quasiparticle states. It
is clear from these results that a quantitative
spectroscopy is possible in these reactions. The
limit on how precise this spectroscopy can be will
likely depend upon how well it is possible to
separate contributions to total energy and multipli-
city from the two transfer products.

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