

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

M.W. GUIDRY, S. JUUTINEN, X.T. LIU, C.R. BINGHAM, A.J. LARABEE, L.L. RIEDINGER
Department of Physics, University of Tennessee, Knoxville, TN 37996, USA
and Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

C. BAKTASH, I.Y. LEE, M.L. HALBERT
Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

D. CLINE, B. KOTLINSKI, W.J. KERNAN
Nuclear Structure Research Laboratory, University of Rochester, Rochester, NY 14627, USA

T.M. SEMKOW, D.G. SARANTITES, K. HONKANEN and M. RAJAGOPALAN
Department of Chemistry, Washington University, St. Louis, MO 63130, USA

Received 25 July 1985

Population of states in ^{160}Dy to $I \sim 20$ has been observed for the reaction $^{161}\text{Dy}(^{58}\text{Ni}, ^{59}\text{Ni})^{160}\text{Dy}$. 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 γ -ray detectors to observe the γ -rays in coincidence with the scattered ions. Such coincident γ -ray spectra measure the deexcitation of the transfer products rather than the primary population pattern. To reconstruct the initial distribution one needs the γ -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 γ -ray energies and multiplicities for the reaction $^{161}\text{Dy}(^{58}\text{Ni}, ^{59}\text{Ni})^{160}\text{Dy}$. The targets were $600 \mu\text{g}/\text{cm}^2$ self-supporting foils enriched to 97%

^{161}Dy , with $< 2\%$ ^{160}Dy contamination. The $E_{\text{Lab}} = 270 \text{ MeV}$ ^{58}Ni beams were produced by the Holifield Heavy Ion Research Facility (HHIRF). Relating the total γ -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 quasicontinuum transitions. In this paper we report on the general features of the total γ -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 Macchiavelli 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 γ -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 converting 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- γ coincidence initiates the storage of spin spectrometer information, which is subsequently analyzed to determine the energy and fold of the resulting γ -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 γ -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 γ -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 γ -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) distri-

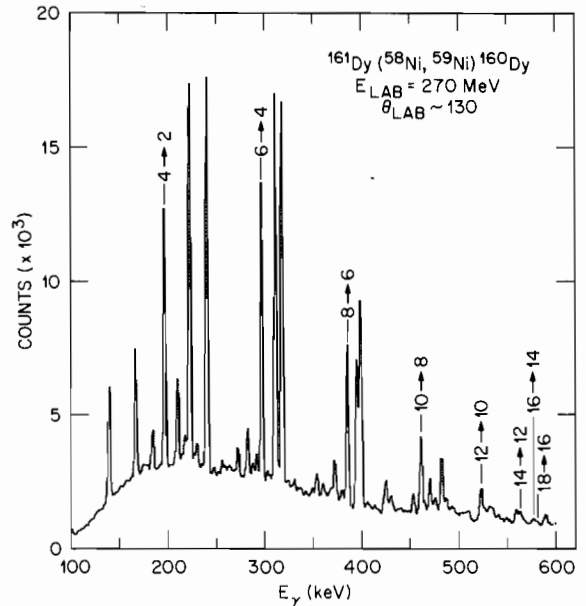


Fig. 1. A particle-particle- γ coincidence spectrum for the reaction $^{58}\text{Ni} + ^{161}\text{Dy}$ at $E_{\text{LAB}} = 270$ MeV and $\theta_{\text{LAB}} = 130^\circ$. The ^{160}Dy peaks in the one-neutron pickup channel are marked.

butions characteristic of heavy-ion xn 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 (I/\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 γ -ray, and the mostly internally converted $2^+ \rightarrow 0^+$ transition. This prescription gives the expected results when checked against the Coulomb excitation reaction

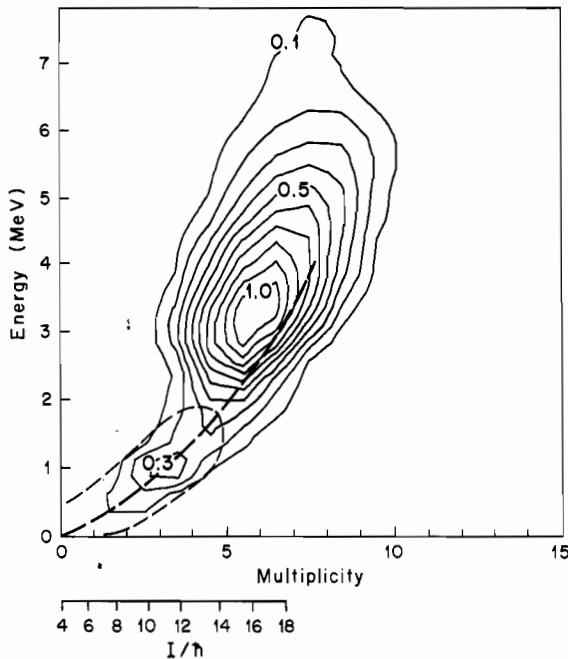


Fig. 2. The total energy-multiplicity (E, M) distribution for the transfer reaction $^{161}\text{Dy}(^{58}\text{Ni}, ^{59}\text{Ni})^{160}\text{Dy}$ (solid lines) and the inelastic reaction $^{161}\text{Dy}(^{58}\text{Ni}, ^{58}\text{Ni}')^{161}\text{Dy}$ (dashed line, 0.1 contour only). The distributions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

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

A preliminary semiclassical analysis incorporating (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 vibrational 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

heavy-ion transfer also is assumed small. Based on the known level structure in ^{59}Ni below ~ 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 populated ($< 12\hbar$) is comparable to that for inelastic scattering of $^{58}\text{Ni} + ^{160}\text{Dy}$ 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-quasiparticle 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 excitation 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 ~ 3 MeV and ~ 2.5 multiplicity units to fig. 2. However, the absence of transitions in the γ -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 excitation.

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

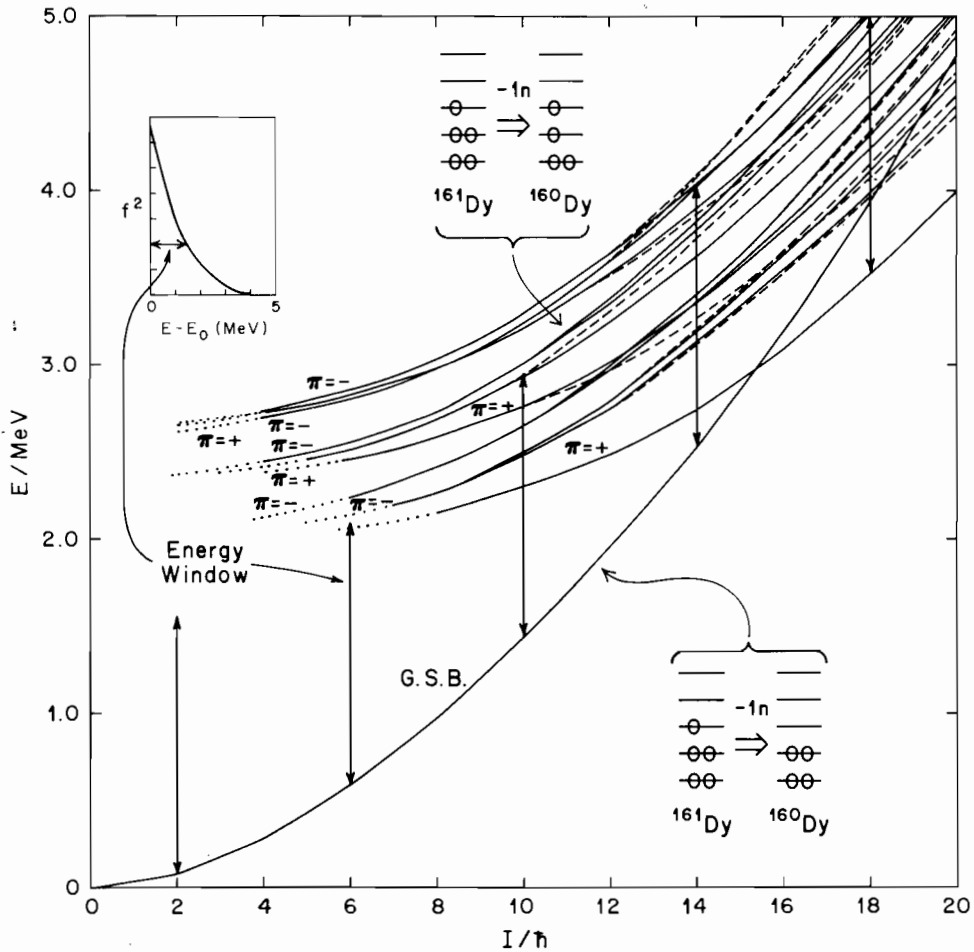


Fig. 3. Low-lying bands in ^{160}Dy calculated using the cranked shell model with parameters reflecting the standard systematics in this region. The energy window discussed in the text is indicated by the inset and the arrows, and strongly suppresses

transfer to states lying outside the window. The other insets indicate schematically the kind of pickup process populating the bands.

conspire in the reaction $^{161}\text{Dy}(^{58}\text{Ni}, ^{59}\text{Ni})^{160}\text{Dy}$ 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, αn 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 vibrational 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 discussion neglects the differences among spectroscopic factors for different two-quasiparticle bands, which should be included to provide more stringent 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 interpretation 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 multiplicity from the two transfer products.

Research supported by the U.S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Research at the University of Tennessee is supported by the U.S. Department of Energy under Contract No. DE-AS05-76ER04936. The National Science Foundation supported the research at the University of Rochester.

References

- [1] M.W. Guidry, T.L. Nichols, R.E. Neese, J.O. Rasmussen, L.F. Oliveira and R. Donangelo, Nucl. Phys. A361 (1981) 275.
- [2] C.H. Dasso, T. Døssing, S. Landowne, R.A. Broglia and A. Winther, Nucl. Phys. A389 (1982) 191.
- [3] M. Jääskeläinen et al., Nucl. Instrum. Methods 204 (1983) 385.
- [4] See, e.g., P. Bond, Comm. Nucl. Part. Phys. 11 (1983) 231, and references therein.
- [5] J. Koenig et al., Phys. Rev. C24 (1981) 2076.
- [6] A.O. Machiavelli, M.A. Deleplanque, R.M. Diamond, F.S. Stephens, E.L. Dines and J.E. Draper, Nucl. Phys. A412 (1985) 436.
- [7] M.W. Guidry, G. Leander, W. Kincaid, J.O. Rasmussen and L.F. Canto, to be published.
- [8] R. Bengtsson and S. Frauendorf, Nucl. Phys. A327 (1979) 139.