Excitation-energy partition in quasielastic transfer reactions at near barrier energies

C.Y. Wu, D. Cline, M. Devlin, K.G. Helmer,* R.W. Ibbotson, and M.W. Simon
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627

P.A. Butler, A.J. Cresswell, G.D. Jones, P.M. Jones, and J.F. Smith
Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom

R.A. Cunningham and J. Simpson
Science and Engineering Research Council, Daresbury Laboratory, Warrington WA4 4AD, United Kingdom
(Received 21 July 1994; revised manuscript received 25 August 1994)

It is demonstrated that the partition of excitation energy between receptor and donor, in quasielastic heavy-ion transfer reactions, at near barrier energies can be studied by γ-ray spectroscopy. Reactions between ^{161}Dy and ^{58,61}Ni at bombarding energies 265 and 270 MeV respectively have been studied using the particle-γ coincidence technique. From the observed deexcitation γ rays originating in Ni, we derived the average excitation energy carried by the receptor to be $\sim$ 0.8 MeV (Q_{gg} = 2.5 MeV) for ^{59}Ni and $\sim$ 2.5 MeV (Q_{gg} = 4.1 MeV) for ^{62}Ni in the one-neutron transfer reaction channel. A broad bump peaking about 1 MeV attributed to intrinsic excitation was observed in ^{160}Dy for the ^{58}Ni beam and about 1–2 MeV for the ^{61}Ni beam. Distorted wave Born approximation analysis reproduces the general features of the excitation-energy partition between the receptor and donor although discrepancies exist when comparing populations of individual final states.

PACS number(s): 25.70.Hi, 25.70.Bc, 24.10.Eq

The study of the partition of excitation energy between reaction partners in heavy-ion collisions is important for characterizing the underlying reaction dynamics and can provide a stringent test of models for the interaction between heavy nuclei [1]. For instance, the measurement of the excitation-energy partition is a measure of the thermal equilibrium state and elucidates possible processes for energy dissipation in an above-barrier collision. Measurements of the excitation-energy partition are almost nonexistent for quasielastic channels for collisions between heavy nuclei near the barrier energy. For the quasielastic one-neutron transfer channel in the system ^{161}Dy + ^{58}Ni at $E_{\rm lab}$ = 270 MeV, the reconstructed total γ-ray energy-multiplicity distribution showed that the average total excitation energy is about 1–2 MeV above the Dy yrast line plus about 2–2.5 MeV of rotational energy [2]. The Dy (donor) was assumed to share the majority of this excitation energy because of the observed weak population of discrete lines from Ni excitation. This was attributed to a preference for population of two-quasiparticle states in the Dy nucleus. A later study of the same system, with a more sensitive experimental arrangement, showed a broad [full width at half maximum (FWHM) 0.5–0.6 MeV] peak, centered around 1 MeV, that was attributed to intrinsic excitation in the Dy nucleus while still no conclusive result was obtained for excitation energy shared by the Ni(receptor) [3].

From the reaction dynamics point of view, the quasielastic nucleon transfer occurs with highest probability near the Fermi surface and the division of excitation energy will be asymmetric between the receptor and the donor. Numerical estimations by Sorensen [4], based on the semiclassical theory of Lo Monaco and Brink [5], showed that the receptor shares typically about 60%–70% of the total excitation energy in one-nucleon transfer reactions. This seems inconsistent with the observation in Refs. [2, 3]. In this paper, we show that the excitation-energy partition between receptor and donor in quasielastic transfer reactions can be measured using γ-ray spectroscopy. The results demonstrate that the receptor receives a substantial fraction of the excitation energy and that nuclear structure is important in the sharing process for one-neutron transfer reactions.

Experiments were carried out with self-supported ^{161}Dy targets, 400–580 μg/cm^2 thick, bombarded by ^{58,61}Ni at $E_{\rm lab}$ = 265 and 270 MeV, respectively. The isotopic abundances for target material were measured by a Coulomb excitation experiment using a 200 MeV ^{58}Ni beam from Rochester Tandem accelerator. The measured enrichment is about 95.9% of ^{161}Dy, 0.25(5)% of ^{160}Dy, and 2.51(25)% of ^{162}Dy, which agrees with the isotopic analysis supplied by Isotope Division of Oak Ridge National Laboratory. The deexcitation γ rays were detected in an array of Compton-suppressed Ge detectors in coincidence with the detection of backscattered Ni-like particles by an annular position-sensitive parallel-plate avalanche counter (PPAC). This position information, plus the assumption of two-body kinematics, was used to correct the Doppler shift of γ rays. The corrected γ-ray energy thus serves to identify the exit channels for

*Present address: Department of Biomedical Engineering, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609.

these reactions. Scaled-down particle single events also were recorded for normalization. The Rochester accelerator facility was employed for experiments with 265 MeV ^{58}Ni and 267 MeV ^{61}Ni using 8 Ge ($\sim$ 20% efficiency each) and 12 NaI detectors plus a PPAC covering $120° < \theta < 154°$. At the Daresbury Laboratory, the EUROGAM array of 45 ($\sim$70% efficiency each) Ge detectors, and a PPAC, covering $108° < \theta < 140°$ were employed with a ^{61}Ni beam at 270 MeV. In the latter case, approximately 4.6×10^6 events, with at least two-fold γ rays, were collected out of a total $\sim$40 $\times10^6$ particle-γ coincident events.

The two- or higher-fold γ-ray spectra, corrected for Doppler shift for Dy-like particles, are shown in Figs. 1(a) and 1(b) with the ^{58,61}Ni beams, respectively. The discrete γ rays are dominated by inelastic and one-neutron transfer reactions. Both pickup (^{160}Dy) and stripping (^{162}Dy) channels were observed. With the ^{58}Ni beam, the transfer probability is about 12% for the pickup channel and an upper limit of 0.7% for the stripping channel. Most of the observed intensity for ^{162}Dy transitions result from inelastic excitation of target impurity and not from the stripping channel. With the ^{61}Ni beam, the transfer probabilities are about 8.6% and 1.7% for the pickup and stripping channels, respectively, obtained at an energy of 267 MeV using the Rochester facility. These probabilities were derived from yields of the $4^+ \rightarrow 2^+$ transitions of the Dy nuclei. This paper emphasizes the one-neutron pickup channel, where the yrast transitions with spins up to 18^+ are observed for ^{160}Dy with both ^{58,61}Ni projectiles. The corresponding Ni-like final nuclei for one-neutron pickup are ^{59,62}Ni.

The γ-ray spectra corrected for Doppler shift for Ni-like particles are shown in Figs. 2 and 3 with the ^{58,61}Ni beams, respectively. The identification of γ rays for Ni-like particles is based on the known transition energies, γ-γ correlations, and the cross correlation with γ rays from the corresponding Dy-like partner. For example,

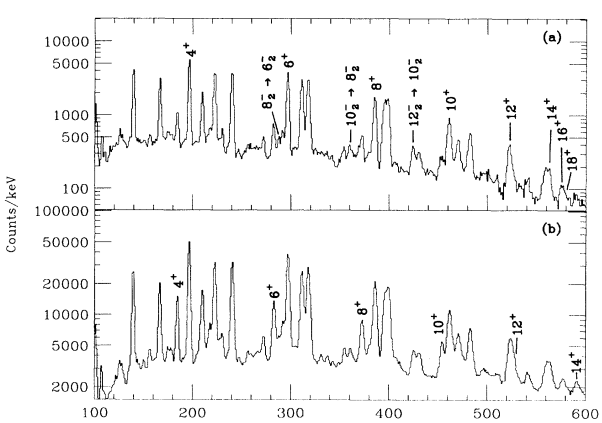

FIG. 1. Two- or higher-fold γ-ray spectra Doppler-shift corrected for Dy-like particles with ^{58}Ni projectile at 265 MeV (a) and ^{61}Ni projectile at 270 MeV (b). The labeled transitions are yrast transitions of ^{160}Dy (a) and ^{162}Dy (b). Non yrast transitions are labeled explicitly. Most of the unlabeled transitions belong to ^{161}Dy.

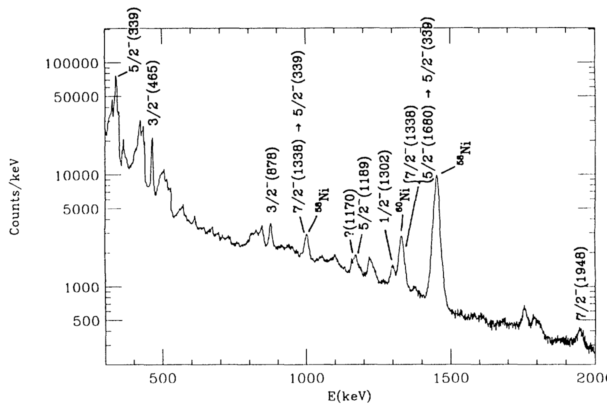

FIG. 2. Doppler-shift corrected γ-ray spectrum for Ni-like particles for ^{58}Ni projectiles at 265 MeV. The labeled transitions belong to ^{59}Ni and all decay directly to the ground state except for those specified. The numbers quoted in parentheses are level energies in keV.

the 1170(3) keV transition seen with the ^{58}Ni beam was identified as arising from ^{59}Ni through its correlations with known γ rays of ^{160}Dy. This transition could be the decay of the $\sim$1160 keV level, with an unknown spin, identified in the ^{58}Ni(α,^{3}He) reaction [6]. The completeness of information on the level scheme up to a few MeV for the Ni isotopes makes it possible to extract the relative population of excited states from the γ-ray yields. After correcting for the relative γ-ray efficiency, internal conversion, and known branching ratios plus feedings [7, 8], the measured relative populations of the excited states were derived and are shown in Figs. 4 and 5 for ^{59,62}Ni, respectively. The effect of the γ-ray angular distribution has been ignored and should be small for the large solid-angle multidetector system used. The ground-state population was obtained by balancing the γ-ray yield between the summed yield of Ni, after correcting for feeding, and the $4^+ \rightarrow 2^+$ of ^{160}Dy. The latter transition should represent more than 90% of the total cross section for this reaction channel because the observed yield

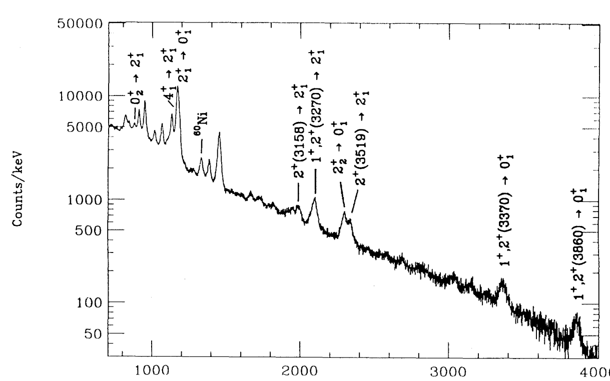

FIG. 3. The same as in Fig. 2 except for ^{61}Ni at 270 MeV. The labeled transitions belong to ^{62}Ni while most of the unlabeled ones belong to ^{61}Ni. The numbers quoted in parentheses are level energies in keV.

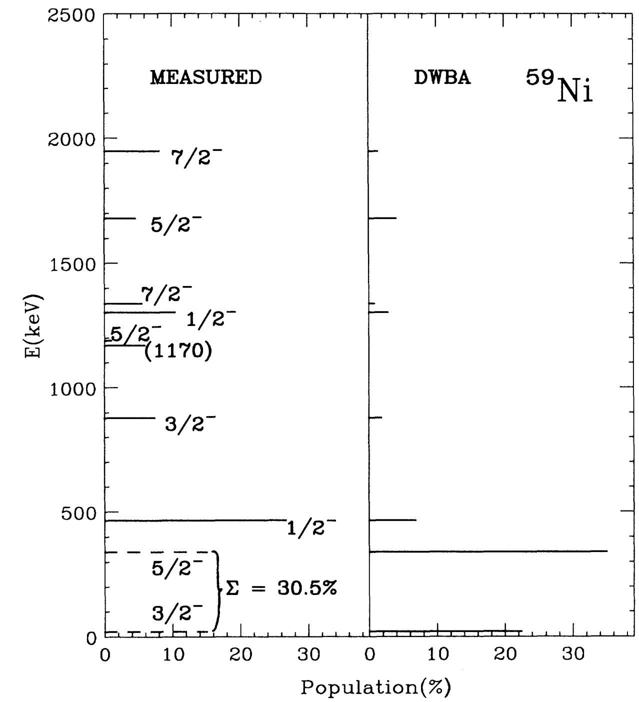

FIG. 4. (left) The relative population of excited states in ^{59}Ni, populated in the ^{161}Dy(^{58}Ni,^{59}Ni) reaction at $E_{\rm lab}$ = 265 MeV. Typical errors range from 10% to 20% of the values shown. (right) The normalized relative populations derived from DWBA calculations. Missing from the plot are levels at 1.17 and 1.19($5/2^-$) MeV for which no spectroscopic factors are available. Also missing is the $9/2^+$ state at 3.06 MeV which is predicted to be 24.9% of the population.

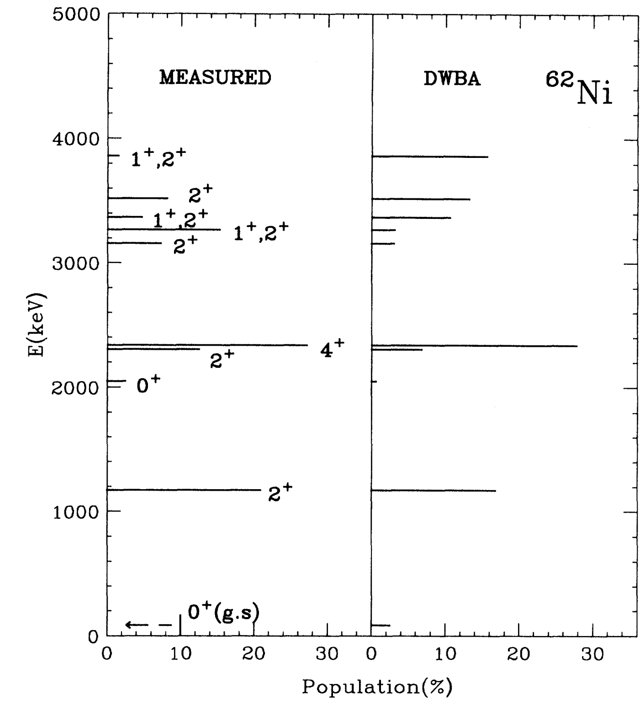

FIG. 5. (left) The relative population of excited states in ^{62}Ni, populated in the ^{161}Dy(^{61}Ni,^{62}Ni) reaction at $E_{\rm lab}$ = 270 MeV. Typical errors range from 10% to 20% of the values shown. (right) The normalized relative populations derived from DWBA calculations.

ratio of the $6^+ \to 4^+$ to the $4^+ \to 2^+$ transition is about 0.9, whereas in a pure Coulomb excitation calculation, this ratio is about 0.85 and the $4^+ \to 2^+$ transition is about 85% of total probability. With the ^{61}Ni beam, the ground-state population of ^{62}Ni is negligible from the above intensity balance procedure and a 10% upper limit (see Fig. 5) was set due to the incomplete representation of the $4^+ \to 2^+$ transition for the total cross section. In a different approach to the same data, the probability for populating the ground state of ^{62}Ni on the order of 2–3% was obtained by comparing the intensity of Ni excitation, gated by the $4^+ \to 2^+$ of Dy, to the total intensity of the latter. This number is difficult to determine because of the ~10% uncertainty for the absolute detection efficiency of γ rays, but it is consistent with the upper limit quoted. This procedure is approximately valid as long as the correlation between receptor and donor of the undetected population is small or negligible. Since the 339 keV γ-ray transition ($5/2^- \to$ ground state) of ^{59}Ni cannot be resolved from the coexisting γ rays of Dy-like particles having an incorrect Doppler-shift correction, only the summed population of the $5/2^-$ and $3/2^-$(ground state) in ^{59}Ni of about 30.5% (see Fig. 4) was obtained from the intensity balance procedure.

For ^{59}Ni excitation, the first three low-lying states, $3/2^-$ (ground state), $5/2^-$(339 keV), and $1/2^-$(465 keV), constitute the major spectroscopic strength for one-neutron transfer as determined by light-ion studies [7], and contribute about 57% of the total population in the present work. Six states between 1 and 2 MeV excitation energy contribute about 36% of the measured population; a highly fragmented distribution of strength is indicated. There is no detectable strength for decay of the $9/2^+$(3055 keV) state even though it has the largest spectroscopic factor measured in light-ion reactions. For ^{62}Ni excitation, the measured population is distributed over a number of states with excitation energy up to 4 MeV, where the spectroscopic factors are known from light-ion studies [8]. Five states between 3 and 4 MeV excitation energy contribute about 37% of the population; again a highly fragmented distribution of intensity is indicated.

The average excitation energy for ^{59}Ni is about 0.8 MeV (Q_{gg} = 2.5 MeV), in contrast to 2.5 MeV (Q_{gg} = 4.1 MeV) for ^{62}Ni. A broad bump in the γ-ray spectrum peaking at about 1 MeV, attributed to intrinsic excitation energy in ^{160}Dy, was observed previously for the ^{58}Ni beam [3] and about 1–2 MeV for the ^{61}Ni beam, derived from our EUROGAM data. In addition, there is about 2–2.5 MeV of rotational energy deposited in ^{160}Dy. Measurements with a better determination of the intrinsic excitation energy carried by the Dy-like particle are desirable and are planned for the near future.

Distoretd-wave Born approximation (DWBA) calculations, using the code PTOLEMY [9], were carried out in an attempt to understand the relative weight of the nuclear structure and reaction dynamics in determination of the excitation-energy partition between the receptor and donor for the one-neutron transfer reaction. It is assumed that the action of nucleon-transfer contributes most of the intrinsic excitation for the final system. Transitions to states $3/2^-$(0.0 and 0.88 MeV), $5/2^-$(0.34, 1.19, and 1.68 MeV), $1/2^-$(0.47 and 1.30 MeV), $7/2^-$(1.34 and 1.95 MeV), and $9/2^+$(3.06 MeV) in ^{59}Ni and 0^+(0.0 and 2.05 MeV), 1^+,2^+(3.27, 3.37, 3.86 MeV), 2^+(1.17, 2.30, 3.16, and 3.52 MeV), and 4^+(2.34 MeV) in ^{62}Ni were included in DWBA calculations for the one-neutron pickup reactions between ^{161}Dy and ^{58,61}Ni. These states covered most of the excited states up to 2 MeV in ^{59}Ni and 4 MeV in ^{62}Ni. For each Ni transition, the Q window for neutron-transfer was calculated individually for four single-particle configurations in ^{160}Dy, $f_{7/2}$, $h_{9/2,11/2}$, and $i_{13/2}$. The optical potential parameters ($V = 100$ MeV, $W = 40$ MeV, $r_0 = r_i = 1.04$ fm, and $a_0 = a_i = 0.85$ fm) were taken from Ref. [10] where they were extracted from fitting to the inelastic data. The calculated Q windows have a width typically about 6 MeV. Population of any Ni transition was calculated by summing contributions from the four single-particle configurations considered in ^{160}Dy and by using the spectroscopic factors measured by light ions [7, 8]. Contributions from individual single-particle configurations were calculated by summing over the Q window weighted by its occupancy number. Distributions of the occupancy number for these single-particle configurations in ^{161}Dy were obtained by using a modified oscillator potential with parameters from Bengtsson and Ragnarsson [11] followed by a BCS pairing calculation. The normalized relative populations for excited states in ^{59,62}Ni are compared in Figs. 4 and 5, respectively, with the experimental data. In a similar manner, the distribution of intrinsic excitation in ^{160}Dy was calculated by summing over contributions from all the Ni transitions and shown in Figs. 6(a) and 6(b) for the ^{58,61}Ni beams, respectively.

The average excitation energy carried by the Ni(receptor), estimated by the DWBA, is about 1.0 MeV for ^{59}Ni and 2.6 MeV for ^{62}Ni. These values are insensitive to the weighting function, such as the Dy occupancy number, for the summation of the Q window but are sensitive to the spectroscopic factors in Ni. For example, the calculated relative population for the $g_{9/2}$ state in ^{59}Ni is 24.9% by including the weight function of the Dy occupancy number and is 18.6% by ignoring this weight function. The overall agreement with the experimental results is reasonable even though the detailed comparison is less satisfactory. There is an overestimation of low-excitation states in ^{59}Ni and of high-excitation states in ^{62}Ni. The calculated distributions of intrinsic excitation energy in ^{160}Dy are almost the same for both ^{58,61}Ni beams despite the 1.6 MeV difference in Q_{gg} values, which indicates that the intrinsic excitation in Dy is primarily determined by the spectroscopic factor distribution. The calculated average intrinsic excitation is about 1.9 MeV for both cases. The observation of a broad bump in the γ-ray spectrum peaking at about 1 MeV when using a ^{58}Ni beam is well reproduced by this calculation.

In summary, we have shown that the population distribution for excited states, with sensitivity down to 1–2%, can be studied in particle-γ coincidence experiments for quasielastic heavy-ion transfer reactions at near barrier energies. For the one-neutron pickup reaction between ^{161}Dy and ^{58,61}Ni, the receptor carries about 0.8 MeV and 2.5 MeV excitation energy for the ^{58,61}Ni beams, respectively. For ^{160}Dy (donor), a broad bump in the γ-ray spectrum peaking at about 1 MeV was observed for the ^{58}Ni beam and about 1–2 MeV for the ^{61}Ni beam and is attributed to intrinsic excitation. The receptor receives a substantial fraction of the total excitation energy. DWBA analyses reproduce the general features and indicate that the partition of excitation energy between the receptor and donor is determined mainly by the spectroscopic factor distribution. It would be very interesting to measure the population distribution for two-neutron transfer reactions since there is an indication of population enhancement for the ground state of the receptor [12]. When completed, the new generation γ-ray detector arrays, Gammasphere and EUROGAM II, can measure the γ-ray cross correlations between excited states for donor and receptor by studying triple γ-ray coincidence events. That is, γ-γ correlations in Dy-like particles, for example, can be studied by gating a particular transition in Ni-like particles. The details of the excitation-energy partition can be studied by this approach and the gating could serve as a measure of the intrinsic excitation energy in Dy-like particles. This may provide a new avenue in the study of the order-chaos transition for the low-spin region and of rotational damping in quasicontinuum γ-ray spectroscopy for the intermediate-spin region at finite intrinsic excitation energy in nuclei [13, 14].

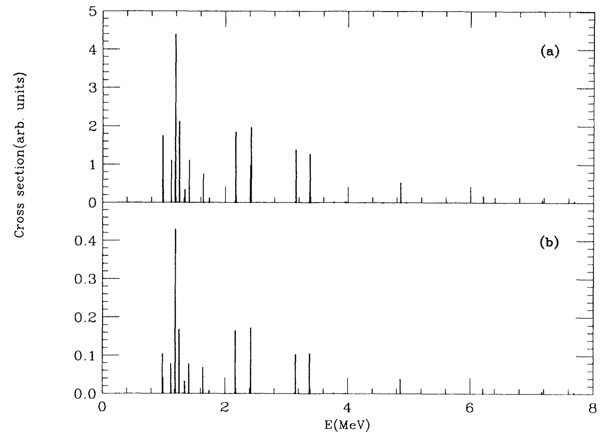

FIG. 6. The calculated intrinsic-excitation distribution in ^{160}Dy for the one-neutron pickup channel for the reaction between ^{161}Dy and ^{58,61}Ni are shown, respectively, in (a) and (b).

We thank Dr. P. Semmes for his help in the calculations of occupancy number for the single-particle orbits. The work at University of Rochester is supported by the National Science Foundation. The work at University of Liverpool and Daresbury Laboratory is supported by the U.K. Science and Engineering Research Council. Travel is partially supported by a grant from NATO.

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