 Cluster-transfer reactions with radioactive beams: A spectroscopic tool for neutron-rich nuclei

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An exploratory experiment performed at REX-ISOLDE to investigate cluster-transfer reactions with radioactive beams in inverse kinematics is presented. The aim of the experiment was to test the potential of cluster-transfer reactions at the Coulomb barrier as a mechanism to explore the structure of exotic neutron-rich nuclei. The reactions $^7$Li($^{98}$Rb,x$n$) and $^7$Li($^{98}$Rb,x$t$) were studied through particle-$\gamma$ coincidence measurements, and the results are presented in terms of the observed excitation energies and spins. Moreover, the reaction mechanism is qualitatively discussed as a transfer of a clusterlike particle within a distorted-wave Born approximation framework. The results indicate that cluster-transfer reactions can be described well as a direct process and that they can be an efficient method to investigate the structure of neutron-rich nuclei at medium-high excitation energies and spins.

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I. INTRODUCTION

At present, there is a rather general consensus that a deeper understanding of nuclear structure and processes can be achieved from a focus on phenomena occurring in unexplored regions of the nuclear landscape. This view is partly based on the assumption that new observations in exotic parts of the nuclear chart will provide severe and crucial tests of the existing theoretical descriptions [1–4].

In this context, high-spin yrast states in nuclei far from the valley of stability are of special interest as such excitations often arise from the maximum spin coupling of the valence particles and holes. Their wave functions usually involve mostly one well-defined configuration and are, thus, rather pure (see Ref. [5] and references therein).

A successful method for investigating the high-spin yrast structure of exotic neutron-rich nuclei uses deep-inelastic reactions occurring during heavy-ion collisions at beam energies around 20% above the Coulomb barrier. However, in such processes, the production yield is spread over many nuclei, resulting in a rather low intensity for individual species [6–17].

A more efficient technique to populate yrast states in neutron-rich nuclei is provided by cluster-transfer reactions. For example, reactions induced by a $^7$Li beam have been exploited extensively for $\gamma$-ray spectroscopy studies of states of relatively high angular momentum in neutron-rich nuclei which are inaccessible with standard fusion-evaporation reactions involving stable beam-target combinations [18–23]. Indeed, with its pronounced alpha ($\alpha$)—triton ($t$) cluster structure

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characterized by a separation energy of only 2.467 MeV [24].

In the present experiment, only the forward CD detector was used in

+ eight lateral square detectors forming a barrel. In the

given in Sec.V.

It is natural to anticipate that t transfer induced by neutron-rich radioactive beams on a 7Li target will populate yrast states in nuclei in the immediate vicinity of the projectile, herewith opening to yrast spectroscopy as yet unexplored parts of the nuclear chart. However, such reactions have not yet been studied and, consequently, data are needed to inform on their feasibility as well as on reaction dynamics when neutron-rich nuclei are involved.

In this paper, cluster-transfer reactions induced by a neutron-rich radioactive beam on a 7Li target were investigated for the first time in a pilot experiment performed at REEX-ISOLDE [26,27]. A 98Rb beam bombarded a 7Li target at a beam energy close to the Coulomb barrier. Particular attention was devoted to γ-ray spectroscopy of t- and α-transfer products. In addition, some aspects of reaction dynamics were also investigated by confronting experimental data with theoretical calculations performed with the FRESCO code [28] using a distorted-wave Born approximation (DWBA) approach. This test experiment is meant as a first step of a broader experimental program aimed at studying the structure of yrast states in neutron-rich nuclei, in particular around doubly-magic 132Sn, by using cluster transfer with a 7Li target.

The paper is organized as follows. In Sec. II, the 98Rb + 7Li experiment is presented along with the apparatus. In Sec. III, the reaction channels observed in the present measurements are briefly described, whereas Sec. IV focuses on the cluster-transfer reaction channels of interest in terms of γ spectroscopy and of reaction dynamics aspects. Conclusions are given in Sec. V.

II. THE EXPERIMENT

The experiment was performed at REEX-ISOLDE [26,27]. A radioactive neutron-rich beam of 98Rb at a nominal energy of 2.85 MeV/nucleon with an average intensity of 2 × 10^9 particles per second was sent onto a 1.5-mg/cm^2-thick 7Li-enriched LiF target. Due to energy loss, the beam energy at midtarget was 2.49 MeV/nucleon. Together with the 98Rb ions, a strong 98Sr isobaric component was observed in the beam. This 59Sr contaminant originates from the limited mass separation and β decay of 98Rb during the bunching and charge-breeding phases [29]. The experimental setup consisted of the HpGe MINIBALL array [30] coupled to the Si detector system T-REX [31], and γ-particle coincidence events were measured. The MINIBALL spectrometer is a high-resolution HpGe detector array consisting of 24 sixfold segmented crystals, characterized by good spatial and energy resolutions. In the present experiment, it had a photocope efficiency of 5% at 1 MeV. T-REX is a Si detector setup optimized for transfer reactions in inverse kinematics, designed to be used with the MINIBALL array. It consists of two compact disk (CD) detectors [32] placed at forward and backward angles plus eight lateral square detectors forming a barrel. In the present experiment, only the forward CD detector was used in a new configuration where it was placed at 22 mm from the target. This arrangement resulted in a wide 21°–62° angular coverage in the laboratory frame of reference. The forward CD detector consists of two layers with 140 and 1500-μm respective thicknesses, used as a ΔE-E telescope in order to detect and identify light charged particles. The first layer is segmented into 16 annular rings and 24 vertical strips, enabling determination of the scattering angles.

The proposed reaction has two distinct features that greatly facilitate detection of the discrete γ rays and their identification. First, the very inverse kinematics guarantees that the product nuclei all travel downstream in a small recoil cone; thus, Doppler reconstruction of the γ-ray data does not require recoil detection. Second, the reaction channels of interest are uniquely associated with the emission of an α(t) particle. By detecting the latter, one should be able to produce a very clean trigger for t(α)-transfer processes.

III. REACTION CHANNELS

It is well known that in heavy-ion collisions many reaction channels are available with intensities depending on several parameters, such as the relative energies, mass, charge, and Q-value matching conditions [33]. In particular, at energies around the Coulomb barrier, “fast” direct reactions compete with “slow” fusion-evaporation ones, and the interplay between these processes can modify significantly the balance between the cross sections for the outgoing channels. In direct reactions, transfer is one of the main processes removing flux from elastic scattering, and the coupling between different channels is a key ingredient to understand both the reaction dynamics and the microscopic structure of the interacting nuclei [9]. Furthermore, the usual couplings between different reaction channels may be altered when weakly-bound neutron-rich nuclei are used as reaction partners [34]. In this section, the reaction channels observed in the present experiment with the help of particle-γ and γ-γ coincidence techniques are presented.

Figure 1 shows charged particles detected by the CD detector and identified with the ΔE-E\_T technique, where E\_T is the total measured energy. The most intense channel corresponds to 7Li elastic and inelastic scatterings with the former being the main component. The elastic channel is primarily associated with Rutherford scattering with a small interference due to the nuclear potential at larger angles as will be shown later. A small part of these events corresponds to the inelastic excitation of both beam components 98Rb and 98Sr - the associated Doppler-corrected γ spectrum is presented in Fig. 2. It is worth noting that both Coulomb and nuclear interactions participate in projectile excitation as the beam energy exceeds the Coulomb barrier. The 2^+ → 0^+ transition at 144 keV in 98Sr can be clearly seen together with three other strong γ lines at 51, 95, and 115 keV. These transitions might possibly belong to the 98Rb decay scheme, which is not known. The γ rays at 51 and 115 keV are not in coincidence with each other nor with the 144-keV line. It is very likely that some of these three γ rays feed the ground state of 98Rb, whereas the other(s) fed(s) the 139-ms isomer at 270 keV in this nucleus - the 98Rb projectiles were delivered.
by ISOLDE in both the ground and the isomeric states [35]. The transitions discussed above could be displayed with higher statistics by requiring a coincidence with particles with mass 7 and higher, that did not punch through the $\Delta E$ detector (diagonal of Fig. 1), as shown in the inset of Fig. 2.

This enhancement in the statistics arises from the presence in the gate of inelastically scattered low-energy $^7$Li nuclei as well as of $^{19}$F reaction partners from the target contaminant by ISOLDE in both the ground and the isomeric states [35]. The transitions discussed above could be displayed with higher statistics by requiring a coincidence with particles with mass 7 and higher, that did not punch through the $\Delta E$ detector (diagonal of Fig. 1), as shown in the inset of Fig. 2.

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clusters is expected to be the highest. The last row refers to the t-98Rb and α-98Rb separation energies (S.E.).

<table>
<thead>
<tr>
<th>Channel</th>
<th>t transfer</th>
<th>α transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_{gg}</td>
<td>13.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Q_{opt}</td>
<td>−5.1</td>
<td>−10.4</td>
</tr>
<tr>
<td>E_{opt}</td>
<td>18.7</td>
<td>18</td>
</tr>
<tr>
<td>S.E.</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

As can be seen from Table I, these channels are characterized by large positive Q_{gg} and negative Q_{opt} values, which result in high excitation energies peaked where the cross section is expected to be the highest. Q_{opt} was calculated according to Ref. [41] using the first-order approximation expression. These energies are larger than the energy threshold for fragment-98Rb separation but still well below the fission barrier such that the final nucleus deexcites initially by neutron evaporation and, subsequently, by γ emission as will be shown below. Furthermore, the simple structure of 7Li ensures that few degrees of freedom are involved in the process so that the main part of the flux in the outgoing transfer channels is in cluster transfer.

In this section, the potential for exploiting this mechanism with radioactive beams in inverse kinematics in order to study neutron-rich nuclei is presented. The reaction dynamics will be discussed in the framework of a binary process as a direct transfer of a clusterlike particle to weakly-bound states located close to the continuum using a DWBA approximation.

Figure 4 presents γ spectra Doppler corrected on an event-by-event basis obtained in coincidence with α and t particles. These correspond to t and α transfers on 98Rb and populate 101Sr* and 102Y*, respectively, followed by neutron evaporation. Since the reaction took place on 98Sr as well, 101Y* and 102Zr* are populated, and transitions from products after neutron evaporation are also identified and are labeled appropriately (Fig. 4). Note that the detection of the cluster in coincidence with γ rays resulted in a clean trigger on the final channel of interest. Several nuclei were identified: they correspond to different numbers of evaporated neutrons depending on the excitation energy of the final systems above the neutron threshold. It is worth noting that a typical neutron separation energy for nuclei in this mass region is between 5 and 6 MeV, whereas the excitation energy of the final systems as measured in this work is between 11 and 23 MeV. For reactions on 98Rb, both 3n and 2n channels are observed, whereas in the case of 98Sr, only the 2n channel is present for both t and α transfers. By comparing the excitation energy in the projectilelike systems following transfer with the respective neutron separation energies (S_{nn}), the difference between reactions on the 98Rb and 98Sr beam components in terms of observed final residues can be understood. In fact, in the case of 98Rb, the average excitation energy of the 101Sr final system is 19 MeV. With S_{3n}(101Sr) = 13.292 MeV,
this accounts for the evaporation of up to three neutrons. In contrast, for $^{98}\text{Sr}$, the average excitation energy in $^{101}\text{Y}$ is 16 MeV and $S_{3n}(^{101}\text{Y}) = 16.674$ MeV. This justifies the absence of the $3n$ channel in this case.

Despite the high excitation energy and high angular momentum of the systems after transfer, yrast states were observed with spins up to $6\hbar$ only in the case of t transfer and up to $4\hbar$ for $\alpha$ transfer. This is mainly due to the limitation imposed by the low intensity of the beam as well as by the beam composition, resulting in insufficient statistics to observe $\gamma$ rays from higher-spin and off-yrast levels. The average expected spins can also be deduced from the measured distribution of neutron-evaporation channels. The difference in the observed distribution of residues was investigated by comparing the measured channel yields with the results of calculations with the statistical model CASCADE [39]. For this purpose, the decay of the final nuclei was studied as a function of entry spin, considering the final systems at their highest measured excitation energies. The results are presented in Fig. 5 where it is seen that the data are reproduced well by assuming a spin of $20\hbar$ for t transfer, whereas $15\hbar$ is required to fit $\alpha$ transfer. This observation supports the expectation that states with medium-high energy and medium-high spin are populated in t and $\alpha$ cluster-transfer processes. Furthermore, an analysis of the results of the CASCADE calculations indicates that, in the case of t transfer on $^{98}\text{Rb}$, an average excitation energy of 6 MeV and an average angular momentum of $16\hbar$ are predicted for the $2n$ channel, whereas 2 MeV and $9.5\hbar$ are expected for the $3n$ one. These characteristics indicate that low-lying states with moderate-to-high spin in exotic nuclei produced in cluster-transfer processes induced by radioactive beams should be available for extensive structure studies with $\gamma$-ray spectroscopy techniques.

In order to make more detailed predictions, a better understanding of the reaction dynamics for cluster-transfer processes involving neutron-rich nuclei is desirable.

In the present paper, the cluster-transfer mechanism was studied for the $^{98}\text{Rb} + ^7\text{Li}$ system through comparisons with the results of calculations with the code FRESCO [28]. (Note that calculations for $^{98}\text{Sr} + ^7\text{Li}$ give similar results [42]). To do so, the elastic cross section was first investigated in order to obtain the optical parameters of the scattering potential in the initial mass partition. Global optical parameters for $^7\text{Li}$ elastic scattering were used [43], resulting in a good fit of the experimental data as demonstrated in the inset of Fig. 6 where the ratio between the cross sections for elastic and Rutherford scatterings is presented. As can be seen, the experimental angular distribution is consistent with essentially pure Rutherford scattering for nearly all the measured angles, except perhaps for the largest ones where interference from the nuclear potential is expected to affect the data. A scaling of the experimental elastic data to the theoretical distribution provided the normalization factor required to obtain absolute experimental cross sections.
The transfer cross section data were interpreted by considering the reaction as a binary process involving the direct transfer of a clusterlike particle. The scattering potentials in the final mass partitions were chosen to fit the present experimental data, starting from optical-model parameters for heavy-ion scattering described in Ref. [33]. These parameters are presented in Table II. The $^7$Li ground-state wave function was described in the framework of a cluster model, considering an $\alpha$(t) core in the case of $t(\alpha)$ transfer [44], resulting in the $t$ and $\alpha$ particles being in a relative $P$ state. Furthermore, a Gaussian interaction was used as a binding mean-field potential $V_{\alpha\,t}$ [45]. The final states accessed by the transfer were also described within a cluster model using a standard Woods-Saxon potential. Since the transfer populates states above the $^{98}$Rb and $^{t\,98}$Rb separation energies, the final levels were treated within a cluster model using a standard Woods-Saxon potential. Several states, in steps of 0.5 MeV, were considered for each angular momentum transferred, rendering the $t$-transfer distribution is peaked at 5 MeV above the $t$-$^{98}$Rb separation energy, rendering the weakly-bound assumption less suitable. Also, in this case, it should be noted that the angular momentum of the final states has no impact on the peak position. These results demonstrate that the transfer can be qualitatively described as a direct process and that such an approach is able to reproduce the main properties of the reaction. Nevertheless, to achieve a more quantitative description, the coupling to other channels should be included, together with a more realistic representation of the states in the continuum with a proper discretization of the phase space.

Figure 6 displays the angular distributions for $t$ and $\alpha$ transfers where experimental data were rescaled with a common factor obtained from the elastic-scattering data.

To test the ability of model calculations to reproduce the difference in relative cross sections between the two transfer channels, theoretical distributions obtained with the FRESCO code are also given in the figure after normalization to the data with a single normalization coefficient. It can be seen that the ratio between the two experimental distributions is reproduced well by theoretical calculations, provided that: (i) states up to $\ell_{\text{max}} = 3$ and $\ell_{\text{max}} = 5$ are included for $t$ and $\alpha$ transfers, respectively, and that (ii) the number of nodes in the case of the $\alpha$ transfer is twice that in the $t$-transfer channel. The choice of the angular momenta was driven by the fact that the cross sections exhibit a maximum at $\ell_{\text{max}}$ for both $t$ and $\alpha$ transfers. Several states, in steps of 0.5 MeV, were considered for each $\ell$ value up to $\ell_{\text{max}}$. Notably, no dependence of the shape of the angular distributions on the angular momentum transferred was observed. The differential cross sections as a function of the excitation energy of the final systems are presented in Fig. 7 for both $t$ transfer [panel (a)] and $\alpha$ transfer [panel (b)]. The experimental distributions were reconstructed, assuming two-body kinematics, by deducing the excitation energies from the angles and the kinetic energy of the detected $t$ and $\alpha$ particles. First, it may be noticed that both distributions exhibit a clear maximum at the energy deduced from the optimum $Q$ value. This is in line with expectations based on semiclassical considerations which predict a pronounced peak for the cross section at high excitation energy. Moreover, the theoretical calculations performed in this paper can reproduce the shape of the experimental distributions (Fig. 7). In the case of $t$ transfer, the cross-section behavior is reproduced better than in the case of $\alpha$ transfer: This is consistent with the weakly-bound approximation as the peak of the former distribution is close to the $t$-$^{98}$Rb separation energy, making such an approximation reliable. On the other hand, the $\alpha$-transfer distribution is peaked at 8 MeV above the $\alpha$-$^{98}$Rb separation energy, rendering the weakly-bound assumption less suitable. Also, in this case, it should be noted that the angular momentum of the final states has no impact on the peak position. These results demonstrate that the transfer can be qualitatively described as a direct process and that such an approach is able to reproduce the main properties of the reaction. Nevertheless, to achieve a more quantitative description, the coupling to other channels should be included, together with a more realistic representation of the states in the continuum with a proper discretization of the phase space.

![Angular distribution](image.png)

**FIG. 6.** (Color online) Angular distribution for $t$ [dots (red)] and $\alpha$ [diamonds (blue)] transfers on $^{98}$Rb compared with theoretical calculations (solid lines) as explained in the text. Data were rescaled with the same normalization factor. Inset: ratio between the elastic scattering potentials $V_{\alpha\,t}$ and $V_{\alpha\,t}$ without considering the remnant terms: $V_{\text{int}}^{\text{rel}} \approx V_{\alpha\,t}$.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$V$ (MeV)</th>
<th>$R_C$ (fm)</th>
<th>$a_C$ (fm)</th>
<th>$W$ (MeV)</th>
<th>$r_W$ (fm)</th>
<th>$a_W$ (fm)</th>
<th>$R_C$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{7}$Li + $^{98}$Rb</td>
<td>114.2</td>
<td>1.286</td>
<td>0.853</td>
<td>15.643</td>
<td>1.739</td>
<td>0.809</td>
<td>5.994</td>
</tr>
<tr>
<td>$\alpha$ + $^{101}$Sr</td>
<td>140.0</td>
<td>1.200</td>
<td>1.200</td>
<td>10.0</td>
<td>1.200</td>
<td>1.200</td>
<td>6.074</td>
</tr>
<tr>
<td>$t$ + $^{102}$Y</td>
<td>80.0</td>
<td>1.250</td>
<td>1.500</td>
<td>10.0</td>
<td>1.250</td>
<td>1.500</td>
<td>6.074</td>
</tr>
</tbody>
</table>

**TABLE II.** Woods-Saxon optical-model parameters for the incoming channel ($^{7}$Li + $^{98}$Rb) and the outgoing $t$- and $\alpha$-transfer channels ($\alpha$ + $^{101}$Sr and $t$ + $^{102}$Y). The former are adopted from Ref. [43] and reproduce the elastic scattering well, whereas the latter were obtained by fitting the present experimental data.
The possibility that part of the measured $\alpha$ and t particles, interpreted here as originating from direct t- and $\alpha$-transfer processes, may come from other reactions, such as incomplete fusion, cannot be entirely ruled out. It has recently been shown in a direct kinematics experiment [46] that the measured cross sections can be reproduced well by considering a two-step process where $^7$Li breakup is followed by the fusion of either fragment. Although it is impossible to disentangle such two-step processes from the direct reactions used above, the satisfactory description achieved here argues in favor of the fact that other reaction mechanisms either only impact the absolute scale of the cross sections or only contribute little for systems and energies, such as those considered here.

V. CONCLUSIONS

In this work, an exploratory study of the $^{98}$Rb + $^7$Li reaction at the Coulomb barrier energy (2.85 MeV/nucleon) was performed at REX-ISOLDE to investigate cluster-transfer processes with radioactive beams in inverse kinematics. The potential of using such cluster-transfer processes to access yrast and near-yrast states in neutron-rich nuclei was verified. The results, based on particle-$\gamma$ coincidences, demonstrate the suitability of the experimental method to populate medium-high energy and medium-high spin states with yields sufficient for $\gamma$-ray spectroscopic studies, even with radioactive beams of relatively low intensity. Furthermore, the reaction dynamics was studied, and comparisons with theoretical calculations achieve a satisfactory description of the process in terms of a direct transfer. Further experimental information is needed to better understand the process, especially in terms of inclusive cross sections.

The experimental technique examined here can be readily exploited to investigate nuclear structure in even more exotic regions of the nuclide chart, once new radioactive beam facilities, such as HIE-ISOLDE, SPIRAL2, SPES, ISAC, FRIB, etc., come on line with beams of higher energy and higher intensity.

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