Multinucleon transfer processes in ^{64}Ni+^{238}U

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Weakly populated multinucleon transfer reactions have been studied in ^{64}Ni+^{238}U at $E_{\mathrm{lab}}=390$ MeV with a time-of-flight magnetic spectrometer. Angular and Q-value distributions for multinucleon transfer channels have been measured up to the pickup of six neutrons and the stripping of six protons. Differential and total cross sections have been extracted and compared with calculations based on the GRAZING model for grazing reactions. The evolution of the system from a quasielastic to a more complex regime and the present limitations to a detailed understanding of these processes are discussed. The results confirm that a clear experimental distinction can be made between the collisions in the grazing (quasielastic and deep-inelastic) regime and in a more complex one (quasifission). [S0556-2813(99)05401-1]

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I. INTRODUCTION

In recent high resolution experiments [1–5] performed with time-of-flight and momentum magnetic spectrometers at bombarding energies close to the Coulomb barrier, transfer channels produced in binary reactions have been identified up to six-neutron pickup and six-proton stripping. Such measurements open new possibilities for detailed investigations of (1) correlation effects in nuclei [6–9], (2) the transition from the quasielastic to deep-inelastic regime [10–12], and (3) coupling effects with other competing channels (e.g., subbarrier fusion) [13,14]. Moreover, multinucleon transfer reactions are a competitive tool for the production of neutron-rich nuclei, and a better knowledge of the underlying mechanisms represents an essential base in view of future research with radioactive beams [15].

An important question to be addressed is which are the relevant degrees of freedom one has to consider in a correct description of the reaction mechanism and how they can be probed experimentally. In particular, to what extent the inclusion in a theoretical framework of single-nucleon transfer modes suffices to describe the experimental observables, and if and how more complex channels, like the transfer of nucleon pairs or clusters, enter into play, is still far from being understood. In connection to these questions, we recently started a systematic program aimed at precision measurements of weakly populated multinucleon transfer channels. We set up at LNL a new time-of-flight (TOF) spectrometer with magnetic quadrupole elements [2], which allows us to detect and identify with high efficiency and resolution ions produced in a binary reaction at near barrier energies. Parallel to this experimental work, the Copenhagen group developed a new model [16–19] treating quasielastic and deep inelastic processes on the same ground, which has been already successfully applied in different cases and which represents an important improvement on the theoretical side.

With the TOF spectrometer we have recently studied two systems, at energies close to the Coulomb barrier, and for each of them new important features of the reaction mechanism have been evidenced. In the system ^{40}Ca+^{124}Sn [2] we observed a ''drift'' of the experimental total cross sections (for the isotope distributions involving proton stripping channels) with respect to calculations [16–18] which include only independent single-nucleon transfer modes. In the system ^{48}Ca+^{124}Sn [20], the drift has been observed both along the proton stripping and pickup directions, and has been interpreted as possible evidence of complex (i.e., pair/cluster) degrees of freedom in the transfer process. The conclusions are based on the analysis of the total integrated cross sections which we consider more suitable, at this stage, for a meaningful quantitative comparison between theory and experiment. Clearly, those conclusions may strongly depend on the choice of the system and, in particular, on the fact that calcium has a closed shell structure and tin is of superfluid nature.

In the present work we investigate the system ^{64}Ni+^{238}U at $E_{\mathrm{lab}}=390$ MeV which is close to the Coulomb barrier. The aims are many. First we wanted to check if the effects observed in the experiments with the ^{40,48}Ca beams persist with these nuclei of completely different shell structure. ^{238}U is the most neutron-rich stable nucleus and, with the rather heavy neutron-rich ^{64}Ni beam, we expect large cross sections for transfer channels both along the pickup and stripping of neutrons and protons, thus, possibly, allowing a better study of nucleon correlations. The system was also chosen because it had been studied in the past [21] at about the same energy, but with a poor mass resolution and without a determination of the charge of the fragments. It would be interesting to see whether their conclusion of a sharp separation between deep-inelastic scattering and quasifission could be confirmed. A measurement of the charge of the ejectile would be an important indication of the validity of this conclusion, since the driving force for multiproton transfer in the grazing region (because of the value of the optimum Q value) is towards stripping reactions, while the driving force after capture is towards mass and charge equilibration. The transitional regime from quasielastic to more complex processes at Coulomb barrier energies has been studied so far, to our knowledge, in only one case with good mass and charge resolution and in a wide range of scattering angles [10]. Since this transition is still very poorly understood in its details, we feel it important to investigate to what extent the various experimental observables (i.e., cross sections, Z, A, and Q-value distributions) can be interpreted on the basis of grazing processes, within the framework of the model of Refs. [16–18]. The same transitional regime, but from the point of view of the N/Z equilibration in damped reactions as a function of the energy loss, has been studied in Ref. [22] with the same reaction but at a much higher bombarding energy.

The paper is organized as follows: in Sec. II we present the experiment, in Sec. III we discuss the experimental results, and in Sec. IV we compare the experimental and theoretical differential and total cross sections and Q-value distributions. Conclusions and final considerations are given in Sec. V. A preliminary report on the experimental results is given in Ref. [3].

II. EXPERIMENT

The experiment has been done at the Tandem + ALPI accelerator complex of the Laboratori Nazionali di Legnaro. A ^{64}Ni beam has been delivered at $E_{\rm lab}=390$ MeV onto a 200 μg/cm^2 $^{\rm nat}$U target. The beam energy spread was $\simeq 0.2\%$, but the central energy had an indetermination of $\pm 2\%$. Light reaction products have been detected and identified with a time-of-flight magnetic spectrometer, whose characteristics were already described in Ref. [2]. Briefly, the spectrometer is equipped with two microchannel-plate (MCP) detectors for TOF signals and a multiparametric ionization chamber of ΔE-E type for nuclear charge and energy determination. Between the MCP detectors, two doublets of magnetic quadrupoles are placed, and the resulting effective solid angle is $\simeq 3$ msr. The spectrometer is connected to a large (1 m in diameter) scattering chamber with a sliding seal, and angular distributions have been measured in the laboratory range $50°-105°$, covering most of the total transfer flux. In the present experiment the mass and nuclear charge resolutions were $\Delta A/A \simeq 1/110$ and $\Delta Z/Z \simeq 1/60$, respectively, for ions with A$\simeq$50–70 and energies 1–3 MeV/nucleon. This allowed a good identification of the reaction products over the whole measured angular range (see the next section).

The transmission of the spectrometer is determined from the yield of quasielastic events as a function of the magnetic fields of the quadrupoles and by calculations performed with ion optical codes. The obtained transmission curve has a flat top part, as expected from the present geometry, which defines a rather constant $B\rho$ acceptance range of $\pm 10\%$. As in our previous experiments, the yields of the elastic and of the one- and two-nucleon transfer channels have been compared, at different angles, with the quadrupole fields switched on and off. The ratios, which directly give the effective solid angle of the instrument for a specific reaction, turn out to be 13.5 ± 2, almost independently of the channel and the angle. This is consistent with that obtained previously [2,20]. It has been further checked that for most of the other detected transfer channels, the $B\rho$ values corresponding to the measured Q values lie within the $\pm 10\%$ acceptance window of the spectrometer. For very weak channels [like, for instance, those belonging to the $(-5p)$ or $(-6p)$ isotope distributions and with total cross sections below $\simeq 500$ μb] the Q-value distributions extend to quite negative values (i.e., $Q \leqslant -80$ MeV). These events begin to be outside the flat acceptance window and, anyway, merge in the ΔE-E matrices with other channels; therefore an additional software cut had to be done. We can estimate that those events affect the cross sections by less than 10–20 %; hence, since even statistics is quite poor, especially at forward angles, no correction has been applied to the data. A more proper investigation of that range of Q values would require specific measurements with different quadrupole fields, but it is outside the present study.

For all the data, the absolute normalization of the cross sections and relative normalization between different runs were ensured by four silicon detectors, placed inside the sliding-seal scattering chamber at $\theta_{\rm lab}=20°$ and on the corners of a square perpendicular to the beam. In this way a proper monitoring of the position and impinging direction of the beam on the target could be done continuously during the experiment. The intensities of the four monitors were rather similar within 10% at the end of each run and their average values have been then used for the normalizations. The efficiencies of the two MCP detectors have been also continuously checked during the experiment; their value, determined through the ratio of TOF and ΔE signals, was in the range 0.82–0.88, and the total counts in each run were correspondingly corrected. The errors in the cross sections (see later Figs. 4 and 8) are $\simeq$10–15 % for the most intense channels, and increase to 20–30 % for the weaker ones. Errors take into account statistics and systematic errors coming from monitor and spectrometer solid angle determination, and integration of the mass and charge spectra.

III. EXPERIMENTAL RESULTS

We show in Fig. 1 examples of ΔE-E matrices at two different angles, in Fig. 2 the Z-A matrix at the grazing angle $\theta_{\rm lab}=80°$, obtained after proper linearization of the parameters defining mass and charge, and in Fig. 3 the projection on the mass axis for some representative Z. One can

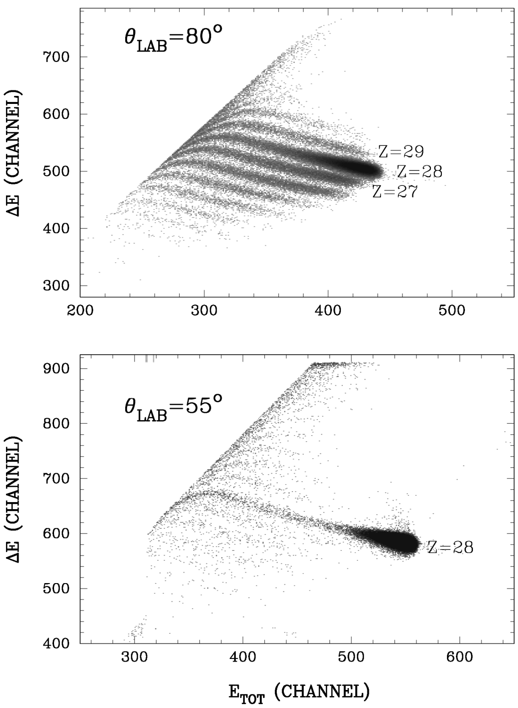

FIG. 1. ΔE-E_{tot} matrices at $\theta_{\mathrm{lab}}=80°$ and 55°.

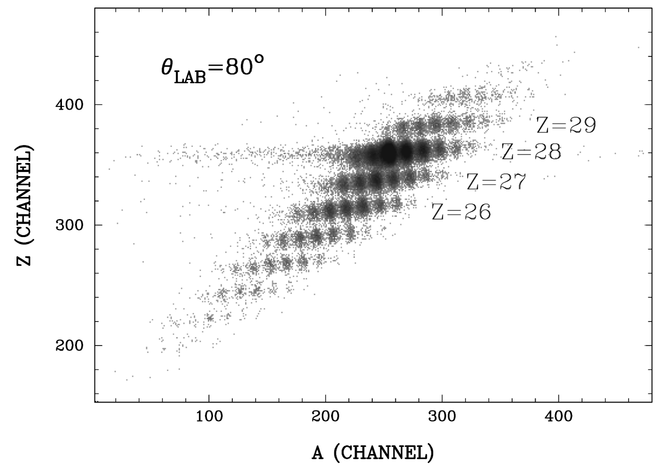

FIG. 2. Z-A matrix at $\theta_{\mathrm{lab}}=80°$. The most intense spot at $Z=28$ corresponds to $A=64$.

immediately observe the large amount of nuclei produced in the reaction, along both the proton and neutron pickup and stripping chains. The efficiency of the spectrometer allowed us to see, with reasonable statistics, events corresponding to the pickup of six neutrons and the stripping of six protons and six neutrons, with differential cross sections down to 50–100 μb/sr. Events belonging to the $-8p$ channels are also visible. We populate conspicuously ejectiles on the neutron-rich side of the nuclide chart, in the Ni-Fe-Cr-Ti region, as qualitatively expected on the basis of simple optimum Q-value arguments, which favor proton stripping and neutron pickup. The data demonstrate (for the ejectiles) that multinucleon transfer reactions at energies close to the Coulomb barrier may represent a competitive tool for the production of neutron-rich nuclei, where other methods (e.g., fusion evaporation) fail.

From Fig. 3 one sees that even pure neutron stripping channels are present with a relatively high yield. They could be clearly observed at backward angles, but around the grazing and at forward angles the tail of the overhelming elastic peak towards lower masses did not allow us to extract reliable cross sections. We can estimate, however, that for the $-1n$ and $-2n$ channels, the cross sections are a factor of $\simeq 4$ smaller than the corresponding values for the $+1n$ and $+2n$ channels. We remark that what is actually measured is the yield of the transfer products after nucleon evaporation from the primary fragments, which may strongly affect the intensity of neutron stripping channels. About the proton pickup isotope distributions, the $(+1p)$ and $(+2p)$ cases could be safely analyzed, but beyond that, apart from decreasing statistics, the events in the ΔE-E matrices tend to merge, due to their negative Q values (see Fig. 1). We observed, especially at forward angles, nuclear charges up to $Z\simeq 40$, but it is difficult to get quantitative estimates of these events, since they are at the border of the spectrum and the ionization chamber was not optimized for them. We argue that these events derive from quasifission processes and from fission of ^{238}U (ternary events), as observed in Ref. [21].

Looking at Fig. 3 and at the total integrated cross sections

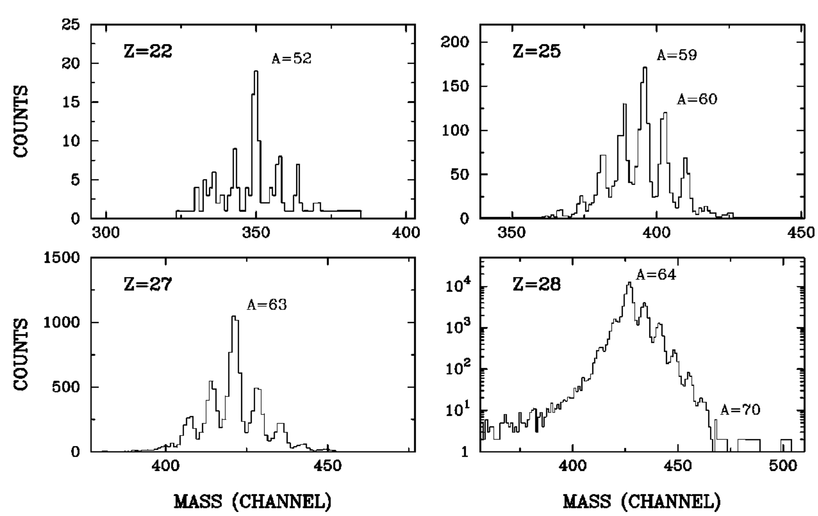

FIG. 3. Projection of the Z-A matrix of Fig. 2 onto the mass axis for $Z=28(0p)$, $Z=27(-1p)$, $Z=25(-3p)$, and $Z=22(-6p)$.

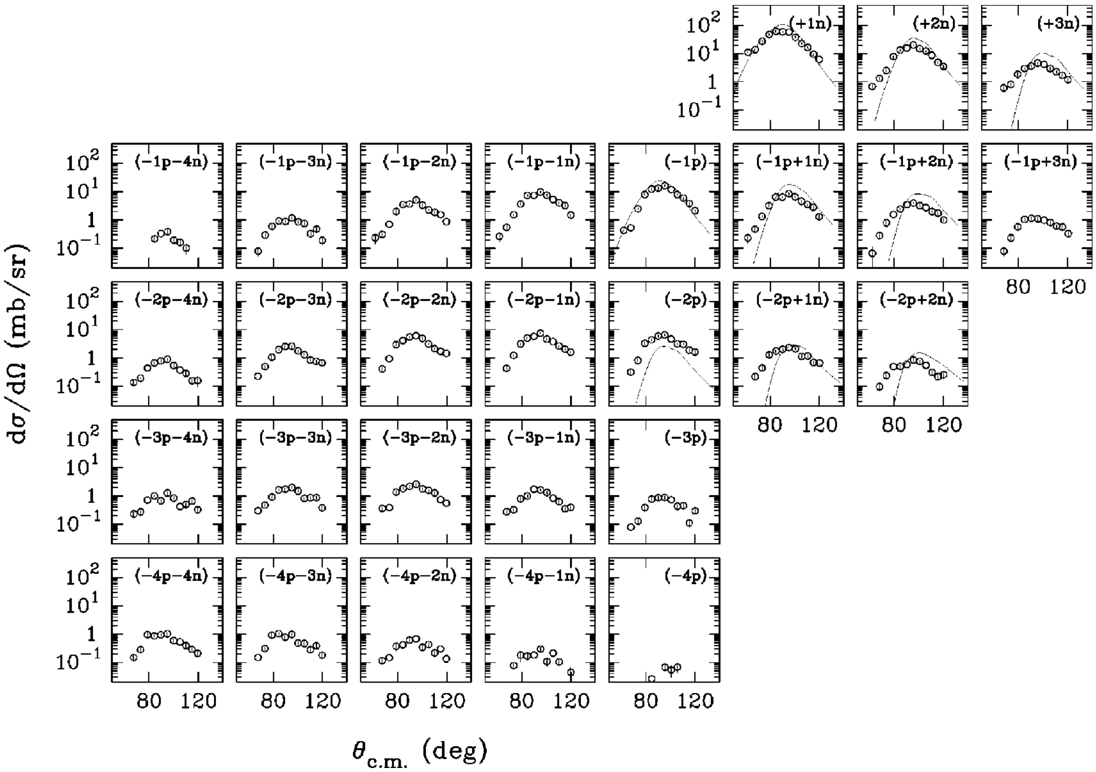

FIG. 4. Experimental (points) and theoretical (lines) Q-value integrated angular distributions for the indicated transfer channels.

of Fig. 8 (see next section), one notices first that for pure neutron pickup transfer channels the yield drops by a constant factor $\simeq 3.6$ for each transferred neutron, in agreement with the observation for $^{40}Ca+^{124}Sn$ [2] and $^{58}Ni+^{100}Mo$ [1]. A similar result comes from the study of $^{112}Sn+^{120}Sn$ [6] and from the newly measured $^{58}Ni+^{124}Sn$ [5]. This seems to indicate, for neutrons, a mechanism near to an independent particle transfer process. However, looking at the yields at forward angles an odd-even staggering appears, which could indicate pairing effects [23]. This might be the case in the data of Ref. [2] for the first neutron pair and, more evidently, in the new data of Ref. [5] for at least the first two pairs. Different Q-value matching conditions in the transfer channels as well as neutron evaporation from the primary fragments may contribute to the effect.

Looking back at Fig. 3 and Fig. 8, for nuclei involving proton transfer, the population pattern along the proton stripping direction favors a corresponding increase in the number of stripped neutrons. For $Z \leqslant 26$, the yields peak at nuclei with about an equal number of transferred protons and neutrons. In a preliminary presentation of the data [3], we remarked on this fact in particular for nuclei having the highest yield in the isotope distributions at $Z=26$, $Z=24$, and $Z=22$, suggesting possible multiple α-cluster transfer effects. The interpretation is actually different, as will become more clear also from the discussion of next section. In fact the trend of the experimental total cross sections does not show any odd-even effect. Moreover, the Q-value distributions for the ''alpha'' channels show little difference with respect to the nearest isotopes, at least for this heavy system. This rather suggests a process close to an independent particle transfer mechanism even for protons.

The experimental observations that the flux proceeds, after the transfer of the first few nucleons, with an almost equal number of transferred protons and neutrons, has been done in Ref. [24] (where only probabilities and not absolute cross sections are quoted), in Ref. [25] (where only average mass and charge distributions were measured), and also in Ref. [22]. In all cases, however, the energies were higher than the Coulomb barrier and the reaction is dominated by deep-inelastic events.

Figure 4 shows the experimental Q-value integrated angular distributions of the main transfer products. Also shown are the calculations, discussed in the next section. The distributions for few-particle transfer channels have the typical bell shape, peak at the grazing angle $\theta_{c.m.} \simeq 95°$ (which slightly depends on the channel), and get wider as the number of transferred nucleons increases. Measurements have not been done at $\theta_{lab} < 50°$. It may be that, at very forward angles, the cross section increases again due to deep-inelastic events. Indeed such a component has been already evidenced, e.g., in Ref. [10], where it is shown that it gets stronger and stronger with decreasing Z. Also, in Ref. [12] the deep-inelastic component is shown to be a conspicuous part of the total reaction cross section even at subbarrier energies.

A global view of the angular and Q-value distributions, for some of the channels with sufficient statistics, is shown in the Wilczynski plots of Fig. 5. They give a very detailed picture of the distributions for each Z and A, and are seen to include truly deep-inelastic events with Q values below -60 MeV. For few-particle transfer, the bulk of the Q-value distribution is concentrated within 5–10 MeV at around the grazing angle, and the peak moves slowly towards forward angles with negative Q values. As the reaction proceeds with a larger number of transferred nucleons, the bulk of the events spreads both in angle and in Q value.

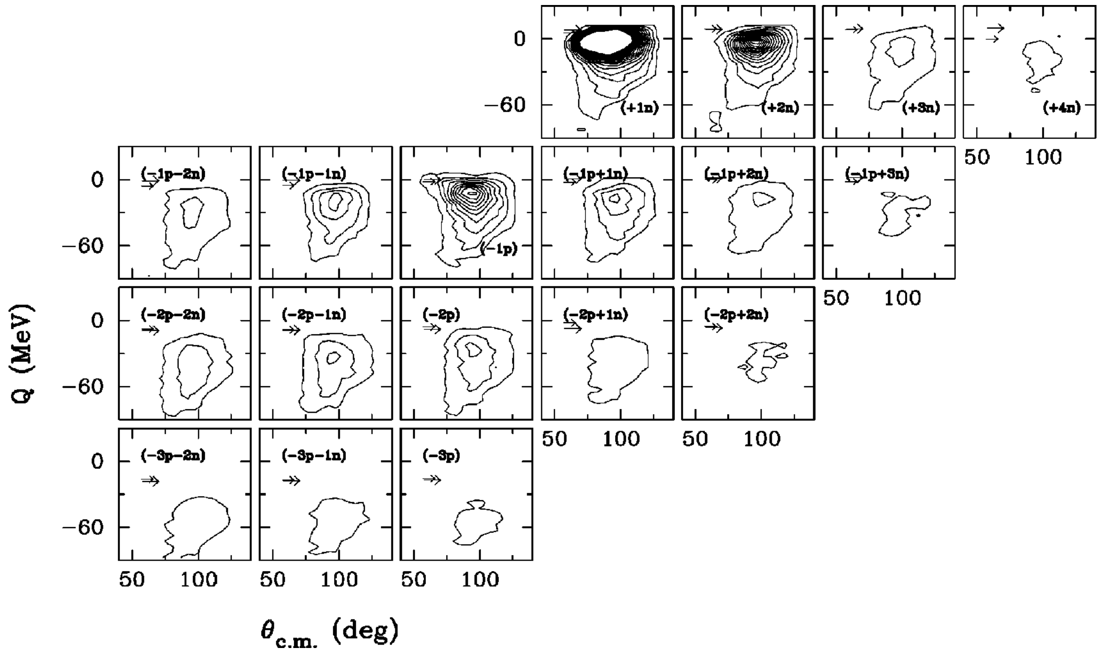

FIG. 5. Wilczynski plots (i.e., Q vs $\theta_{\mathrm{c.m.}}$) for the indicated transfer channels (see text). The contours are drawn in all the frames, every 100 mb/sr/MeV starting from 25 mb/sr/MeV. The short (long) arrows indicate the ground state (optimum) Q values. The optimum Q values have been calculated according to Refs. [27,28].

Looking at the various isotopes for each Z, one sees that the bulk of the Q values for different neutron pickup and stripping channels changes very smoothly (on this scale) within a few MeV's. Qualitatively this fact supports the idea that neutrons behave as independent particles in the transfer process. For protons, one observes, however, a shift in the centroid of the Q values of about 15 MeV at each proton step, which cannot be understood on the basis of optimum Q-value arguments only (cf. figure caption). In fact, one has also to take into account the exponential increase of the single-particle level density, which is incorporated in the program GRAZING [26] (see next section). For instance, for the $-1p$ channel (cf. Fig. 7) the maximum in the yield predicted by GRAZING is at -11.5 MeV, which is higher than the calculated [27,28] optimum Q value of -7.4 MeV.

A main conclusion of the experimental results shown in Figs. 3–8 is that all the data that we can analyze form a systematic and coherent picture of reactions developing from a few-nucleon transfer at forward angles to multinucleon transfer at larger angles. The reactions are dominated by proton stripping as to be expected in grazing collisions. The missing quasifission reactions, which were observed in Ref. [21], are spread over many charges and angles and therefore escape a detailed study in our setup.

IV. COMPARISON WITH CALCULATIONS

The existence of a clear distinction between the regimes of grazing (quasielastic and deep-inelastic) reactions and quasifission reactions has been noticed in several calculations, where the surface modes of the colliding nuclei have been seriously taken into account [29,30]. It is the main theme of Ref. [18], where it is shown that in collisions where the nuclear surfaces get close the surface-surface attraction will force the nuclei to deform, such that the surfaces clutch together, i.e., suddenly form a large neck. Whether the two nuclei thereafter fuse or go apart again is a question of the magnitude of the angular momentum and the total charge and is a regime where the system tends towards equilibrium. In the grazing regime the simple model described in Ref. [17] may be applied. Briefly, it considers independent single-nucleon transfer modes and inelastic excitations to the lowest nuclear levels, and estimates in a simple way neutron evaporation from the primary fragments. On the basis of average form factors and single-particle level densities, an analytic expression is derived for the characteristic function describing the distributions in mass, charge, energy, and angular momenta of binary reaction products after a grazing collision.

The model is implemented in the program GRAZING [26], which we used for the calculations, although, unfortunately, it still does not take into account that ^{238}U is a deformed nucleus. In Refs. [2,20] we discussed the total integrated cross sections. In the present work, besides the total cross sections for each isotope, we studied also the angular and Q-value distributions for some selected channels.

Before presenting the results for the transfer channels, we discuss the quasielastic channel, mainly to demonstrate the general consistency with the data of Ref. [21] using the same nuclear potential which will be used later for the transfer reactions. In Fig. 6 we show the experimental and theoretical differential cross sections for the quasielastic channel, normalized to the Rutherford cross section. Experimentally, the points derive from the integration of the events corresponding to $Z=28$, $A=64$, i.e., the elastic + (unresolved) inelastic channels. The solid line is the pure elastic scattering as predicted by the program GRAZING, leading to a reaction cross section of $\simeq 1.6$ b, neglecting Coulomb excitation. It has been checked that the same curve is obtained with the

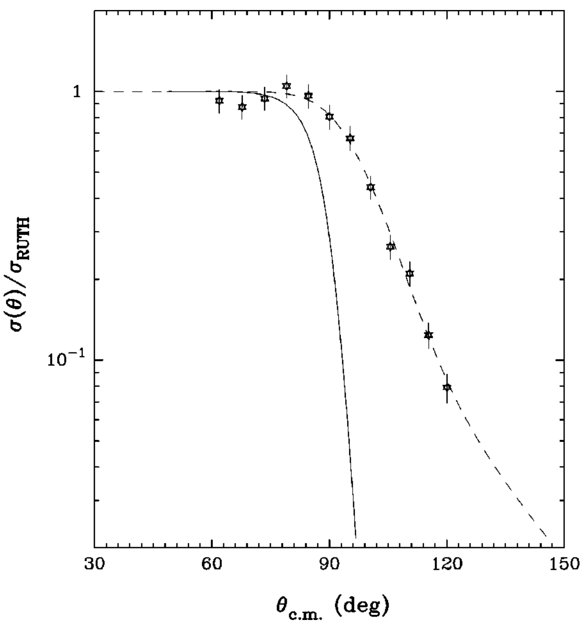

FIG. 6. Plot of $d\sigma_{el}/d\sigma_R$ for the elastic+inelastic channels. The points are the experimental data corresponding to $Z=28$, $A=64$, i.e., the elastic + (unresolved) inelastic channels. The solid line is the pure elastic scattering calculated with the program GRAZING. The dashed line is an optical model fit done with the code PTOLEMY, in which the following parameters for the nuclear potential have been used: $V_0=40$ MeV, $r_0=1.1$ fm, $a_0=0.25$ fm (real part), $V_{0I}=2.7$ MeV, $r_{0I}=1.34$ fm, $a_{0I}=0.41$ fm (imaginary part).

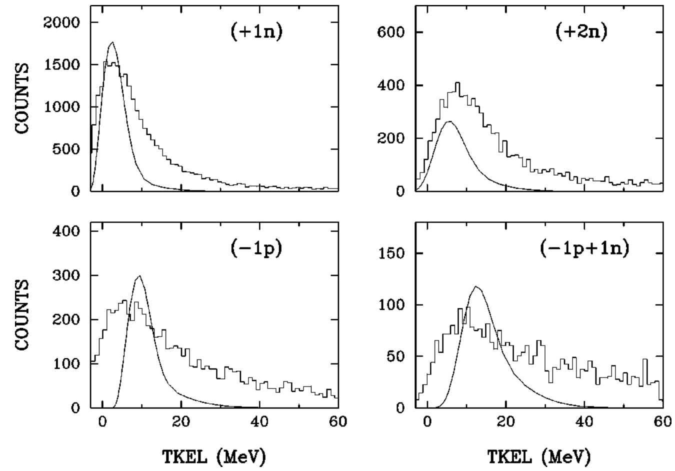

FIG. 7. Experimental (histograms) and theoretical (lines) total kinetic energy loss (TKEL) distributions for the indicated transfer channels.

code PTOLEMY [31], by using the Akyüz-Winther potential for the real part and the macroscopic calculated imaginary potential (cf. Refs. [27,28]). The dashed line is a fit to the experimental data done with PTOLEMY (see figure caption). From that fit we derive a total reaction cross section of $\simeq 850$ mb which is consistent with the value quoted in Ref. [21]. Subtracting from it the sum of the total transfer cross sections, amounting to $\sigma_{tr}\simeq 670$ mb, we obtain a ''residual'' cross section of $\sigma_{res}\simeq 180$ mb to be compared with the 150 mb quoted in Ref. [21] and which they denote as quasifission reactions. The program GRAZING predicts 615 mb and 330 mb for the two reactions, respectively.

The theoretical angular distributions for some selected transfer channels are shown in Fig. 4. We stress that no normalization factors have been used to ''match'' the data. We see how theory reproduces well the experimental data for the $(+1n)$ and $(-1p)$ cases, in both the forward and backward angular ranges. Looking at other channels differences between the data and theory start to appear, especially at forward angles, indicating the need for a better treatment of the small impact parameters.

In Fig. 7 we show the experimental (histogram) and theoretical (curves) TKEL ($-Q$-value) distributions for the indicated transfer channels at $\theta_{lab}=80°$. The theoretical curves have been normalized with a common factor to the data. In all four cases the shapes of the experimental distributions are reasonably well reproduced, while, especially for the proton stripping channels, have a too compact shape. Discrepancies are in general evident for large TKEL, which are less pronounced for neutrons but get stronger for protons. It is a striking feature that the missing cross section at large TKEL is about the same in all cases. A partial explanation of the discrepancies may be attributed to evaporation effects, which surely play an important role in channels involving the transfer of many nucleons, but which may also influence the final distributions for the few-nucleon transfer cases, as those shown in the figure. Also these discrepancies point to the need for a better treatment of the small impact parameters that lead to large energy losses.

The total cross sections, obtained after integration of the angular and Q-value distributions for all the channels where statistics is reasonable, are shown in Fig. 8, together with calculations. Neutron stripping channels, for the reasons explained before, have been omitted. First of all we remark on how well theory reproduces the data for pure neutron transfer channels, similarly to the case of the previously measured systems [2,20], thus confirming the correct treatment of neutron transfer on the basis of independent single-nucleon transfer modes. Calculations predict well the isotope distributions also for the $(-1p)$ case, but as one moves along the proton stripping direction, a larger drift of the data appears, despite maintaining a good agreement in the neutron pickup side. Very similar results were observed in the cited references. We notice that the drift is present also in the proton pickup isotope distributions, reminding us of the results of the experiment with the ^{48}Ca beam, where the drift was observed in an almost symmetric way along the proton stripping and pickup directions which suggested the possible influence of pair/cluster degrees of freedom in the transfer process. In the present experiment, where we can follow the trend of the cross sections down to the $(-6p)$ channels, we do not have evidence for the transfer of clusters since, as has been remarked before in Sec. III, the isotope distributions evolve in a very smooth and regular way, suggesting that also the protons behave as independent objects in the transfer process.

To get a deeper insight into the behavior of the experimental yields, we plot, in Fig. 9, the total cross sections, this time not as a function of the mass number, but as a function of the number of transferred protons (ΔZ). On the left-hand side we display the cross sections involving neutron pickup while on the right-hand side the ones involving neutron strip-

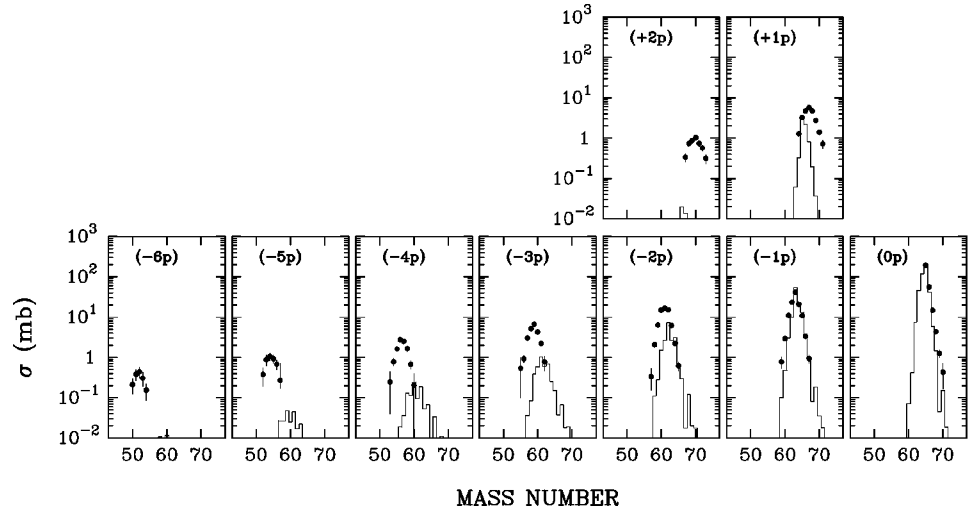

FIG. 8. Experimental (points) and calculated (histograms) angle- and Q-value integrated cross sections for the indicated transfer products.

ping. As is apparent from this kind of plot the neutron pickup and neutron stripping reactions have a very different behavior [32]. The neutron pickup decreases in a very smooth way as the number of transferred protons increases, while neutron stripping reactions have a maxima when the number of transferred protons is almost equal to the number of transferred neutrons (also observed in the experiment of Ref. [22] performed at a much higher bombarding energy). This is a clear indication that the two kinds of reactions are populated by different mechanisms. While the neutron pickup behavior indicates a direct population in terms of the independent transfer of neutrons (pickup) and protons (stripping) the neutron stripping side shows that the yield of these reactions depends on a more complicated mechanism. They are much more influenced by neutron evaporation, in fact, from optimum Q-value arguments one knows that neutron stripping reactions are strongly hindered. It is thus tempting to add, for

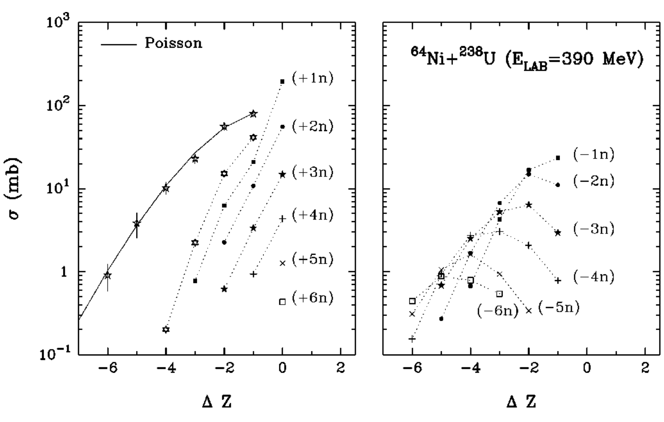

FIG. 9. Experimental total cross sections as a function of the number of transferred protons ΔZ for channels involving neutron pickup (left side) and neutron stripping (right side). To guide the eye we connected, with a dashed line, the different proton transfer channels corresponding to an equal number of neutrons. The symbol with no label corresponds to the $(0n)$ channels. The solid line is a Poisson distribution, normalized to the data and calculated with an average number of 2. The points close to this line are obtained by adding to each pure proton transfer $(0n)$ channels all those corresponding to neutron stripping.

each ΔZ, the cross section of all the neutron stripping channels. In doing so one obtains the points labeled with stars on the left-hand side of Fig. 9. These can be nicely fitted (solid line) with a Poisson distribution defined by an average number of 2. Since the Poisson distribution describes the transfer of independent modes, it is clear that this finding points to the direction that also protons are transferred independently.

V. CONCLUSIONS AND FINAL CONSIDERATIONS

We have measured with high Z and A resolution and high detection efficiency the multinucleon transfer channels produced in the reaction ^{64}Ni+^{238}U at a near barrier energy. Differential and total cross sections and Wilczynski plots have been produced, demonstrating the possibility of a detailed study, even of weakly populated channels. Our experimental results confirm unambiguously for this system the existence of a grazing regime consisting of quasielastic and deep-inelastic events, clearly distinct from more complex reactions. These more complex reactions were identified in Ref. [21] as quasifission events, but for this heavy system they could not make a quite unambiguous separation between the two regimes. The experimental observables have been compared with the GRAZING model for transfer reactions, showing the present understanding of these complicated processes. The theory, which uses an independent particle description, describes quite well the main features of the data. Discrepancies start to appear at large energy loss and in the description of channels that are weakly populated and which correspond to a large number of transferred nucleons. A closer inspection of the experimental isotope distributions shows a different behavior for channels involving neutron pickup and neutron stripping, suggesting that neutron evaporation from the primary fragments strongly affects the final yields. This, in turn, demands a more proper treatment of the small impact parameters that are leading to reaction products with high excitation energy.

Further investigations of this subject, both experimentally and theoretically, are important also in connection with future research with radioactive beams. Besides the production rate of neutron-rich light nuclei, an interesting question is what happens to the heavy partners of the reaction, which may strongly undergo fission. A determination of the survival probability against fission would give, for instance, a quantitative basis to estimate the production rate of very heavy nuclei [23]. Experimental work in view of preliminary tests in this direction is in progress.

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