Weak channels in backscattering of ^{20}Ne on ^{nat}Ni, ^{118}Sn, and ^{208}Pb

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To further our understanding of the influence of weakly coupled channels on the distribution of Coulomb barrier heights, we have measured transfer cross sections for ^{20}Ne ions backscattered from ^{nat}Ni, ^{118}Sn, and ^{208}Pb targets at near-barrier energies. The Q value spectrum in the case of ^{208}Pb target has been determined too. The transfer channels appear to be especially important for ^{208}Pb, whose double-closed-shell nature leads to a relatively low level density for noncollective inelastic excitations.

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I. INTRODUCTION

The study of the dynamics of heavy-ion fusion at near- and sub-barrier energies is important for many reasons. Among these is the well known enhancement of the fusion cross section (in comparison with simple barrier penetration model calculations) caused by coupling of the relative motion of the reaction participants to their collective excitations. In addition to these strongly coupled reaction channels, weak but numerous channels can also influence the tunneling process; in particular they may enhance the fusion cross section at deeply sub-barrier energies, but also hinder it at even lower energies, with obvious consequences for nucleosynthesis [1], superheavy element production, and reactions with halo nuclei or radioactive beams [2]. However, the importance of these studies goes even beyond these applications, as the phenomenon belongs to the more general category of "tunneling in the presence of an environment," where the interacting bodies are not isolated and thus should be treated as "open systems." In the case of nuclear physics the "environment" means in fact the internal degrees of freedom (nuclear structure), but this phenomenon also has important consequences in other branches of physics and chemistry as well as technology [3–6].

By "weak channels" we mean here transfers as well as excitation of noncollective levels. The role of (mainly neutron) transfer channels in fusion reactions has been studied in many papers. The results of older investigations were presented in Refs. [2] and in the review paper [7]. The results of more recent studies, reported, e.g., in Refs. [8–33] are frequently contradictory. This controversy is caused in part by the complexity of the problem, which results in the necessity of many approximations in the theoretical description. As a result, some (especially older) works compared experimental data with calculations performed with coupled-channels (CC) codes which did not include transfer channels in an appropriate way. However, at the empirical level it was noted that in the majority of cases additional fusion enhancement (with respect to that caused by collective effects) was observed when positive Q-value transfer reactions were possible. This tendency is nicely described by the Zagrebaev model [19]. However, the problem is still not finally settled, as this observation does not seem to be of general validity: as recent papers [30,32,33] demonstrate, the existence of this correlation can be system dependent. In particular, Ref. [32] suggests that the impact of transfer depends mainly on the resulting change in the deformations of the colliding nuclei.

Fusion enhancement at sub-barrier energies is reflected in a broadening and/or shifting to lower energies of the Coulomb barrier distribution, the only exception being in Ref. [29], where taking into account transfer channels caused narrowing and shifting of the barrier distributions by a few MeV to higher energies (about the $D_{\rm fus}$ and D_{QE} distributions, see the companion paper [34]). Much less is known about the influence of weak channels on the structure of the distribution, usually considered as a fingerprint of the couplings involved [7,35], since existing experimental results are scarce and contradictory. This is because close to the maximum the shape of the distribution seems to be dominated by collective effects but the observed structure is frequently weak and/or its statistical significance is disputable. Also, drawing conclusions as to the influence of transfer channels on the shape of the barrier distribution from fitting experimental data by means of approximate CC codes is questionable. One

should stress that at present codes designed specifically for the analysis of fusion data treat transfer reactions in a very schematic way or not at all, whereas those codes which do treat transfer using the full coupled reaction channels (CRC) theory are designed for the analysis of direct reaction data and thus treat the fusion process in a simplified manner. It should also be pointed out that for more complex reaction paths, e.g., two-step transfers via inelastic excitations and sequential transfers, much of the requisite nuclear structure information is lacking, even if the necessary computing power to deal with the large number of channels were available.

All this explains why in the majority of cases the observation and interpretation of barrier smoothing by weak channels should be, in our opinion, considered as tentative and at best not unique [8–11,16,18,24]. A good example of the above mentioned problems of interpretation is the case of the loss of structure in $D_{\rm fus}$ for the ^{40}Ca + ^{96}Zr system compared with the ^{40}Ca + ^{90}Zr system. This result has been interpreted as due to multineutron transfers in the former case [7,15,21,36,37], but according to the most recent paper [23] the dominant role in smoothing the distribution is apparently played by the octupole phonon state in ^{96}Zr. A similar situation occurs for the ^{32}S + ^{90,96}Zr systems [25,28].

Almost nothing is known about the role of noncollective excitations in either fusion or quasielastic (QE) backscattering. However, in Ref. [38] we studied the ^{20}Ne + ^{90,92}Zr reactions and noted that, because the deformation of the ^{20}Ne nucleus is so large, the collective excitations of the Zr isotopes have a practically negligible effect on the barrier distributions. Because it was found that the total transfer cross sections in both systems are very similar, any differences in the distributions for these two isotopes are most probably due to noncollective excitation effects. We advanced the hypothesis that the weak but numerous reaction channels influence the shape of the barrier distributions by smoothing out the distinct structures generated by the few strong couplings. This explained qualitatively the absence for ^{20}Ne + ^{92}Zr of the structure clearly observed in the ^{20}Ne + ^{90}Zr reaction. The dominance of the projectile deformation that permits the above observation remains true for all the targets we have investigated, and this is the great advantage of studies with this beam.

One should mention that recently Zagrebaev [39] has remarked that the QE method determines a threshold distribution for all reaction processes rather than just for fusion, and that this has important implications in the case of heavy or weakly bound projectiles, where contributions from deep-inelastic collisions or breakup processes are important. Here, however, the "total reaction threshold distribution" should be very similar to the "barrier distribution" since we will concentrate on systems where these processes are negligible.

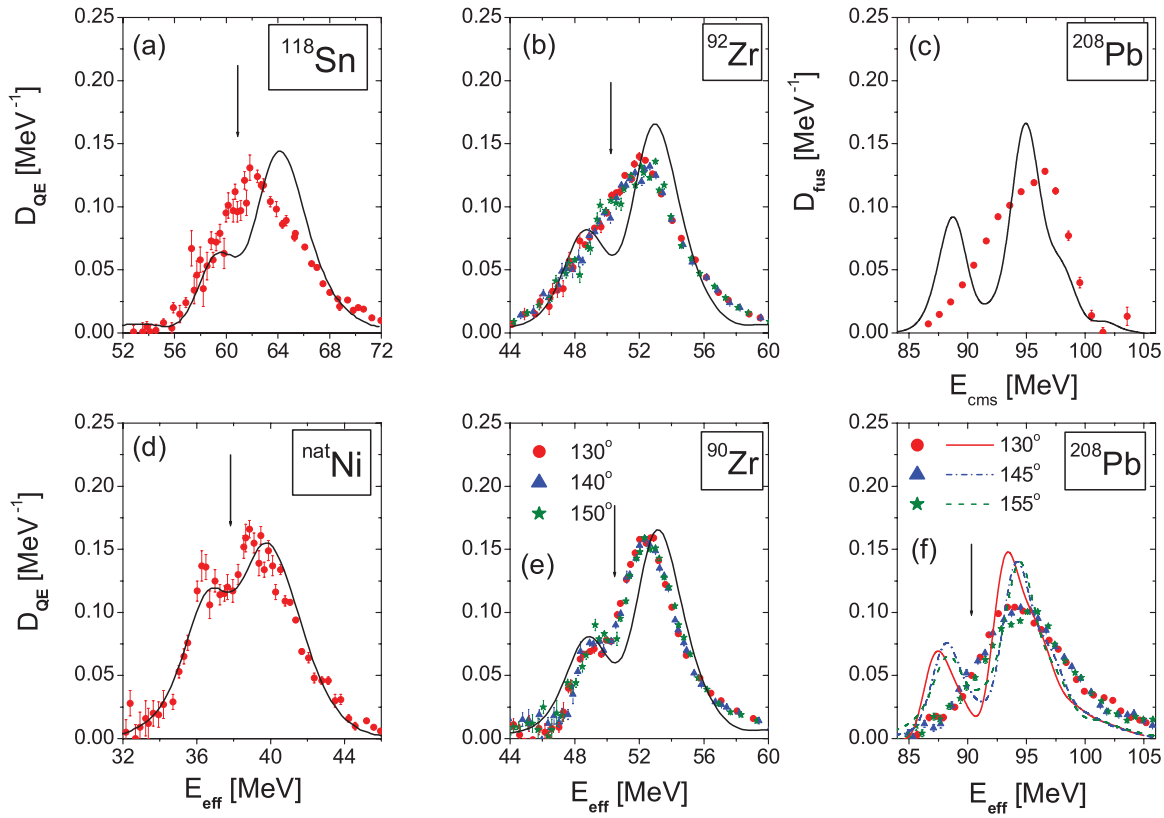

FIG. 1. (Color online) Compilation of barrier distributions for ^{20}Ne interacting with several targets, measured in our previous works. The curves denote the results of CC calculations folded with the experimental energy resolution. Different symbols refer to different laboratory detector angles. For the ^{208}Pb target we show the results of $D_{\rm fus}$ and $D_{\rm QE}$ distributions in the panels (c) and (f), respectively. The arrows denote the energies at which we measured the transfer cross sections.

II. MOTIVATION OF THE EXPERIMENT

Preliminary results of our barrier distribution studies for the ^{20}Ne + ^{208}Pb system utilizing both the fusion ($D_{\rm fus}$) and quasielastic backscattering ($D_{\rm QE}$) methods were reported in conference proceedings [40] (the final results will be published in a companion paper [34]). We have also determined $D_{\rm QE}$ distributions for the ^{20}Ne + $^{\rm nat}$Ni [41], ^{90,92}Zr [38], and ^{118}Sn [42,43] systems and noted that while for the $^{\rm nat}$Ni and ^{90}Zr targets the distributions are structured, in agreement with the predictions of CC calculations, for the ^{92}Zr, ^{118}Sn and ^{208}Pb targets the measurements yielded smooth distributions, in strong disagreement with theory. A compilation of these results is given in Fig. 1 as a function of $E_{\rm eff}$, which takes account of the "angle-dependent" centrifugal energy [37], namely $E_{\rm eff} = \frac{2E}{1+{\rm cosec}(\theta/2)}$, where E and θ are the center-of-mass energy and scattering angle.

To the best of our knowledge no transfer data exist for these systems at energies around their Coulomb barriers. Thus, to compare the transfer probabilities for ^{20}Ne scattering on $^{\rm nat}$Ni, ^{90,92}Zr, ^{118}Sn, and ^{208}Pb targets, we have performed the measurements reported in the present paper. The results for ^{20}Ne + ^{90,92}Zr were published in Ref. [38] and are shown here for comparison only.

III. EXPERIMENTAL SETUP

The experiments were performed using the University of Jyväskylä cyclotron beam and then repeated with a very similar experimental setup at the Warsaw Heavy Ion Laboratory. The two sets of results are in good agreement, but while the mass resolution was better in Warsaw, due to details in the construction of the scattering chamber the background conditions were better in Jyväskylä. Because of this, Figs. 2–5 show the Warsaw results, while Fig. 7 presents spectra obtained in Jyväskylä.

The beam energies were $E_{\rm lab}$ = 51.7, 62.8, 62.6, 72.1, and 102.0 MeV for $^{\rm nat}$Ni, ^{90,92}Zr, ^{118}Sn, and ^{208}Pb, respectively; that is, energies at which the structure in $D_{\rm QE}$ was either observed or predicted by CC calculations (see arrows in Fig. 1). The target thicknesses were 250, 100, 130 (250 in Jyväskylä), and 150 μg/cm^2 for Ni, Zr, Sn, and Pb, respectively. The experimental method used and the results obtained for Zr

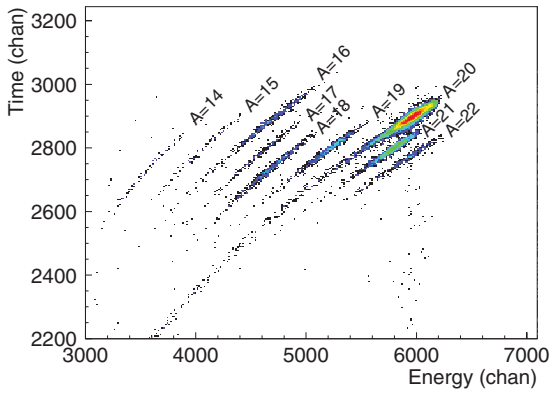

FIG. 2. (Color online) The raw E-TOF results after one of the runs during the ^{20}Ne + ^{208}Pb transfer measurements.

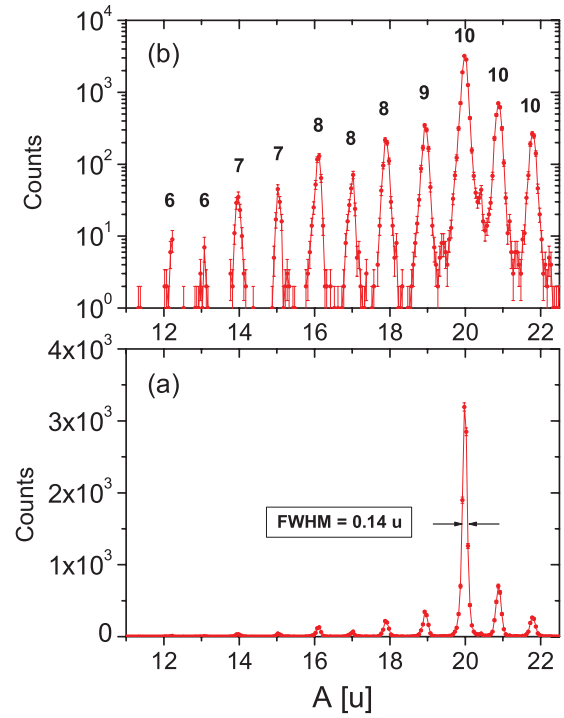

FIG. 3. (Color online) The raw mass distribution of reaction products for ^{20}Ne + ^{208}Pb backscattering on logarithmic (upper panel) and linear (lower panel) scales. Numbers in the upper panel denote the charge numbers corresponding to the peaks (see text).

targets were described in Ref. [38], where the experimental setup was presented. Briefly, the TOF (time-of-flight) technique was used to identify the masses of the backscattered ions. The "start" signal was given by a MCP (microchannel plate) detector. The "stop" signal was triggered by an array of four 20 mm × 20 mm semiconductor detectors, placed at an angle of 142.5° (in the laboratory system). At the energies studied (just below the mean barriers) the transfer angular distribution generally has a flat maximum at backward angles. Thus a measurement performed at the chosen angle gives good information on the relative importance of different transfer channels. The flight base of 750 mm, the time resolution of ∼120 ps, and the energy resolution of 120 keV resulted in a good mass resolution of 0.14 u (full width at half maximum); see Figs. 2 and 3.

In addition, an isobutane-filled E-ΔE detector telescope (at 142.5°) ensured a low-energy threshold and perfect identification of all detected ion charges; see Fig. 4. Two ancillary silicon ("Rutherford") detectors placed at forward angles of 38° were used to monitor the beam energy.

IV. DATA ANALYSIS

As one can see from Figs. 2 and 4, mass and charge identification is straightforward; more difficult is the question of correcting for detection efficiency. While the detection efficiency of heavy ions in gas telescopes is ∼100% (in any case it does not depend on (A, Z) of the ions nor on their energy, provided that they stop in the E detector), the efficiency

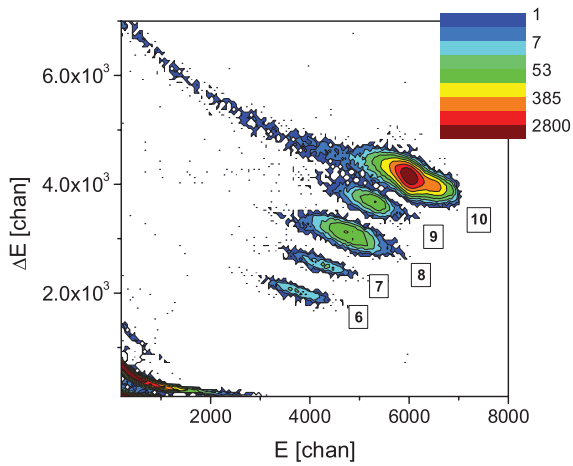

FIG. 4. (Color online) Sample raw gas-telescope E-ΔE spectrum showing charge identification ($Z = 6$–10) of backscattered ions in the gas telescope. Counts are on a logarithmic scale. Note the absence of events corresponding to $Z > 10$.

of MCP devices is known to be dependent on the applied voltage and on the Z and energy of the detected ions [44], tending to be lower than 100% for the lighter ions. This is connected with the number of electrons generated by the ions during their passage through the carbon foil of the MCP device, connected in turn with the stopping power dE/dx. The problem is that since mass and charge identifications could not performed for the same events (i.e., in the same detector), in order to determine the efficiency correction we must make some assumption concerning the most probable charge corresponding to the different masses seen in Fig. 2. We assume that the products will be close to the most stable isobars for the measured A values; see the peak labels in Fig. 3. We stress that these approximate Z values are used only for the efficiency correction, and we check below that this assumption is not in conflict with our other results.

Since the detection efficiency of the Si stop detectors was 100%, the efficiency of the TOF device could also be determined experimentally as the ratio of the number of events with time information to all counts registered by the stop detectors. This efficiency was close to 100% for $A = 20$ but decreased down to about 60% for $A = 12$, depending somewhat on the registered ion energy.

After efficiency corrections, the $Y(A, Z)$ distributions as defined above were summed over A to yield approximate $Y(Z)$ distributions, which could be compared with those measured directly with an E-ΔE gas telescope. For $Z = 7$–10 we obtained agreement between the two distributions to better than 15%, though for $Z = 6$ we found a factor of ∼4 more events in the gas telescope than in the TOF device. This discrepancy is not important because the yield from this channel is less than 1% of all the measured transfers.

In this way the contributions $\sigma_{\rm tr}/\sigma_{\rm QE}$ of different transfer channels to the quasielastic scattering were determined. Next, for each system studied, the differential transfer cross section at a given backward angle (for the energy where the structure in $D_{\rm QE}$ was observed or predicted) was determined using the relation

$$\sigma_{\rm tr} = \frac{\sigma_{\rm tr}}{\sigma_{\rm QE}} \times \frac{\sigma_{\rm QE}}{\sigma_{\rm Ruth}} \times \sigma_{\rm Ruth.} \qquad (1)$$

Here $\sigma_{\rm Ruth}$ is the calculated Rutherford cross section, while the ratios $\sigma_{\rm QE}/\sigma_{\rm Ruth}$, equal to 0.61, 0.7, 0.65, 0.74, and 0.88 for $^{\rm nat}$Ni, ^{90}Zr, ^{92}Zr, ^{118}Sn, and ^{208}Pb, were read off from the experimental excitation functions [34,38,41–43].

V. RESULTS AND DISCUSSION

At the energies corresponding to the predicted or observed structure in the barrier distributions, the differential cross sections for production of the most abundant projectile-like nuclides scattered at $\Theta_{\rm lab} = 142.5°$ (see the experimental setup) are given in Table I and Fig. 5. We would like to emphasize that both ratios used in Eq. (1) were directly available experimentally, thus precise knowledge of target thickness, detector solid angles, and beam intensity was not necessary. This resulted in reasonably good measurement precision. Statistical and relative errors of the measured transfer cross sections are of the order of 5%; however, overall systematic errors (caused mainly by efficiency corrections) could amount to another 10% (larger for the lighter ions).

Concerning the above Z assignments one should add that the E-ΔE telescope did not register any events with $Z > 10$. This was not because of any failure, but due to the very low production cross section of such ions. Thus the $A = 21$ and 22 events are certainly Ne isotopes. This is understandable in light of the Rehm systematics [45], according to which there is a strong positive correlation between the transfer probability and the effective Q value $Q_{\rm eff}$ [46]. This implies that transfer to Ne (pickup) is mainly due to neutrons, while in the opposite direction (stripping), charged-particle transfer is preferred. For

TABLE I. Transfer-product cross sections at near-barrier energies (mb/sr). Z values are approximate assignments used only for efficiency corrections (see text).

Target	A	14	15	16	17	18	19	21	22
	Z	7	7	8	8	8	9	10	10
$^{\rm nat}$Ni		6×10^{-3}		0.8	0.06	6.5×10^{-2}	6.5×10^{-2}		4.6×10^{-2}
^{90}Zr		2×10^{-2}	9×10^{-2}	3.0	0.19	5.1×10^{-2}	0.23		
^{92}Zr		5.4×10^{-2}	0.11	2.1	0.21	0.23	0.56	0.50	0.17
^{118}Sn		6×10^{-2}	0.2	1.7	0.38	0.98	2.0	2.1	1.7
^{208}Pb		2.4	1.4	2.5	1.2	3.8	4.2	9.4	3.8

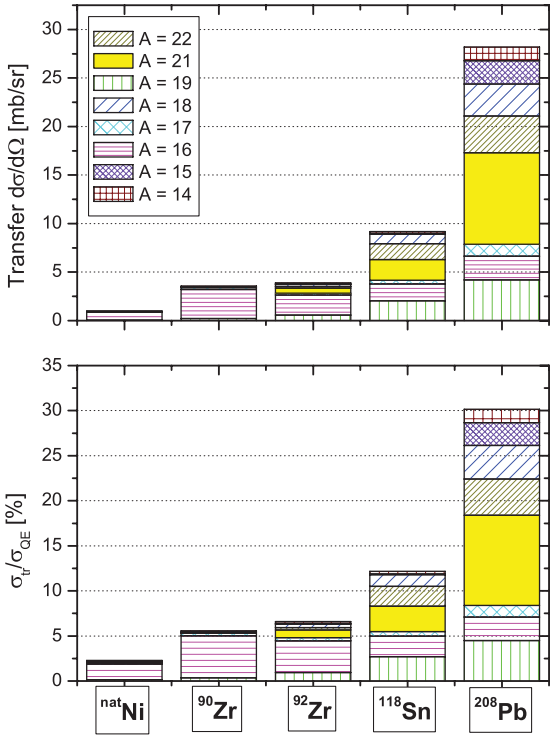

FIG. 5. (Color online) Contributions of different transfer channels to the quasielastic scattering at 142.5° (lower panel) and corresponding differential cross sections (upper panel) for ^{20}Ne + various targets at near-barrier energies. Contributions are labeled by the measured masses (see text).

example, in the case of the ^{208}Pb target, for $1n$ stripping we have $Q_{\rm eff} = -11.7$ MeV, while for $1p$ stripping $Q_{\rm eff} = +0.7$ MeV. This is consistent with our assumption that $A = 19$ is principally ^{19}F rather than ^{19}Ne. On the other hand, for the $1p$ and $2p$ pickup processes $Q_{\rm eff} = -14.1$ and -24.3 MeV, respectively. It is therefore not surprising that events with $Z > 10$ are not observed.

As was recently demonstrated [38,47], the QE barrier distributions could be smoothed out not only by transfers but also by a large number of weak noncollective excitations. In the latter case the effect could be caused by the so-called decoherence phenomenon [6], characteristic of open quantal systems. However, the doubly magic ^{208}Pb target should give rise to a relatively small number of noncollective excitations, as the density of single-particle levels is relatively low compared to the other targets. This can be seen in Fig. 6, where the total level densities predicted within the statistical partition-function approach [48] are compared as a function of excitation energy.

We compared experimentally the excitations of ^{90}Zr and ^{208}Pb determining the Q-value spectra (see Eq. (5) of Ref. [49]) for nontransfer scattering events. The results reflected expectations based on the theoretical level densities; see Fig. 7. (We do not show here the results obtained during this experiment for $^{\rm nat}$Ni nor ^{118}Sn because, due to the large target thickness, the Q-value resolution was poor in these cases.)

In Ref. [38] we showed that above 2–3 MeV the excitations are essentially noncollective. In Fig. 7 we see that for the

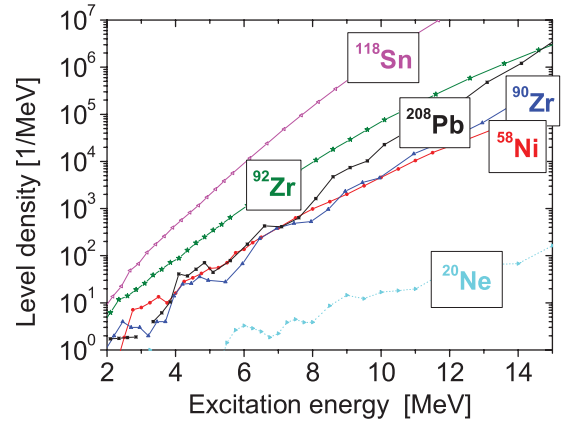

FIG. 6. (Color online) Comparison of the total level densities as a function of excitation energy, calculated within the statistical partition-function approach.

^{20}Ne + ^{208}Pb system the noncollective excitations are even less abundant than for ^{20}Ne + ^{90}Zr, where they do not smooth out the QE barrier distribution. This suggests that the absence of the expected marked structure for the doubly-closed-shell ^{208}Pb target is more likely to be due to the observed strong transfer channels (see Fig. 5). On the other hand, on the basis of Figs. 5 and 6 one can presume that for the ^{118}Sn target both transfers and non-collective excitations are responsible for the barrier distribution smoothing.

Unfortunately, proper and complete CC calculations including transfers are at present impossible. The code CCQEL cannot be used to this end since it does not treat properly transfers to excited states or sequential transfers. The Zagrebaev model [19] is not applicable here as the $+1n$ and $+2n$ channels do not dominate the transfer channels in our systems. As one can see in Table I, for the ^{208}Pb target they constitute only 45% of the total measured transfer cross section (and even less for the lighter targets), while the majority of the transfer strength is due to charged-particle stripping reactions. Such calculations could, in principle, be performed with the coupled reaction channels code FRESCO [50]. However, complete calculations

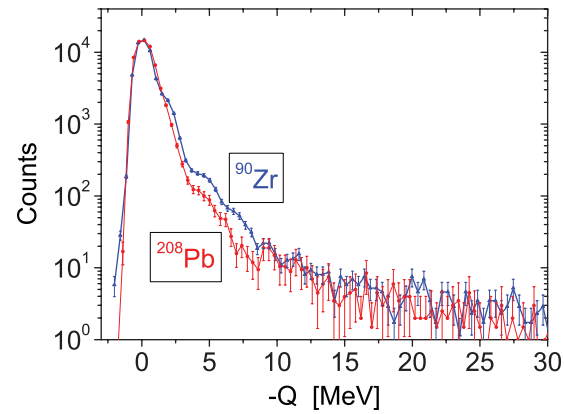

FIG. 7. (Color online) Inelastic (nontransfer) Q-value spectra at near-barrier energies for ^{20}Ne + ^{90}Zr, ^{208}Pb systems. The distributions are normalized to the same value at the elastic peak.

including all the observed transfer channels would be beyond present computer capabilities. Moreover, many input data for such calculations (e.g., spectroscopic factors, especially for sequential transfers) are unknown. The results of limited calculations for the ^{20}Ne + ^{208}Pb system including the single-nucleon pickup and stripping channels in addition to the strong collective excitations will form the subject of a future publication.

VI. SUMMARY AND CONCLUSIONS

Transfer cross sections have been measured for ^{20}Ne ions backscattered from ^{nat}Ni, ^{118}Sn, and ^{208}Pb targets at near-barrier energies. The Q spectra for the systems ^{20}Ne + ^{90,92}Zr, and ^{208}Pb measured close to their barrier energies show that for ^{208}Pb noncollective excitations are the least important (unsurprisingly, in view of the doubly magic nature of this nucleus), so they are unlikely to be responsible for the smoothing of the barrier distribution observed in this system [34,40]. On the other hand, the measurements show that the total transfer cross section for the ^{20}Ne + ^{208}Pb system is the largest amongst those measured by us, making transfer a good candidate for the barrier-smoothing mechanism in this system. Confirming this theoretically remains a major but important challenge, as any other reason for the disagreement between experiment and calculations, that we can imagine, would point to some serious limitation of the standard CC codes.

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