# Quasielastic barrier distributions for the $^{20}$Ne + $^{58,60,61}$Ni systems: Influence of weak channels

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**Background:** Near-barrier fusion can be strongly affected by the coupling between relative motion and internal degrees of freedom of the collision partners. The coupled channels (CC) method is a usual way of describing the reaction dynamics in this energy region. In the standard approach in the CC method only strong reaction channels (collective excitations) are taken into account. However, in some cases this approach fails to describe experimentally obtained barrier height distributions.

**Purpose:** The influence of weak (noncollective) reaction channels on barrier height distributions was studied.

**Method:** The barrier height distributions were determined from quasielastic scattering of $^{20}$Ne on $^{58,60,61}$Ni targets. The scattered ions were registered at backward angles (130–150 degrees).

**Results:** In the $^{58}$Ni and $^{60}$Ni cases one observes a "structure" (two peaks) in the barrier height distribution which is completely smoothed out for $^{61}$Ni.

**Conclusions:** The results support the hypothesis that noncollective excitations of the target nuclei, much more numerous in $^{61}$Ni than in $^{58}$Ni and $^{60}$Ni, influence the barrier height distribution and are responsible for smoothing out the structure.

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## I. INTRODUCTION

Nuclear reactions at sub-barrier energies are very important for many phenomena taking place in nature, e.g., in star evolution and element creation. One of the most important near-barrier reactions is fusion. It is known that the interplay between the relative motion of two colliding nuclei and their internal degrees of freedom results in a strong enhancement of the sub-barrier fusion cross section. Due to this fact, heavy-ion reactions around the Coulomb barrier cannot be described in terms of a simple energy-independent potential model [1–3], as the couplings lead to a distribution of potential barriers, $D_{\mathrm{fus}}$ [4,5].

$D_{\mathrm{fus}}$ can be determined directly from fusion excitation function measurements [6]. There is also an alternative method: It has been shown both theoretically and experimentally that rather difficult fusion measurements can be replaced by much simpler quasielastic scattering measurements at backwards angles, giving rise to the barrier height distribution $D_{QE}$ [1,7–9]. The latter method consists of determining the quasielastic (QE)—elastic, inelastic, and transfer—excitation function $\sigma_{QE}(E,\theta)$ for projectile-like nuclei at large center-of-mass scattering angles $\theta$ with no need to distinguish the particular channels involved. As the excitation function determined in the QE method depends on the angle $\theta$ at which the measurement is made, one can transform it to the one determined for 180° at an "effective energy" [10]:

$$E_{\mathrm{eff}} = \frac{2E}{1+\mathrm{cosec}(\theta/2)}, \tag{1}$$

where $E$ and $\theta$ are the projectile energy and the scattering angle in the center-of-mass system, respectively. This scaling works better the lighter the system is.

A barrier height distribution $D_{QE}$ can be obtained from the excitation function $\sigma_{QE}(E)$ using the following formula:

$$D_{QE}(E) = -\frac{d}{dE}\left[\frac{\sigma_{QE}}{\sigma_{\mathrm{Ruth}}}(E)\right], \tag{2}$$

where $\sigma_{\mathrm{Ruth}}(E)$ is the Rutherford scattering cross section for a given system.

The method has many advantages: (a) There is no need to distinguish reaction channels involved. (b) For a given beam energy one can simultaneously obtain data for several effective energies [Eq. (1)] using detectors placed at different angles. (c) There is no need for expensive instrumentation to distinguish fusion products from the beam. (d) There are much smaller statistical errors than in $D_{\mathrm{fus}}$, especially above the barrier. In [1,7] also possible limitations of the method are indicated and discussed. Namely, there is one known case ($^{16}$O + $^{144}$Sm) in which some details of the barrier distribution are seen in a fusion experiment, while they are not visible when results are obtained using the quasielastic method. The reason for this

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difference is still not known [11], although it was suggested in [1,7] that numerous weak channels (like transfers) can be responsible for the loss of resolution of the latter method. This explanation assumes that fusion is less sensitive to weakly coupled channels, which was never proven experimentally or theoretically.

In [12] Zagrebaev remarked that the QE method determines a threshold distribution for all reaction processes rather than just for fusion. This has important implications in the case of heavy or weakly bound projectiles, where the contributions from deep-inelastic collisions or breakup processes are important. However, for the systems studied by our group at near-barrier energies these processes are negligible.

## II. MOTIVATION OF THE EXPERIMENT

In our experiments we have focused on the $^{20}$Ne projectile, since this nucleus has extremely large deformation parameters: $\beta_2 = 0.46$, $\beta_3 = 0.39$, $\beta_4 = 0.27$ [13–15]. Due to the strong deformation it was expected that the shape of a barrier height distribution for $^{20}$Ne and any target would result mainly from $^{20}$Ne properties, and a “structured” (with two maxima) distribution for any medium or heavy target was predicted by the coupled channels (CC) code CCQEL [16].

A series of experiments determining barrier height distributions for $^{20}$Ne interacting with several targets, $^{112,116,118}$Sn, $^{\mathrm{nat}}$Ni, $^{90,92}$Zr, and $^{208}$Pb, was performed [17–19]. Only for $^{\mathrm{nat}}$Ni and $^{90}$Zr did the experimentally obtained barrier height distributions have a shape in a fair agreement with calculation predictions, i.e., with clearly visible structure. In all other cases $D_{QE}$ turned out to be smooth.

In the recent articles [18–20] the possible explanations of the observed disagreement were discussed and the transfer channels and/or noncollective excitations were indicated as the possible causes of smoothing the barrier distributions.

The role of (mainly neutron) transfer channels in fusion reactions has been studied in many papers [1,21–53]; however, the problem of smoothing the barrier distribution structure was not commonly discussed.

For $^{20}$Ne interacting with $^{90,92}$Zr targets the experimentally obtained barrier height distributions are clearly different [18], while the CC calculations predict the same distribution shapes with a “structure” determined by the $^{20}$Ne deformation. The transfer cross sections were also measured for the systems $^{20}$Ne + $^{90,92}$Zr. It turned out that, at near-barrier energy, at a backward angle of 142 degrees in the laboratory system (which for this energy is in the region of maximum transfer cross section) the total transfer cross sections are very similar for both Zr isotopes [18]. This suggests that some other mechanism is responsible for the clear difference between the barrier distributions for the two Zr isotopes. In the article [18] we conjectured that the difference in barrier distribution shapes was due to the differences in noncollective excitations of the two targets. Namely, in the heavier Zr isotope the level density is significantly higher due to two neutrons above the closed neutron shell. Comparing experimental and calculated $Q$-value spectra for $^{20}$Ne + $^{90,92}$Zr systems one can observe [18] that, above 5 MeV for $^{90}$Zr and even lower for $^{92}$Zr, the excitations are essentially noncollective, and for $^{92}$Zr they are more numerous than in the $^{90}$Zr case. The hypothesis that single-particle excitations influence the shape of the barrier height distribution seems to be supported by recent calculations performed by Yusa and collaborators [54].

Ni isotopes: $^{58}$Ni, $^{60}$Ni, and $^{61}$Ni also differ significantly by level density—see Fig. 1; they are good candidates to test the hypothesis of influence of single-particle excitations on the barrier height distribution shape. One could expect that, for the semimagic $^{58}$Ni nucleus, having relatively low level density, the barrier distribution would be “structured” in agreement with the coupled channels prediction. For $^{60}$Ni—the isotope with level density similar to the level density of $^{58}$Ni—the barrier height distribution also should have the structure. A different result was expected for an isotope with higher level density, $^{61}$Ni: for this case the barrier height distribution should be smoothed, at least partly.

Preliminary experimental results confirming our expectation were presented at conferences [55,56]

## III. EXPERIMENT

### A. Setup

The experiment was performed at the Heavy Ion Laboratory, University of Warsaw. The $^{20}$Ne beam of energies in the 43–62 MeV range and intensity ∼25 $e$ nA, delivered by the

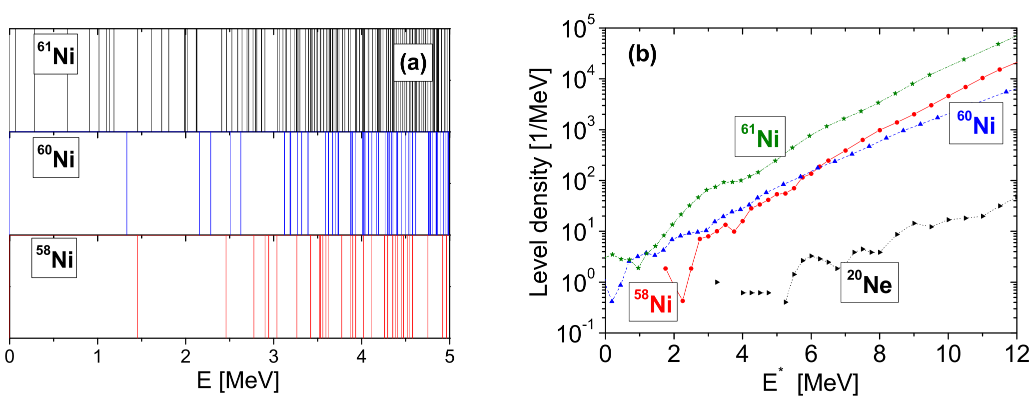


FIG. 1. (Color online) Comparison of level densities in $^{58,60,61}$Ni: (a) experimental levels adopted from [57] and (b) single-particle level densities calculated with the HFB method based on the BSk14 Skyrme interaction [58].

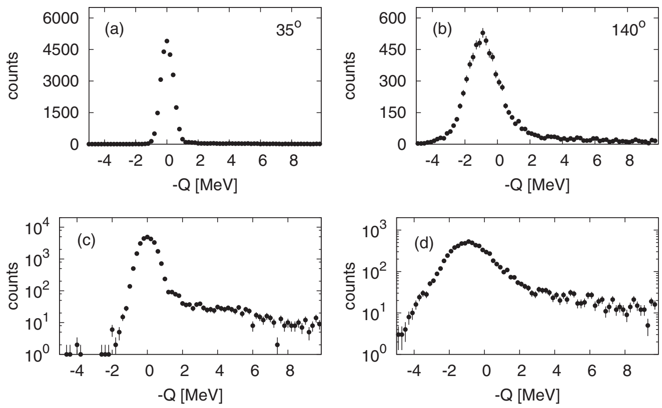


FIG. 2. $Q$-value spectra for the $^{20}$Ni + $^{61}$Ni system (for beam energy 51 MeV) obtained from data registered at 35 degrees [panels (a) and (c)] and 140 degrees [panels (b) and (d)] presented in linear and logarithmic scales.

Warsaw Cyclotron U200-P, bombarded the targets of $^{58,60,61}$Ni (enrichment 99.92%, 99.79%, and 92.92% respectively) of 100 $\mu$g/cm$^2$ thickness, prepared in the GSI Target Laboratory and at the University of Jyväskylä. The targets were placed in the compact (40 cm diameter) CUDAC chamber [17]. Changes of beam energy in small steps ($\sim$0.5 MeV) were obtained using of the degrader consisting of thin $^{nat}$Ni foils.

The scattering chamber was equipped with an array of 30 Si detectors (PIN diodes) placed at backward angles of 150, 140, and 130 degrees and two detectors placed at a forward angle of 35 degrees registering "Rutherford" scattered ions. The data from the latter detectors were used to measure beam energy and to normalize the intensity in the appropriate $Q$ windows (see Fig. 2). The detectors also constantly monitored the energy resolution which was equal to 0.9 MeV (FWHM) in the center-of-mass system and was determined mainly by beam properties.

Energy calibration was performed using a precise pulse generator and an $^{241}$Am source. Stability of electronics during measurement was continuously controlled using the pulser.

### B. Results

The method of data analysis is described in [17] and [18]. The energy spectra for registered ions were transformed to the $Q$-value spectra assuming two-body kinematics; formula (5) in [17]. Examples of the spectra obtained from data registered by forward and backward detectors are presented in Fig. 2.

The number of counts was determined integrating the $Q$-value spectra in the range $(-3.5,4.0)$ MeV. It was shown in [17] that the shape of $D_{QE}$ does not depend on the integration range (if the integration window is selected so that it does not contain background events). The effective energy, see Eq. (1), was calculated and, after binning over 0.3 MeV intervals, $\sigma_{QE}/\sigma_{\rm Ruth}$ was constructed. The data were normalized by setting $\sigma_{QE}/\sigma_{\rm Ruth}$ at the lowest energy equal to 1.0. In this way precise knowledge of detector solid angles, the target thickness, and absolute beam current was not necessary, and corresponding errors were avoided.

The excitation functions are presented in Fig. 3. The barrier height distributions, presented in Fig. 4, were determined from

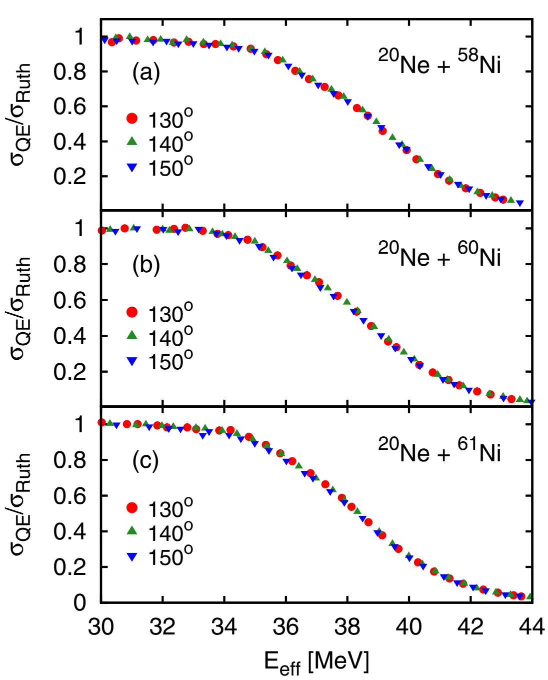


FIG. 3. (Color online) Excitation functions for quasielastic backscattering of $^{20}$Ne on $^{58,60,61}$Ni targets registered at 130°, 140°, and 150° (in the laboratory).

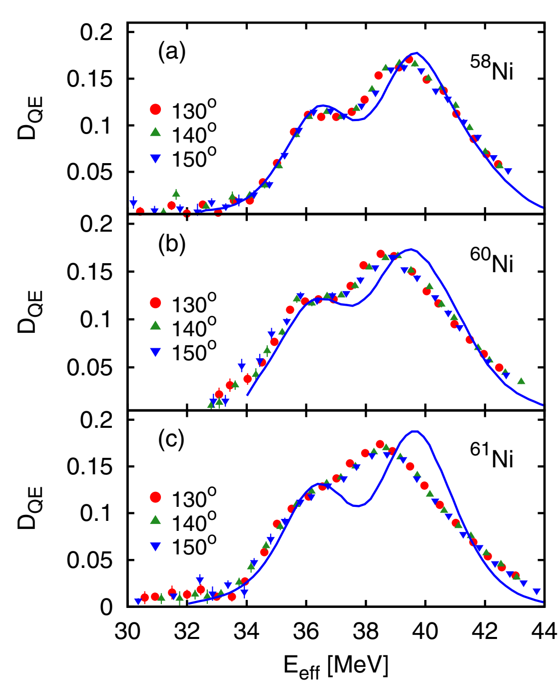


FIG. 4. (Color online) Barrier height distributions for the $^{20}$Ne + $^{58,60,61}$Ni systems derived using the Eq. (2) from the excitation functions presented in Fig. 3. Theoretical predictions obtained by means of the CCQEL code, convoluted with experimental resolution, are marked with solid lines.

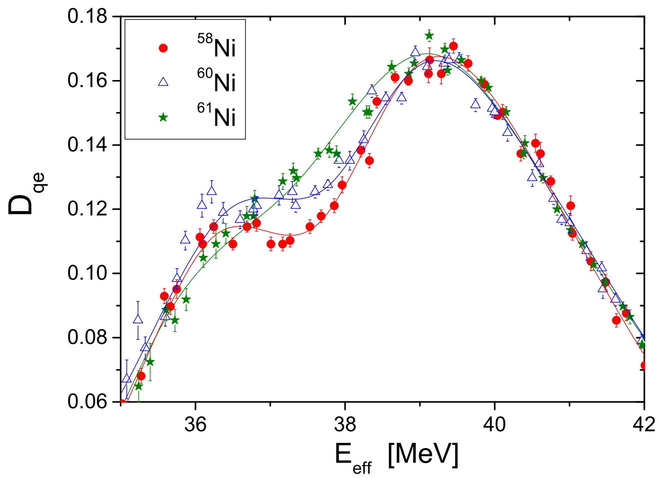


FIG. 5. (Color online) Comparison of barrier height distributions shown in Fig. 4 after renormalization of barrier positions for $^{60}$Ni and $^{61}$Ni, taking into account in an approximate way sizes of the target nuclei (see the text). The lines, being spline approximations of experimental distributions, are to guide the eye.

these data according to Eq. (1) using the finite-difference method with a step of 0.9 MeV.

The experimental results are in agreement with our expectations: for the semimagic $^{58}$Ni target, where the level density is low, the barrier height distribution is structured. For the $^{60}$Ni target the structure is also marked, whereas for $^{61}$Ni, where the level density is the highest, the structure at 37–38 MeV is almost completely smoothed out (Figs. 4 and 5). One should emphasize that experimental energy resolution for all cases was the same. In Fig. 5 the barrier distribution for three Ni isotopes are compared. As the barrier height is approximately proportional to $1/R \sim 1/A^{1/3}$, the $E_{\rm eff}$ for $^{60}$Ni and $^{61}$Ni were renormalized by the factor $(A/58)^{1/3}$. Such renormalized distributions have the same width and differ only by a shape: the structure seen for $^{58}$Ni and $^{60}$Ni disappears completely in the $^{61}$Ni case.

## IV. DISCUSSION

The experimental data were compared with theoretical results convoluted with experimental energy resolution; see Fig. 4. The interaction potential used in the calculation was of Woods-Saxon type with the following parameters: $V = 57.23$ MeV, $r_{\rm ov} = 1.15$ fm, $a_v = 0.642$ fm, $W = 20$ MeV, $r_{ow} = 1.0$ fm, and $a_w = 0.4$ fm. The real part of the potential is the Akyüz-Winther potential [59] with $r_{\rm ov}$ sightly adjusted in order to reproduce mean barrier height. The “interior” imaginary potential (used also in our previous works) simulates the ingoing-wave boundary condition. The calculations include couplings between the $0^+,2^+,4^+$ states in the $^{20}$Ne rotational band. The results converge rapidly as the number of rotational states is increased, and it was verified that truncating the calculations at the $4^+$ level is entirely sufficient for our purposes. The strong octupole-phonon state of the projectile (and all mutual excitation channels) as well as the vibrational excitations of the target (two-phonon) were also taken into account. For the latter, $\beta_2$ parameters in $^{58}$Ni and $^{60}$Ni were taken from [13]: 0.183 and 0.201 respectively. In the odd $^{61}$Ni isotope case the analog of first collective state $2^+$ in even Ni isotopes is split into a multiplet [60]. It is formed by coupling the $2p_{3/2}$ ground state with the one-phonon state in $^{60}$Ni. In the calculations the multiplet was introduced as a single effective state given as a spin average of the four states. The effective energy of this state, $E_{\rm eff}^{\rm multiplet}$, was calculated according to the formula

$$E_{\rm eff}^{\rm multiplet} = \frac{\sum_{i=1}^{4}(2j_i+1)E_i}{\sum_{i=1}^{4}(2j_i+1)}, \quad (3)$$

where $E_i$, energies of multiplet members, were taken from [60,61]. The coupling strength was given as

$$\beta_2^{\rm multiplet} = \sqrt{\sum_{i=1}^{4} {\beta_2^i}^2}, \quad (4)$$

where $\beta_2^i$ are the deformation parameters of the states in the multiplet, calculated from reduced electric quadrupole transition probabilities, $B(E2)\uparrow$, determined in [61]. The following values were obtained: $E_{\rm eff}^{\rm multiplet} = 964.3$ keV, $\beta_2^{\rm multiplet} = 0.1052$.

The mathematical foundation for Eqs. (3) and (4) is that the effective state is given as

$$|{\rm eff}\rangle = \sum_i \beta_i \,|i\rangle \Big/ \sqrt{\sum_j \beta_j^2}. \quad (5)$$

Assuming that $T_i\,|0\rangle = \beta_i\,|i\rangle$, where $T_i$ is the operator which excites the state $|i\rangle$ from the ground state $|0\rangle$, one obtains (after a simple algebra)

$$\sum_i T_i\,|0\rangle = \sqrt{\sum_j \beta_j^2}\,|{\rm eff}\rangle\,. \quad (6)$$

Thus, the effective beta is given as in Eq. (4) [2,62].

Experimentally obtained barrier height distributions for $^{20}$Ne + $^{58}$Ni and $^{20}$Ne + $^{60}$Ni are similar: the barrier distributions have a visible structure. For the $^{61}$Ni target $D_{QE}$ is smooth. This result is in contradiction with standard CC calculations, where a similar shape of barrier height distribution is predicted for all three systems since it should be determined by the strongly deformed $^{20}$Ne nucleus, while influence of the collective vibrational excitations of Ni isotopes should be marginal. In fact, due to the somewhat smaller value of deformation parameter of $^{61}$Ni, the calculated BD structure for this target turns out to be even slightly stronger than for the $^{58}$Ni one.

In a separate experiment transfer cross sections for these three systems, $^{20}$Ne + $^{58,60,61}$Ni, were measured. The preliminary results show that differential cross sections for these three systems are small (∼1 mb/sr) and similar [63].

Simultaneously, the results are in agreement with our qualitative expectations: for the isotope with the highest level density the predicted structure is smoothed out. This supports our hypothesis that noncollective excitations can be responsible for the $D_{QE}$ smoothing, similarly to what was observed for the $^{20}$Ne + $^{92}$Zr system [18].

A quantitative proof of above hypothesis—the influence of non-collective excitations on $D_{QE}$ —is not straightforward: one needs an alternative to the standard CC method [54,64,65]. In the standard CC calculation it is impossible because of the size of the calculation and lack of knowledge of the necessary coupling strengths for the sequential transitions involving excited states in the intermediate and final channels. To this end, Yusa *et al.* have used the random matrix theory and obtained the barrier height distributions for $^{20}$Ne + $^{90}$Zr and $^{92}$Zr systems; they are in fair agreement with experimental data [54].

## V. SUMMARY AND CONCLUSIONS

We have determined the quasielastic barrier height distributions ($D_{QE}$) for the $^{20}$Ne + $^{58,60,61}$Ni systems. The shapes of the distribution for $^{20}$Ne + $^{58}$Ni and $^{20}$Ne + $^{60}$Ni are in fair agreement with the one predicted by CC calculations. The barrier distribution for $^{20}$Ne + $^{61}$Ni is very different from theoretical prediction; namely, it has no structure. The results support our hypothesis that the weak but numerous couplings to noncollective levels give rise to smoothing of the barrier height distribution structure.

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