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**Author(s):** Piasecki, E.; Swiderski, L.; Keeley, N.; Kisielinski, M.; Kowalczyk, M.; Khlebnikov, Sergey; Krogulski, T.; Piasecki, K.; Tiourin, G.; Sillanpää, Mikko; Trzaska, Wladyslaw; Trzcinska, A.

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## Smoothing of structure in the fusion and quasielastic barrier distributions for the $^{20}\text{Ne} + ^{208}\text{Pb}$ system

E. Piasecki,<sup>1,2</sup> Ł. Świdorski,<sup>2</sup> N. Keeley,<sup>2</sup> M. Kisieliński,<sup>1,2</sup> M. Kowalczyk,<sup>1,3</sup> S. Khlebnikov,<sup>4</sup> T. Krogulski,<sup>5</sup> K. Piasecki,<sup>3</sup> G. Tiourin,<sup>6</sup> M. Sillanpää,<sup>6</sup> W. H. Trzaska,<sup>6</sup> and A. Trzcińska<sup>1</sup>

<sup>1</sup>Heavy Ion Laboratory, Warsaw University, Warsaw, Poland

<sup>2</sup>National Centre for Nuclear Research, ul. Soltana 7, Otwock, Poland

<sup>3</sup>Institute of Experimental Physics, Warsaw University, Warsaw, Poland

<sup>4</sup>Khloplin Radium Institute, St. Petersburg, Russia

<sup>5</sup>Faculty of Physics, University of Białystok, Białystok, Poland

<sup>6</sup>Department of Physics, University of Jyväskylä, Jyväskylä, Finland

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We present simultaneously measured barrier distributions for the  $^{20}\text{Ne} + ^{208}\text{Pb}$  system derived from large-angle quasielastic scattering and fusion, in the latter case by means of the detection of fission fragments. Both distributions turned out to be smooth, in spectacular disagreement with the results of standard coupled-channels calculations. Namely, they do not possess the strong structure expected from coupled-channels calculations, even if apparently they take into account explicitly all relevant strong couplings. This points to the importance of weak channels, i.e., transfer reactions and scattering connected with noncollective excitations.

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### I. INTRODUCTION

One of the most important near-barrier reactions is fusion. It turns out that there is a connection between the reaction mechanism and the structure of the interacting nuclei which manifests itself as a strong enhancement of the fusion cross-section at sub-barrier energies. This can be understood as a result of the interplay between various reaction channels: elastic and inelastic scattering, transfer reactions, breakup, and fusion. The coupling to collective (rotational and/or vibrational) excitations, connected with the static or dynamical deformations, is particularly important. This leads to a decrease in the fusion barrier, manifesting itself in a strong enhancement of the fusion cross sections at sub-barrier energies; see the review papers [1,2] and references therein. The importance of this phenomenon in low-energy nucleosynthesis is evident; see, e.g., Ref. [3]. However, such effects also have important analogs in other branches of science and belong to the general phenomenon known as “tunneling in the presence of an environment” [4–6]. In the case of nuclear physics the “environment” is the structure of the interacting nuclei. It has been demonstrated experimentally in many systems that the fusion barrier between two nuclei does not have a unique value but rather a weighted distribution of heights,  $D_{\text{fus}}$ , which can be determined directly from fusion excitation function measurements [7]:

$$D_{\text{fus}}(E) = \frac{1}{\pi R_B^2} \frac{d^2}{dE^2} (\sigma_{\text{fus}} E), \quad (1)$$

where  $E$  is the projectile energy in the center of mass system and  $R_B$  is the mean barrier radius. Distributions obtained by this method have been published and discussed in many papers [1,2,8–29]

It has been shown both theoretically [30–32] and experimentally [30] that the difficult fusion measurements can be replaced by much simpler quasielastic (QE) scattering

measurements at backward angles, giving rise to the barrier distribution  $D_{QE}$ . The latter method consists of determining the excitation function of the quasielastic scattering of the projectile-like nuclei at large angles. The quasielastic cross section is the sum of the elastic, inelastic, and transfer channels, with no need to identify individually the particular channels involved. The barrier distribution is obtained directly from the data as the first derivative with respect to energy of the ratio of the quasielastic cross section to the Rutherford cross section:

$$D_{QE} = -\frac{d(\sigma_{QE}/\sigma_R)}{dE}. \quad (2)$$

The advantages of this method are discussed in Refs. [1,33].

Recently, Zagrebaev [34] 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, we will concentrate on a system where these processes are negligible and, thus, the “total reaction threshold distribution” should really reflect the “barrier distribution.”

Experimentally, the measurements reduce to counting the number of projectile-like nuclei (in some excitation-energy window) registered at backward and forward angles, the latter being used as a measure of the Rutherford scattering. Since the publication of Ref. [30], this method has been widely used; see Refs. [1,35–48]. When the barrier distributions are structureless, the two approaches (i.e., fusion and quasielastic scattering) usually give similar results [30,35,40,49–51]. However, when the barrier distributions exhibit structure the situation is less clear, as data are scarce. In one case ( $^{40}\text{Ca} + ^{90}\text{Zr}$ ) the agreement is very good [52], while in another system ( $^{16}\text{O} + ^{144}\text{Sm}$ ) the structure is visible only in the  $D_{\text{fus}}$  distribution, while  $D_{QE}$  is without any trace of structure [30,43]. Why this should be so is not certain, although in

Ref. [53] we suggested that this could be due to the stronger sensitivity of  $D_{QE}$  to the smoothing action of numerous weak channels.

The best theoretical description of barrier distributions can be made in the framework of the coupled-channels (CC) method, according to which the distribution is a manifestation of strong coupling of the relative motion to different reaction channels, in particular to strong collective excitations of the participating nuclei. In some cases the distribution turns out to be markedly structured and gives a fingerprint of the couplings involved [1,54]. However, the role of the weaker direct-reaction channels is less clear as their inclusion in a CC scheme is usually difficult or impossible owing to their large number and the complexity of their couplings.

## II. MOTIVATION OF THE EXPERIMENT

Our program of measurements has concentrated on the  $^{20}\text{Ne}$  projectile, since this nucleus has spectacularly large deformation parameters:  $\beta_2 = 0.46$ ,  $\beta_3 = 0.39$ , and  $\beta_4 = 0.27$  [55–57]. According to calculations performed using the coupled-channels codes CCQEL [58] and FRESKO [59], this projectile, used in conjunction with a relatively inert target nucleus, should give rise to a strongly structured barrier distribution.

The results of our measurements were perplexing: the barrier distributions for  $^{20}\text{Ne} + ^{112,116,118}\text{Sn}$  turned out to be smooth [60]. On the other hand, the simultaneously performed measurements for the  $^{20}\text{Ne} + ^{\text{nat}}\text{Ni}$  system resulted in a clearly structured distribution [61], in very good agreement with calculations based on the coupled-channels method.

The natural suspicion is that the smoothing of the distributions in the case of the Sn targets is due to some couplings not taken into account in our calculations; for example, those connected with transfer channels. Nothing is known about the influence of  $\alpha$ -particle transfer on the barrier distributions (which is expected to be particularly strong for this projectile because of its cluster structure), but our measurements with a  $^{22}\text{Ne}$  beam (where the  $\alpha$ -transfer reaction turned out to be much weaker than in the  $^{20}\text{Ne}$  case) apparently eliminated from our investigations this channel as the main source of the smoothing [62].

A possible hypothesis is that the smoothing is due to the neutron pickup and proton stripping channels, as it is known that sometimes transfers significantly influence the barrier distribution (see, e.g., Ref. [63]). We expected that for the Ni target the transfers should be much weaker than for Sn. This expectation relies on the Rehm transfer cross-section systematics [64], for which the effective  $Q$  value [65] is the main factor influencing the transfer probability. While for both cases the  $Q$  values are negative, the expected neutron transfer cross sections are much smaller for the magic  $^{58}\text{Ni}$  nucleus than for  $^{118}\text{Sn}$ .

However, in Ref. [53] we showed that there is still another possibility. Namely, our experiment suggested that, at least for the  $^{20}\text{Ne} + ^{92}\text{Zr}$  system, the QE barrier distribution is smoothed due to the numerous weakly coupled noncollective inelastic channels. Recent theoretical papers [66,67] seem to confirm such a possibility.

To continue these studies on the influence of weak couplings on the barrier distributions we performed the experiment presented below, in which we measured simultaneously both  $D_{QE}$  and  $D_{\text{fus}}$  distributions for the  $^{20}\text{Ne} + ^{208}\text{Pb}$  system. A doubly magic nucleus was chosen as the target because in this way we expected to minimize the noncollective excitations. Moreover, the width of the barrier distribution roughly scales as  $Z_{\text{proj}} * Z_{\text{targ}}$  [1], thus we could expect a kind of ‘‘Coulomb zoom’’ of the barrier distribution, where the high  $Z$  value of the target should give rise to a strong barrier distribution structure, confirmed explicitly by the results of CC calculations. The aims of the experiment were thus to check

- (i) whether for this system the  $D_{\text{fus}}$  and  $D_{QE}$  distributions are similar, and
- (ii) whether they possess the strong structure predicted by the CC calculation.

Some partial, preliminary results were reported previously in conference proceedings [68].

## III. EXPERIMENTAL SETUP AND DATA ANALYSIS

The method and experimental setup were similar to those described in Ref. [33]. That is, we measured large-angle quasielastic scattering and (this was new with respect to our previous measurements) the fusion/fission excitation function using semiconductor detectors placed at  $130^\circ$ ,  $145^\circ$ , and  $155^\circ$  (with  $2^\circ$  aperture) in the laboratory system. In addition four ‘‘Rutherford’’ semiconductor detectors were placed symmetrically at  $14^\circ$  (collimated to  $\pm 0.1^\circ$ ) with respect to the beam. The forward detectors were used both for normalization [see Eq. (2)] and the precise determination of the beam energy.

A  $^{20}\text{Ne}$  beam, with an intensity of  $\sim 20$  p nA, from the K-130 Jyväskylä cyclotron (the acceleration of noble gas ions, such as Ne, cannot be performed with the tandem accelerators usually used in this kind of study) bombarded a  $150 \mu\text{g}/\text{cm}^2$  target of  $^{208}\text{Pb}$  (enriched to 99%) on a  $60 \mu\text{g}/\text{cm}^2$   $\text{Al}_2\text{O}_3$  backing. To enable measurements with small energy steps (in the range 93–117 MeV in the laboratory reference system), we used nickel foils as energy degraders. Energy calibration was performed using a precise pulse generator and a  $^{226}\text{Ra}$   $\alpha$ -particle source (the estimated pulse-height defect of the semiconductor detectors was less than 0.3 MeV).

The energy resolution was continuously monitored during the experiment using the energy spectra measured in the forward detectors, and was found to be 0.6–0.7 MeV, full width at half maximum (FWHM); much smaller than the expected  $\sim 4$  MeV structure width. About half of the resolution came from the characteristics of the beam; the rest was due to straggling in the degrader and the target. Other effects, for example detector geometry, had very little influence on the energy resolution. The stability of the electronics and detectors was continuously monitored using a precise pulse generator and the elastic scattering peak.

Usually in this kind of experiment the fusion excitation function is measured via detection of the evaporation residues

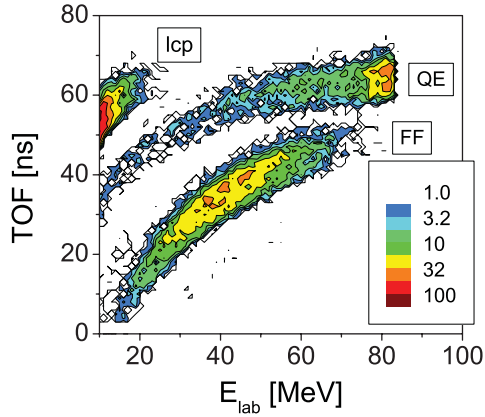


FIG. 1. (Color online) Sample  $E$ -TOF spectrum (on a logarithmic scale) registered in the detector placed at  $130^\circ$  at a beam energy of 113 MeV. The light charged particles (lcp) of the background, quasielastically scattered projectiles (QE), and fission fragments (FF) can be easily separated.

(ERs), requiring the use of some equipment (e.g., an electromagnetic deflector) enabling separation of the ERs from the beam ions. Instead, we used a novel method, exploiting the fact that the complete fusion product ( $^{228}\text{U}$ ) mainly undergoes immediate fission. The semiconductor detectors registered simultaneously both backscattered ions and fission fragments. To distinguish between them we identified the mass of the detected ions using the time-of-flight (TOF) technique, with the start/stop generated by the semiconductor detector and cyclotron RF signals, respectively. A sample  $E$ -TOF spectrum is presented in Fig. 1. In this way we could determine simultaneously (which is rather unique) both  $D_{\text{fus}}$  and  $D_{QE}$  distributions.

The data analysis was performed in a similar way to that described in Refs. [33,53]. The fusion-fission and QE events were extracted from the data by applying appropriate gates to the  $E$ -TOF spectra. From the quasielastic kinetic-energy spectra we calculated the  $Q$ -value spectra for the forward and backward detectors, assuming two-body kinematics. The spectra were then integrated over wide limits:  $[-3, 10]$  MeV for the forward and  $[-3, 50]$  MeV for the backward detectors (the results are almost independent of these values). In this way the number of counts ( $N_{QE}$  and  $N_{\text{Ruth}}$ ) was obtained. Next,  $E_{\text{eff}}$  (which takes account of the “angle-dependent” centrifugal energy [52]) was calculated:  $E_{\text{eff}} = \frac{2E}{1 + \cos^2(\theta/2)}$  ( $E$  and  $\theta$  are the center-of-mass energy and scattering angle) and the ratios  $N_{QE}/N_{\text{Ruth}}$  as a function of  $E_{\text{eff}}$  were calculated. Then, the  $N_{QE}/N_{\text{Ruth}}(E_{\text{eff}})$  results were binned over 0.75 MeV intervals and normalized (separately for every detection angle) to 1.0 at the lowest measured energy. This makes precise knowledge of the target thickness, beam intensity, and detector solid angles unnecessary.

For the fusion, the full fission fragment spectra (from the  $E$ -TOF gates) were integrated and from the  $E_{\text{cms}}$  dependence of the ratios  $N_{\text{fus}}/N_{\text{Ruth}}$  the fusion excitation function was determined. This procedure assumes that in the excitation energy range covered by the experiment  $\sigma_{\text{fiss}}$  changes only weakly, which (according to Ref. [69]) seems to be the

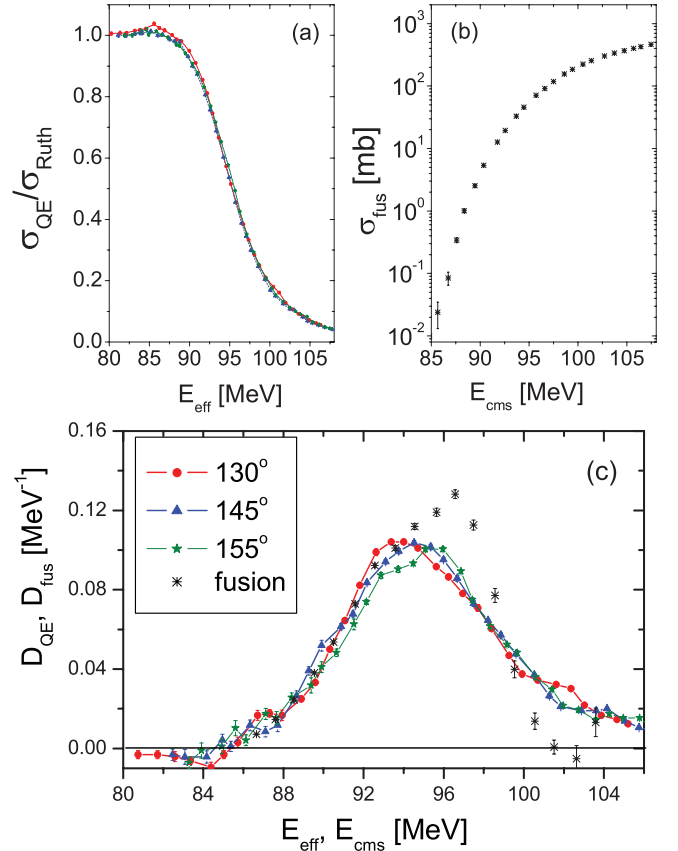


FIG. 2. (Color online) Excitation functions (upper panels) of the QE backscattering (a) and fusion (b) obtained for the  $^{20}\text{Ne} + ^{208}\text{Pb}$  system. The lower panel (c) presents the quasielastic and fusion barrier distributions as functions of  $E_{\text{eff}}$  and  $E_{\text{cms}}$ , respectively. Different symbols refer to different laboratory detector angles. Lines connect experimental points to guide the eye.

case. The  $N_{\text{fiss}}/N_{\text{Ruth}}(E_{\text{cms}})$  data were binned over 1.0 MeV intervals and normalized to the calculated value at the highest energy, where couplings have very weak influence on the result.

The barrier distributions were determined using the numerical finite-difference method. The results are shown in Fig. 2. The experimental method employed resulted in spectacularly small statistical errors. The most important observation is that while  $D_{\text{fus}}$  and  $D_{QE}$  are similar (although they admittedly differ in some details) no significant structure is observed in either of them, in striking disagreement with calculations (see below).

It is important to mention that the correctness of the experimental procedure for the determination of  $D_{QE}$  was confirmed through barrier distribution measurements performed using the same experimental method for  $^{20}\text{Ne} + ^{\text{nat}}\text{Ni}$  and  $^{20}\text{Ne} + ^{90}\text{Zr}$ , where structured distributions were observed [53,61] even though the energy resolution was no better than in the present experiment, while the predicted barrier distribution structure was much weaker than in the present case. Therefore, the observed smoothing is not a result of the experimental energy resolution.

#### IV. COUPLED-CHANNELS CALCULATIONS

We followed the same approach applied previously with success in the case of other targets. All calculations used the code CCQEL [58].

The interaction potential, which we also used in our previous papers, was of Woods-Saxon type with the following parameters:

$$\begin{aligned} V &= 50 \text{ MeV}, & r_{ov} &= 1.23 \text{ fm}, & a_v &= 0.63 \text{ fm}, \\ W &= 20 \text{ MeV}, & r_{ow} &= 1.0 \text{ fm}, & a_w &= 0.4 \text{ fm}. \end{aligned}$$

The “interior” imaginary potential simulates the ingoing-wave boundary condition. The couplings taken into account are given in Table I.

The values of the deformation parameters for  $^{20}\text{Ne}$ ,  $\beta_2 = 0.46$ ,  $\beta_3 = 0.39$ ,  $\beta_4 = 0.27$ , and  $\beta_3 = 0.11$  for  $^{208}\text{Pb}$ , were taken from Refs. [55–57]. The results converge rapidly as the number of states is increased, due to the large excitation energy of the first excited state of  $^{20}\text{Ne}$  ( $E_2 = 1634$  keV). The 1- and 2-phonon  $3^-$  octupole states ( $E_3 = 2.615$  MeV) in the target were also included. It was verified that truncation of the calculations at the  $6^+$  level is entirely sufficient for our purposes and, as one sees in the upper panel of Fig. 3, including the  $6^+$  level and the second octupole vibrational level of  $^{208}\text{Pb}$  changes only the details of the calculated fusion barrier distribution.

Calculations were performed including reorientation and mutual excitation terms, but the latter influenced only the minor details of the resulting distributions. To compare with experimental data, the calculated results were folded with our experimental resolution of 0.7 MeV (FWHM), which (since the structure width is much wider) influenced the distributions only marginally.

In Fig. 3 we see that the coupled-channels calculations result in  $D_{QE}$  and  $D_{fus}$  distributions possessing two distinct peaks, in contrast to the experimental data which are quite smooth. One should emphasize that this structure cannot be removed by changing the coupling-constant values within the observed scatter quoted in Ref. [57]. By changing the optical model parameters (with only one exception) one can only shift or slightly change the details of the calculated distributions. The exception is the imaginary potential in the surface region, where most of the interactions take place: by increasing it, the distribution structure can be smoothed out. This may be achieved, e.g., by increasing the parameter  $r_{ow}$ . The results are shown in Fig. 4.

We would like to stress that we did not try to fit the experimental barrier distribution; we wished only to test the influence of the surface imaginary potential on the structure. This purely phenomenological test cannot, of course, be

TABLE I. Couplings taken into account in our CC calculations.

Coupling	$^{20}\text{Ne}$ levels	$^{208}\text{Pb}$ levels
A	$2^+, 4^+, 6^+; 3^-$ (1 phonon)	$3^-$ (2 phonons)
B	$2^+, 4^+; 3^-$ (1 phonon)	$3^-$ (1 phonon)

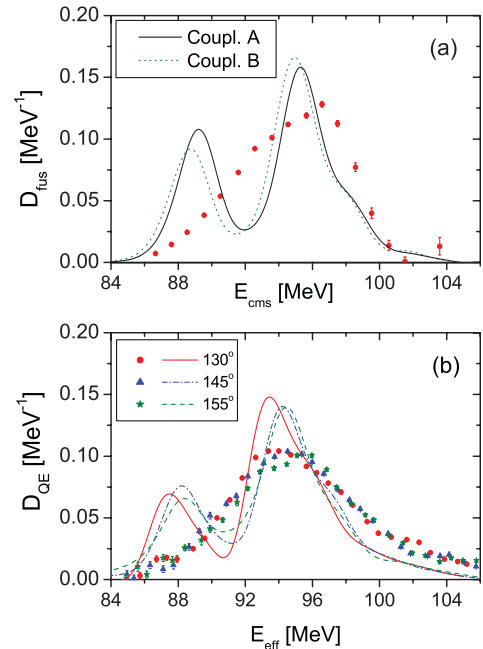


FIG. 3. (Color online) Comparison of the measured (points) and calculated (lines) barrier height distributions  $D_{QE}$  (b) and  $D_{fus}$  (a) for the  $^{20}\text{Ne} + ^{208}\text{Pb}$  system. For the calculated curves the experimental resolution of 0.7 MeV (FWHM) was taken into account.  $D_{QE}$  distributions were measured and calculated (according to coupling scheme A of Table I) for  $130^\circ$ ,  $145^\circ$ , and  $155^\circ$  in the laboratory system. In the upper panel we show the degree of sensitivity of our calculated results to the coupling scheme taken into account in our calculations.

considered an explanation of the smoothing, since it only mocks up the mechanism responsible for the lack of barrier structure observed in the system under study, but which is apparently much weaker in the case of the  $^{20}\text{Ne} + ^{\text{nat}}\text{Ni}$  and  $^{20}\text{Ne} + ^{90}\text{Zr}$  interactions. It suggests, however, that perhaps some couplings were not taken into account in our CC calculations. Since we believe that we included all the relevant strong reaction channels, the obvious candidates for

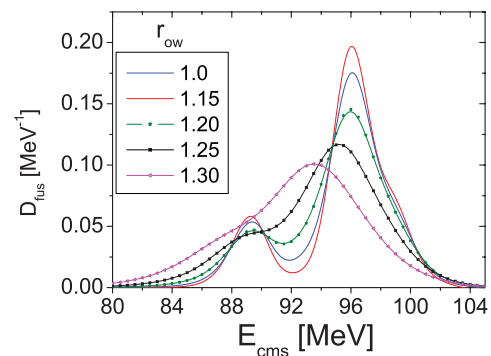


FIG. 4. (Color online) Smoothing of the fusion barrier distribution by the surface imaginary potential. Similar results were obtained for the  $D_{QE}$  distribution. The  $r_{ow}$  parameter was set to 1.23 fm. For other optical model parameters see the text.



the observed smoothing are the weak couplings, such as transfers and noncollective excitations.

## V. SUMMARY AND CONCLUSIONS

We have simultaneously determined the fusion and quasielastic barrier height distributions ( $D_{\text{fus}}$  and  $D_{QE}$ ) for the  $^{20}\text{Ne} + ^{208}\text{Pb}$  system and concluded that their shapes are similar to each other but spectacularly different from those predicted theoretically. Namely, they do not possess the strong structure expected from coupled-channels calculations, even if apparently we take into account explicitly all relevant strong couplings. This points to the importance of weak channels, i.e., transfer reactions and scattering connected with noncollective excitations. An experimental study of these

channels in this and several other systems was performed in a separate experiment [70].

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