Elastic two-neutron transfer reactions of ^{58}Ni+^{60}Ni and ^{62}Ni+^{64}Ni around the Coulomb barrier

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We have measured elastic scattering angular distributions for ^{58}Ni+^{60}Ni at $E_{^{58}\mathrm{Ni}}$=204, 220, 236, and 250 MeV and for ^{62}Ni+^{64}Ni at $E_{^{64}\mathrm{Ni}}$=250 MeV. The measured angular distributions show bell-shaped structures at backward angles for both systems at E_{lab}=250 MeV which are due to the neutron pair exchange between identical cores for the projectile and target. The pair exchange has been analyzed by using the macroscopic form factor. For elastic scattering the coupled-channels analyses have been performed. The data are reproduced well. The possibility of a nuclear Josephson effect is discussed. [S0556-2813(97)50201-9]

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It is known that angular distributions of elastic scattering show oscillatory patterns in collisions of almost identical nuclei. These characteristic patterns have been attributed to an interference between the truly elastic process and the one involving the transfer of nucleons, since the exchange of nucleons between the identical cores can reach the final configuration the same as that of the entrance channel.

Detailed analyses of elastic transfer reactions have been performed and reviewed by von Oertzen and Bohlen [1]. They have pointed out that, in the vicinity of the Coulomb barrier, elastic two-nucleon transfer reactions in superfluid nuclei of medium and heavy weights seem to be the best way to measure pair exchanges as a test of possible existence of the nuclear Josephson effect. However, there have been no experimental data of elastic two-nucleon transfer reactions for superfluid systems, since such measurements are very difficult mainly due to the limited energy resolution. The heaviest system so far measured was ^{32}S+^{34}S [2]. For this system neutron pair exchange between identical cores for ^{32}S and ^{34}S nuclei were analyzed by optical model and exact finite range distorted-wave Born approximation. From the enhancement of the experimental cross sections with respect to the theoretical ones, they suggested evidence of a nuclear Josephson effect [3].

We measured elastic scattering for the ^{58}Ni+^{60}Ni and ^{62}Ni+^{64}Ni systems by using the JAERI tandem accelerator and the heavy-ion magnetic spectrograph ''ENMA'' [4]. The spectrograph has a characteristic feature that the kinematic energy spread which typically amounts to $\approx$2–3 MeV/deg for the ^{58}Ni+^{60}Ni and ^{62}Ni+^{64}Ni systems is effectively corrected for by the combined effect of the magnetic elements. An energy resolution of about 600 keV was achieved for the horizontal opening angle of 2.3° which was enough to obtain a clear separation between the elastic peak and the low-lying inelastic peaks. ^{58}Ni and ^{64}Ni beams with a typical intensity of 10 p nA were obtained from the JAERI tandem accelerator. The incident beam energy was $E_{^{58}\mathrm{Ni}}$=204, 220, 236, and 250 MeV for the ^{58}Ni+^{60}Ni system and $E_{^{64}\mathrm{Ni}}$=250 MeV for the ^{62}Ni+^{64}Ni system. We used targets of ^{60,62}Ni of 30 μg/cm^2 which were evaporated on 10 μg/cm^2 carbon backing by bombarding the Ni isotope in a Ta crucible with an electron beam. The enrichments of ^{60,62}Ni targets were 99.08% and 96.64%, respectively. The outgoing particles were momentum analyzed in the magnetic spectrograph ENMA [4] and detected in the focal plane with a 100 cm long hybrid focal plane detector. In order to identify the mass number of Ni isotope, we measured additionally a time of flight (TOF) of the outgoing particle passing through the entrance position to the focal plane of the spectrograph whose flight pass length was about 8 m. A typical TOF spectrum obtained at θ_{lab}=25° from the ^{58}Ni+^{60}Ni reaction at E_{lab}=204 MeV is shown in Fig. 1. ^{58}Ni and ^{60}Ni with a charge state $q=22^+$ are clearly separated. The peak at a channel number of 280 corresponded to ^{58}Ni with $q=23^+$ elastically scattered from Ta impurities in the target which was amalgamated with the Ni isotope in a target evaporation process. A momentum spectrum of recoil ^{60}Ni obtained after setting a proper window in the TOF spectrum is shown in Fig. 1.

Angular distributions of elastic scattering for the ^{58}Ni+^{60}Ni and ^{62}Ni+^{64}Ni systems are shown in Figs. 2 and 3. The data were obtained by measuring charge state distributions on Ni ions at several angles. These were fitted with Sayer's semiempirical formula [6] to estimate the charge state distribution for the other angles. The data at backward angles larger than $\theta_{\mathrm{c.m.}}$=90° were obtained by detecting the forward recoiling Ni ions. A bell-shaped structure is clearly observed at the backward angles for both systems at E_{lab}=250 MeV which is due to the two-neutron transfer process.

The cross section for the elastic two-neutron transfer reaction can be written

$$\sigma(\theta)=|f_{\mathrm{el}}(\theta)+f_T(\pi-\theta)|^2 \tag{1}$$

for a zero spin system. Here $f_{\mathrm{el}}(\theta)$ and $f_T(\pi-\theta)$ are the amplitudes for elastic scattering and the two-neutron transfer

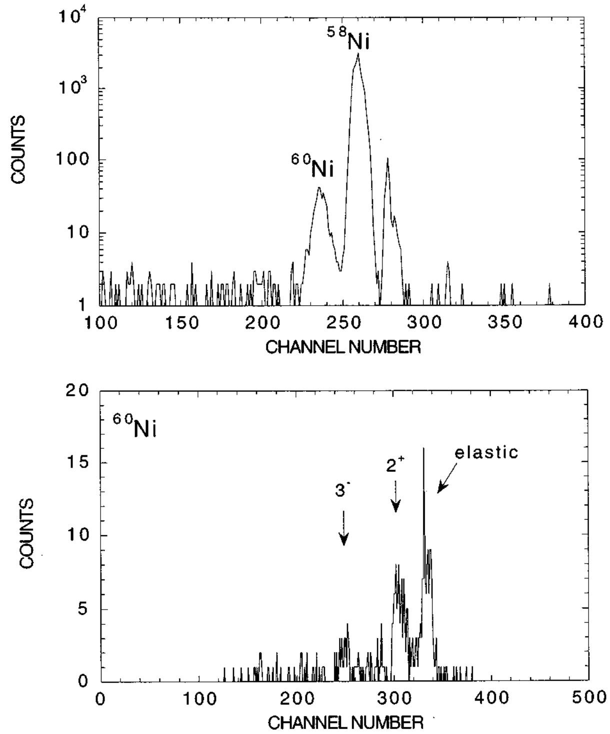

FIG. 1. A typical TOF spectrum (upper) and a momentum spectrum of ^{60}Ni (lower) obtained at $\theta_{\rm lab}=25°$ from the ^{58}Ni+^{60}Ni reaction at $E_{\rm lab}=204$ MeV. The peak at a channel number of 280 in the TOF spectrum is explained in the text.

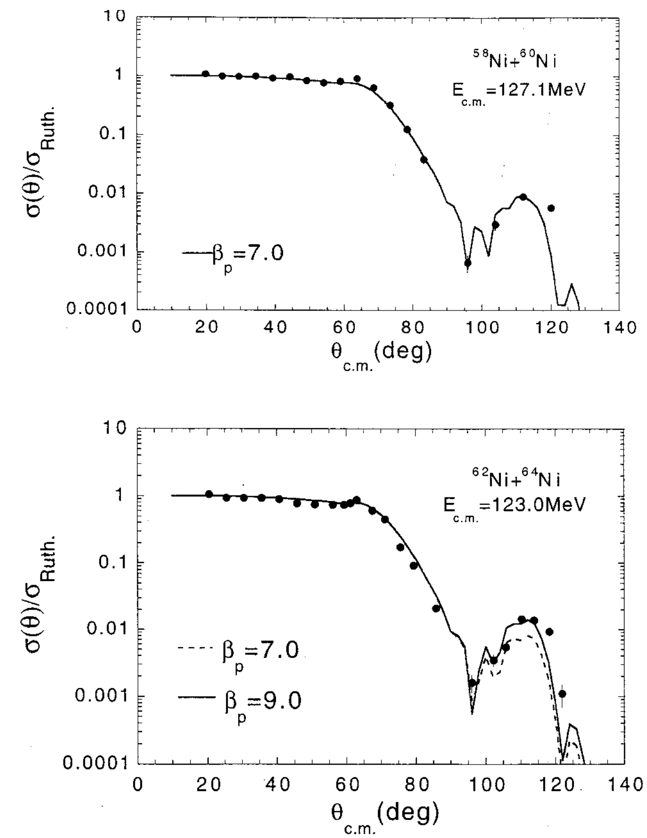

FIG. 3. Angular distributions of elastic two-neutron transfer reactions for ^{58}Ni+^{60}Ni (upper) and ^{62}Ni+^{64}Ni (lower) at $E_{\rm lab}=250$ MeV. Solid and dashed lines are the results of the theoretical calculations of Eq. (1).

reaction, respectively. We analyzed elastic scattering data by CC approaches with the code Ptolemy [5] in order to obtain the bare ion-ion potential. The nuclear ion-ion potential we use is based on the semiempirical expression given by Broglia and Winter [7] as

$$V(r)=-31.67 \ \text{MeV fm}^{-1}\frac{R_1R_2}{R_1+R_2} \times\{1+\exp[(r-R_1-R_2-\Delta R)/a]\}^{-1}, \qquad (2)$$

where $R_i=1.233A_i^{1/3}-0.98A_i^{-1/3}$ (fm) and $a=0.63$ fm. ΔR is adjusted in order to improve the fits. This potential has been used successfully in the analysis for subbarrier fusion cross sections of Ni+Ni systems [8]. We used the same geometry for the imaginary part and adjusted the strength W. The first-order couplings to inelastic excitations of collective 2_1^+ and 3_1^- states of both projectile and target were used in the coupling constant (CC) calculations whose deformation parameters were $\beta_2=0.18$ and $\beta_3=0.12$. The results of the calculations are shown by solid lines in Fig. 2. At $E_{\rm lab}=250$ MeV the experimental elastic scattering angular distribution up to $\theta_{\rm c.m.}=80°$ is reproduced well, while the data shows a bell-shaped curve at backward angles which is due to the interference between the elastic and transfer amplitudes. The interference effect is not clear at the other energies since the transfer amplitude becomes much smaller than the one of elastic scattering. The data are reproduced well with the energy-independent optical potential whose parameters are listed in Table I.

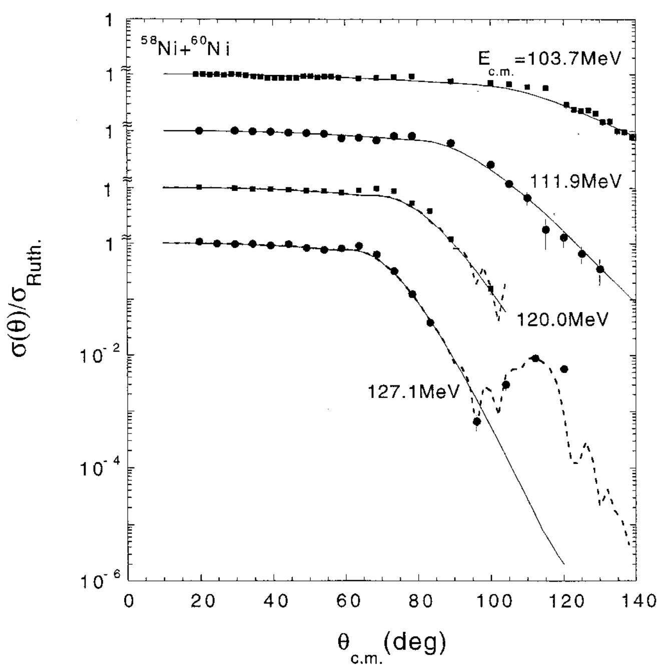

FIG. 2. Elastic scattering angular distributions of ^{58}Ni+^{60}Ni. The solid lines are the results of the CC calculations including the first-order couplings to inelastic excitations of collective 2_1^+ and 3_1^- states of both projectile and target. The dashed lines are the results including the pair transfer process.

Mermaz and Girod used a microscopic form factor for the pair exchange between identical cores for ^{32}S and ^{34}S. They took into account of only the simultaneous process and the sequential process which could be important was neglected [3]. We adopted here the macroscopic pair-transfer form factor introduced by Dasso and Pollarolo [9] in order to calcu-

TABLE I. Optical potential parameters and pair-deformation parameter β_p obtained from the present analyses.

Systems	$E_{c.m.}$ (MeV)	V (MeV)	W (MeV)	ΔR (fm)	β_p
$^{58}Ni+^{60}Ni$	103.7∼127.1	72.0	40.0	0.14	7.0
$^{62}Ni+^{64}Ni$	123.0	73.8	40.0	0.21	9.0

[a]Obtained at $E_{c.m.}=127.1$ MeV.

late the amplitude of the two-neutron transfer reaction. This picture exploits the identification of a local pair transition density whose magnitude can be related to the variation of the nuclear density as a function of particle number. The relevant scale is controlled by the pair-deformation parameter β_p, which plays the analogous role to the surface deformation parameter β_s. This quantity measures the collective character attained by the correlated superposition of two-particle and two-hole configurations that build up pair mode. Within this scheme the macroscopic pair-transfer form factor is given by

$$F(r)=\frac{\beta_p R}{3A}\,\frac{\delta U(r)}{\delta r.} \tag{3}$$

in terms of the ion-ion potential U, the radius R, and mass number A of the nucleus. For the case of superfluid systems, a large pair-transfer cross section is predicted by the Barden-Cooper-Schrieffer (BCS) approximation in which pair-deformation parameter amounts to $\beta_p=2\Delta/G$, where Δ and G are the gap parameter and the pairing strength, respectively [10].

The amplitude of the two-neutron transfer reaction was calculated with the code Ptolemy [5]. We used the bare optical potentials in Table I which were obtained from the CC analyses to elastic scattering. The pair deformation parameter β_p was searched in order to fit the data. Then the angular distribution for the elastic two-neutron transfer reaction was calculated by using Eq. (1). The calculated results are shown in Fig. 3. The data of the $^{58}Ni+^{60}Ni$ system is reproduced well with a pair-deformation parameter of $\beta_p=7.0$ (a solid line), while for the $^{62}Ni+^{64}Ni$ system the calculation with $\beta_p=7.0$ (a dashed line) underestimates the data. We fit the data by increasing the parameter to $\beta_p=9.0$ (a solid line). This result indicates that the pair-transfer cross section increases as the number of valence neutrons. In order to investigate the influence of the pair transfer process on the angular distribution at the lower energies, we made the calculations for the $^{58}Ni+^{60}Ni$ system with $\beta_p=7.0$. The results are shown by dashed lines in Fig. 2. The peak of the pair transfer strength with a cross section of about 1 mb/sr shifts to more forward angles where the elastic scattering strength becomes larger, as the incident energy becomes lower. As the result the interference between the elastic and pair transfer processes becomes less prominent at lower energies. The oscillatory pattern becomes visible at $E_{c.m.}=127.1$ MeV and 120.0 MeV in this figure.

In the BCS approximation mentioned above, the pair-deformation parameter is estimated as $\beta_p\approx 9.5$ from the relations of $\Delta\approx 12/A^{1/2}$ (MeV) [11] and $G\approx 20/A$ (MeV) [12]. Therefore, the $^{62}Ni+^{64}Ni$ system is seen to have a large pair-transfer cross section comparable to the one predicted for the g.s. BCS wave function. This result can suggest possible existence of the nuclear Josephson effect in $^{62}Ni+^{64}Ni$ system.

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