Multipair transfer in collisions between heavy nuclei

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On the basis of recent progress in our ability to predict cross sections for pair transfer, the interesting possibility of observing multipair transfer in collisions between heavy nuclei is reexamined. The results indicate that 3–4 pair transfer between pairing vibrational and pairing rotational states should be observable at low bombarding energies.

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I. INTRODUCTION

The possibility of observing the transfer of several correlated pairs of nucleons through the surface of contact of two superfluid heavy nuclei in a grazing collision was proposed many years ago [1, 2]. In this nuclear Josephson effect, the difference in the Fermi levels of the two colliding nuclei is not observable directly as an alternating current, since it will be folded with the time-dependent tunneling probability, and essentially gives rise to a damping of the net transfer probability observed after the collision.

Still, interesting oscillations in the cross section for multipair transfer could in principle be observed as a function of the distance of closest approach between the surfaces, which can be varied by changing the scattering angle. These oscillations arise because of the interference between the transfer amplitudes for different initial orientations in gauge space of the colliding nuclei, in much the same way as oscillations occur in the cross sections for Coulomb excitation of deformed nuclei [3, 4].

To make a realistic estimate of cross sections for multipair transfer has proved to be quite difficult because the tunneling, as in the Josephson junction, is caused by the mean field as a second-order effect and because of the difficulties in estimating the absorptive potential. Reliable estimates of the absorption are now available [5], and recently an effective energy-dependent interaction has been derived which reproduces pair-transfer cross sections from knowledge of the pair deformation parameters of the colliding nuclei [6, 7].

The present work has been prompted by a recent publication [8], where multipair transfer was estimated at high bombarding energies in a Glauber approximation. The calculations give, however, misleading results, mainly because of the neglect of the important recoil effect [9]. The best hope of observing multipair transfer between heavy nuclei is, in fact, at low bombarding energies.

In the following, we shall use the macroscopic description of pairing of Refs. [4, 10] together with the effective form factors (including recoil) [6], and the semiquantal scattering theory of Ref. [4] to estimate neutron-pair transfer in two cases: (1) a pairing vibrator colliding with a pairing rotor exemplified by ^{48}Ca on ^{124}Sn and (2) a collision between two pairing rotors exemplified by ^{124}Sn on ^{124}Sn.

II. PAIRING VIBRATOR ON PAIRING ROTOR

For the collision between a pairing vibrator and a pairing rotor we may according to Ref. [4] write the effective interaction

$$H = H_0 + V_{\text{eff}} \;, \tag{1}$$

where the intrinsic Hamiltonian of the two nuclei is given by[1]

$$H_0 = \hbar\omega_+ \,\Gamma^\dagger(+2)\,\Gamma(+2) + \hbar\omega_- \Gamma^\dagger(-2)\,\Gamma(-2) + \frac{\hbar^2 N_A^2}{2\Im} + \frac{2\lambda_A}{\hbar} N_A \;. \tag{2}$$

The pair-addition and pair-removal modes of the projectile are characterized by the frequencies

$$\omega_\pm = \omega_0 \pm \frac{2\lambda_a}{\hbar} \;, \tag{3}$$

while N_A indicates the number of pairs added to the target A. The effective interaction in the prior representation (α) is given by

$$V_{\text{eff}}(t) = G_{-2}^{\nu S(\alpha)}(t)\,\Gamma^\dagger(-2)\,e^{i\Phi'_A} + G_{-2}^{\nu P(\alpha)}(t)\,\Gamma(-2)\,e^{-i\Phi'_A} + G_{+2}^{\nu S(\alpha)}(t)\,\Gamma(+2)\,e^{i\Phi'_A} + G_{+2}^{\nu P(\alpha)}(t)\,\Gamma^\dagger(+2)\,e^{-i\Phi'_A} \;, \tag{4}$$

where Φ'_A indicates the orientation in gauge space of the pairing deformation of the target. The effective form factor for the stripping reaction associated with a pair removal is given by [6]

[1] In [4] there is an error of sign on the terms proportional to λ_A and λ_a.

$$G_{-2}^{\nu S(\alpha)}(t) = \frac{1}{\sqrt{4\pi}} \exp\left\{ i\bar{\sigma}^{(\alpha)}[k_{\|}(t)] + i\gamma_{\alpha\beta}(t)/\hbar - [\delta_y^{(\alpha)} k_\perp(t)/2]^2 \right\} \times \left(\alpha_{-2}^{(a)}\right)_0 \alpha_0^{(A)} \left(\frac{\partial\rho^{(a)}[r(t)-R_A]}{\partial N}\right)_- \frac{\partial\rho^{(A)}(R_A)}{\partial N} \left(\frac{R_a R_A}{R_a+R_A}\right)^2 L^{\nu S(\alpha)}(\tau). \quad (5)$$

The annihilation of a pair removal is associated with a pickup form factor $G_{-2}^{\nu P(\alpha)}$, which is related to the same stripping form factor (5) in the post representation.

The first factor in (5) is associated with the recoil effect, while $\left(\alpha_{-2}^{(a)}\right)_0$ is the zero-point vibrational amplitude for the pair-removal mode, the quantity $(\partial\rho^{(a)}/\partial N)_-$ being the change in density (per nucleon) by removing a pair of neutrons from the closed-shell nucleus a. The pairing rotor is correspondingly described by the pairing deformation parameter $\alpha_0^{(A)}$ and the associated pair density $\partial\rho^{(A)}/\partial N$. The quantities are defined in [6] (cf. also Sec. IV below). For pair addition we have a similar expression with $(\partial\rho^{(a)}/\partial N)_-$ substituted by $(\partial\rho^{(a)}/\partial N)_+$, indicating the change in density by the addition of a pair of neutrons.

In the following we neglect the "rotational" energy $\hbar^2 N_A^2/(2\Im)$ and use the conservation of neutrons ($N_A + n_{+2} - n_{-2} = 0$) to write

$$\begin{aligned} H_0 &= \hbar\left(\omega_0 + \frac{2(\lambda_a - \lambda_A)}{\hbar}\right) n_{+2} + \hbar\left(\omega_0 - \frac{2(\lambda_a - \lambda_A)}{\hbar}\right) n_{-2} \\ &= \hbar\omega_{+2}\,\Gamma^\dagger(+2)\,\Gamma(+2) + \hbar\omega_{-2}\,\Gamma^\dagger(-2)\,\Gamma(-2)\,, \end{aligned} \quad (6)$$

where $\hbar\omega_{+2}$ is the change in energy (negative Q value) for the pair-addition pickup reaction, while $\hbar\omega_{-2}$ is the corresponding negative Q value for the pair-removal reaction.

We write the S matrix in the semiclassical approximation

$$S = \exp\left\{ -\frac{i}{\hbar}\int_{-\infty}^{\infty} \widetilde{V}_{\rm eff}(t)\,dt - \frac{1}{2\hbar^2}\int_{-\infty}^{\infty} dt \int_{-\infty}^{t} dt' \left[\widetilde{V}_{\rm eff}(t), \widetilde{V}_{\rm eff}(t')\right] + \cdots \right\} \quad (7)$$

in powers of multiple commutators, where

$$\begin{aligned} \widetilde{V}_{\rm eff}(t) &= e^{iH_0t/\hbar}\, V_{\rm eff}(t)\, e^{-iH_0t/\hbar} \\ &= G_{-2}^{\nu S(\alpha)}(t)\, e^{i\omega_{-2}t}\,\Gamma^\dagger(-2)\, e^{i\Phi'_A} + G_{-2}^{\nu P(\alpha)}(t)\, e^{-i\omega_{-2}t}\,\Gamma(-2)\, e^{-i\Phi'_A} \\ &\quad + G_{+2}^{\nu S(\alpha)}(t)\, e^{-i\omega_{+2}t}\,\Gamma(+2)\, e^{i\Phi'_A} + G_{+2}^{\nu P(\alpha)}(t)\, e^{i\omega_{+2}t}\,\Gamma^\dagger(+2)\, e^{-i\Phi'_A}\,. \end{aligned} \quad (8)$$

The integrals in (7) are to be performed along a trajectory of relative motion of angular momentum $(l+\frac{1}{2})\hbar$. We find the commutator

$$\begin{aligned} [\widetilde{V}_{\rm eff}(t), \widetilde{V}_{\rm eff}(t')] &= -G_{-2}^{\nu S(\alpha)}(t)\, G_{-2}^{\nu P(\alpha)}(t')\, e^{i\omega_{-2}(t-t')} + G_{-2}^{\nu P(\alpha)}(t)\, G_{-2}^{\nu S(\alpha)}(t')\, e^{-i\omega_{-2}(t-t')} \\ &\quad + G_{+2}^{\nu S(\alpha)}(t)\, G_{+2}^{\nu P(\alpha)}(t')\, e^{-i\omega_{+2}(t-t')} - G_{+2}^{\nu P(\alpha)}(t)\, G_{+2}^{\nu S(\alpha)}(t')\, e^{i\omega_{+2}(t-t')}\,, \end{aligned} \quad (9)$$

which is a c-number implying that all higher-order commutators in (7) vanish. One may thus write the S matrix

$$\begin{aligned} S = e^{iG} \exp\{ & a_{-2}^{(1)}(l)\,\Gamma^\dagger(-2)\, e^{i\Phi'_A} - [a_{-2}^{(1)}(l)]^*\Gamma(-2)\, e^{-i\Phi'_A} \\ & + a_{+2}^{(1)}(l)\,\Gamma^\dagger(+2)\, e^{-i\Phi'_A} \\ & - [a_{+2}^{(1)}(l)]^*\Gamma(-2)\, e^{i\Phi'_A}\}\,, \end{aligned} \quad (10)$$

where $a_{-2}^{(1)}(l)$ is the first-order expression for the amplitude of the stripping reaction $a + A \to (a-2) + (A+2)$,

$$a_{-2}^{(1)}(l) = -\frac{i}{\hbar}\int_{-\infty}^{\infty} e^{i\omega_{-2}t}\, G_{-2}^{\nu S(\alpha)}(r(t), k_{\|}(t), k_\perp(t))dt, \quad (11)$$

while

$$a_{+2}^{(1)}(l) = -\frac{i}{\hbar}\int_{-\infty}^{\infty} e^{i\omega_{+2}t}\, G_{+2}^{\nu P(\alpha)}(r(t), k_{\|}(t), k_\perp(t))dt \quad (12)$$

is the first-order amplitude for the pickup reaction $a + A \to (a+2) + (A-2)$. In deriving (10) we used that the first-order amplitude for the pickup reaction inverse to (11) is given by $-[a_{-2}^{(1)}(l)]^*$ and for the stripping reaction inverse to (12) is given by $-[a_{+2}^{(1)}(l)]^*$.

The matrix element from the entrance channel

$$|0\rangle = |n_{+2} = n_{-2} = N_A = 0\rangle$$

to the final channel

$$|n_{+2}, n_{-2}, N_A = n_{-2} - n_{+2}\rangle$$

can now be evaluated by writing the S matrix in the form

$$S = e^{-|a^{(1)}_{-2}(l)|^2/2} \exp\left\{a^{(1)}_{-2}(l)\,\Gamma^\dagger(-2)\,e^{i\Phi'_A}\right\} \exp\left\{[a^{(1)}_{-2}(l)]^*\Gamma(-2)\,e^{-i\Phi'_A}\right\}$$
$$\times e^{-|a^{(1)}_{+2}(l)|^2/2} \exp\left\{a^{(1)}_{+2}(l)\,\Gamma^\dagger(+2)\,e^{-i\Phi'_A}\right\} \exp\left\{[a^{(1)}_{+2}(l)]^*\Gamma(+2)\,e^{i\Phi'_A}\right\} e^{iG} \qquad (13)$$

using the Baker-Hausdorff theorem. Since the wave function for the rotational state is given by

$$|N_A\rangle = \frac{e^{iN_A\Phi'_A}}{\sqrt{2\pi}}, \qquad (14)$$

we find the result

$$\langle n_{+2}, n_{-2}, N_A|S|0\rangle = \frac{[a^{(1)}_{+2}(l)]^{n_{+2}}}{\sqrt{n_{+2}!}}\, e^{-|a^{(1)}_{+2}(l)|^2/2} \times \frac{[a^{(1)}_{-2}(l)]^{n_{-2}}}{\sqrt{n_{-2}!}}\, e^{-|a^{(1)}_{-2}(l)|^2/2}\, e^{iG}, \qquad (15)$$

where $N_A = n_{-2} - n_{+2}$. The phase G, which arises from the commutator (9), is a real number quadratic in the amplitudes and acts as a polarization potential.

III. PAIRING ROTOR ON PAIRING ROTOR

The intrinsic Hamiltonian for a collision between two superfluid nuclei is

$$H_0 = \frac{\hbar^2 N_a^2}{2\Im_a} + \frac{2\lambda_a}{\hbar}N_a + \frac{\hbar^2 N_A^2}{2\Im_A} + \frac{2\lambda_A}{\hbar}N_A, \qquad (16)$$

while the interaction energy is given by [cf. Ref. [4], Eqs. (V.12.55) and (V.13.17)]

$$V_{\text{eff}}(t) = G^{\nu S(\alpha)}(t)\, e^{i(\Phi'_A-\Phi'_a)} + G^{\nu P(\alpha)}(t)\, e^{-i(\Phi'_A-\Phi'_a)}, \qquad (17)$$

where

$$G^{\nu S(\alpha)}(t) = \frac{1}{\sqrt{4\pi}} \exp\left\{i\bar\sigma^{(\alpha)}[k_\parallel(t)] + i\gamma_{\alpha\beta}(t)/\hbar - [\delta_y^{(\alpha)}k_\perp(t)/2]^2\right\}$$
$$\times \alpha_0^{(a)}\alpha_0^{(A)} \frac{\partial\rho^{(a)}[r(t)-R_A]}{\partial N} \frac{\partial\rho^{(A)}(R_A)}{\partial N} \left(\frac{R_aR_A}{R_a+R_A}\right)^2 L^{\nu S(\alpha)}(\tau). \qquad (18)$$

Neglecting the "rotational" energies, we use $N_A = -i\partial/\partial\Phi'_A$ and $N_a = -i\partial/\partial\Phi'_a$ to find

$$\widetilde V_{\text{eff}}(t) = e^{iH_0t/\hbar}\, V_{\text{eff}}(t)\, e^{-iH_0t/\hbar}$$
$$= G^{\nu S(\alpha)}(t)\, e^{i\omega t}\, e^{i(\Phi'_A-\Phi'_a)} + G^{\nu P(\alpha)}(t)\, e^{-i\omega t/\hbar}\, e^{-i(\Phi'_A-\Phi'_a)}, \qquad (19)$$

where $\hbar\omega = 2(\lambda_A - \lambda_a)$ is the negative Q value for the neutron-pair stripping reaction $a+A \to (a-2)+(A+2)$. Since (19) is a c-number, we find the S matrix

$$S = \exp\left\{-\frac{i}{\hbar}\int_{-\infty}^{\infty} \widetilde V_{\text{eff}}(t)\,dt\right\}$$
$$= \exp\left\{a^{(1)}\, e^{i(\Phi'_A-\Phi'_a)} - (a^{(1)})^* e^{-i(\Phi'_A-\Phi'_a)}\right\}, \qquad (20)$$

where $a^{(1)}$ is the first-order amplitude,

$$a^{(1)} = -\frac{i}{\hbar}\int_{-\infty}^{\infty} e^{i\omega t}\, G^{\nu S(\alpha)}(r(t), k_\parallel(t), k_\perp(t))\,dt. \qquad (21)$$

Using the wave functions (14) we find the matrix element ($\Phi' = \Phi'_A - \Phi'_a$)

$$\langle n_a = n, n_A = -n|S|0,0\rangle$$
$$= \int \frac{d\Phi'}{2\pi}\, e^{in\Phi'} \exp\left\{a^{(1)}\, e^{i\Phi'} - (a^{(1)})^* e^{-i\Phi'}\right\}$$
$$= e^{in(\pi - \arg a^{(1)})}\, J_n\left(2\left|a^{(1)}\right|\right), \qquad (22)$$

where J_n is the Bessel function [1].

IV. EXAMPLES

In the calculation of the expected cross sections for multipair transfer, we use the semiquantal scattering theory explained in Ref. [4]. For the cases at hand, where all nuclear spins are zero, the scattering amplitude for a given reaction $\alpha \to \beta$ can be written

$$f_{\alpha\to\beta}(\theta) = -\frac{i}{2k}\sum_l (2l+1)\, e^{i(\beta_l^\alpha+\beta_l^\beta)}\langle\beta|S|\alpha\rangle\, P_l(\cos\theta). \qquad (23)$$

The elastic scattering amplitude is

$$f_\alpha(\theta) = f^C(\theta) + f_\alpha^N(\theta), \qquad (24)$$

in terms of the Coulomb scattering amplitude $f^C(\theta)$ and the nuclear scattering amplitude

$$f_\alpha^N(\theta) = \frac{i}{2k}\sum_l (2l+1)\left(e^{2i\beta_l^C} - e^{2i\beta_l^\alpha}\right) P_l(\cos\theta), \qquad (25)$$

where β_l^α and β_l^β are the phase shifts in the entrance and exit channels for the optical potential $Z_aZ_Ae^2/r + U^N(r) + iW(r)$. The amplitudes (11), (12), and (21) entering in the S-matrix elements (15) and (22) should be evaluated along a trajectory with angular momentum $(l+\frac{1}{2})\hbar$ in the same complex optical potential.

As an example of the collision of a pairing vibrator on a pairing rotor, we have evaluated pair transfer in the collision of ^{48}Ca on ^{124}Sn at a bombarding energy of about 10% above the Coulomb barrier. For the real part of the nuclear potential U^N, we used the empirical ion-ion potential of Ref. [11]. The absorptive potential $W(r)$ was calculated on the basis of the depopulation due to transfer reactions and inelastic processes [5], and the result is given in Fig. 1 together with the calculated cross section for elastic scattering. In order to evaluate the amplitudes entering in the S matrix (15), we use the exponential behavior of the form factors and a parabolic expansion in time. The result is

$$a^{(1)}_{-2}(l) = -i\,\frac{\tau}{\sqrt{2}\hbar}\,\exp\left\{-\left(\frac{\delta_y^{(\alpha)}}{2}\,k_\perp(r_0)\right)^2\right\} \times F^{\nu S(\alpha)}_{-2}(r_0)\,\exp\left\{-\tfrac{1}{2}q^2_{-2}\right\}\,, \tag{26}$$

where the form factor

$$F^{\nu S(\alpha)}_{-2}(r_0) = \left(\alpha^{(a)}_{-2}\right)_0 \alpha_0^{(A)} \left(\frac{\partial\rho^{(a)}(r_0 - R_A)}{\partial N}\right)_- \times \frac{\partial\rho^{(A)}(R_A)}{\partial N}\left(\frac{R_a R_A}{R_a + R_A}\right)^2 L^{\nu S(\alpha)}(\tau) \tag{27}$$

is evaluated at the (complex) outer turning point r_0 in the optical potential. The collision time τ is given by

$$\tau = \sqrt{\frac{1}{\kappa\ddot{r}_0}}\,, \tag{28}$$

where $\ddot{r}_0$ is the (complex) acceleration at the turning point, and κ is the exponential slope of the form factor. For the quantity $L(\tau)$ we use the simple approximation

$$L(\tau) = \left(2^{3/2}\pi\right)^3\left(\frac{\hbar^2}{M}\right)^2 \frac{\tau}{\hbar}\,e^{-i3\pi/4}\,, \tag{29}$$

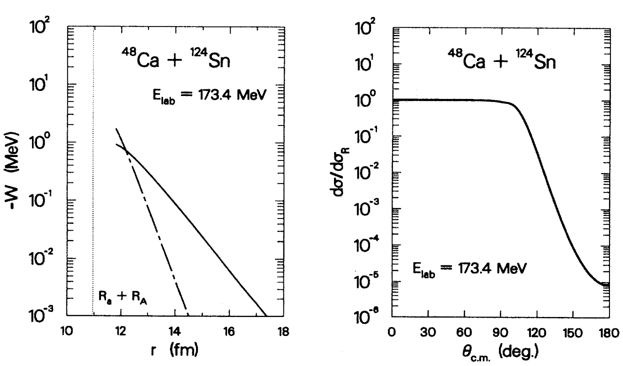

FIG. 1. Absorptive potentials and elastic angular distribution for ^{48}Ca on ^{124}Sn at 173.4 MeV. The absorptive potential $W(r)$ is calculated according to Ref. [5], and the contributions from single-particle transfer and from inelastic scattering are shown by the solid and dashed curves, respectively. The ratio of elastic to Rutherford cross sections is calculated with the real potential of Ref. [11], and Coulomb excitation is neglected.

while

$$q_{-2} = \frac{\tau}{\hbar}\left(-\hbar\omega_{-2} - Q_{\rm opt} + \Delta^{(\alpha)}\right)\,. \tag{30}$$

Other quantities involved are defined in Ref. [6].

The resulting amplitudes are given in Fig. 2 as a function of (the real part of) the distance of closest approach. It is seen that the amplitudes approach unity at small distances, indicating that multipair transfer may occur. At these distances, however, many other reactions take place, which compete with pair transfer, and the resulting cross sections are correspondingly reduced.

In order to calculate the cross sections, we use (23) with the S matrix (15). Within the approximations used above, the time-ordered integral in (7) with the commutator (9) can be evaluated leading to the phase G,

$$G = \tfrac{1}{2}\left[\left|a^{(1)}_{-2}(l, q_{-2} = 0)\right|^2 h(\mathrm{Re}\, q_{-2}) + \left|a^{(1)}_{+2}(l, q_{+2} = 0)\right|^2 h(\mathrm{Re}\, q_{+2})\right]\,, \tag{31}$$

where the amplitudes $a^{(1)}$ are given by (26) (with q_{-2} set equal to zero) and the corresponding expression for the pair-addition mode. The function h is related to the

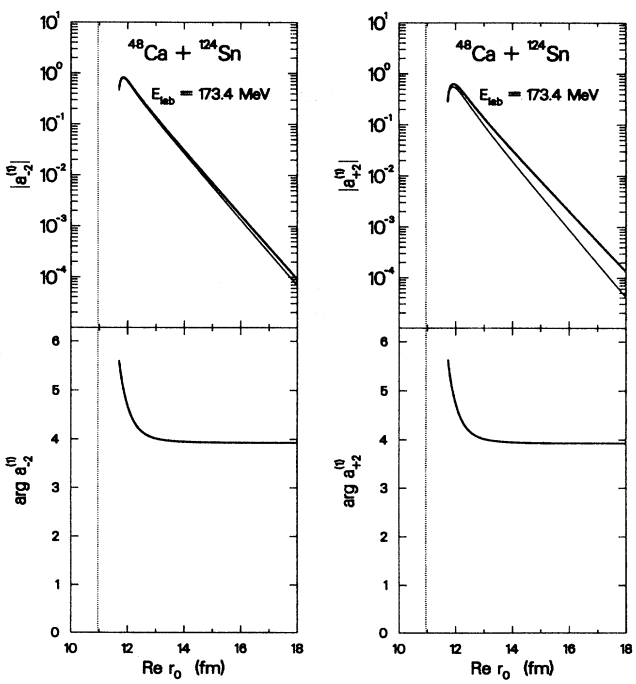

FIG. 2. Amplitudes $a^{(1)}_{-2}$ and $a^{(1)}_{+2}$ for pair transfer in the collision between ^{48}Ca and ^{124}Sn at 173.4 MeV. The quantities (11) and (12) are evaluated according to (26) on the basis of the parametrization given in Ref. [6]. The results are given as modulus and phase in the prior as well as in the post representations (thin line) as functions of (the real part of) the distance of closest approach, which is related to the angular momentum.

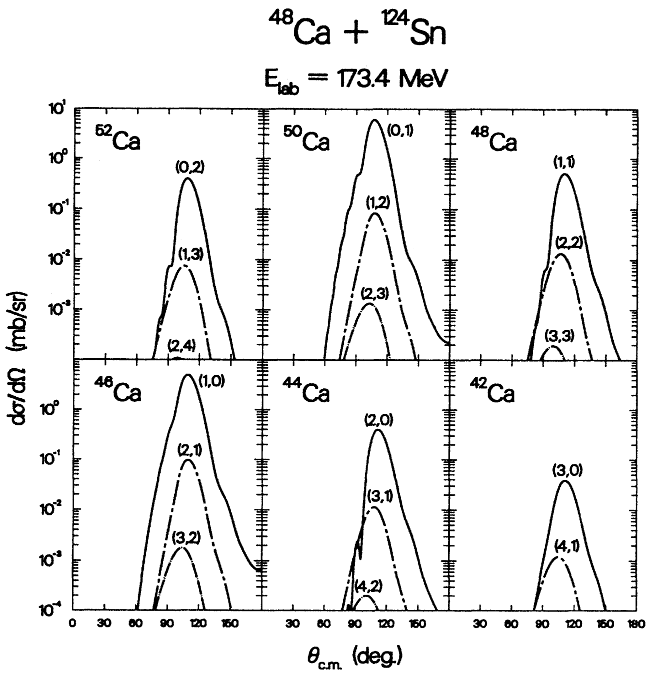

FIG. 3. Angular distributions for multipair transfer to the pairing vibrational states around ^{48}Ca in the collision of ^{48}Ca with ^{124}Sn at 173.4 MeV. The curves are labeled by (n_{-2}, n_{+2}), indicating the number of pair-removal and the number of pair-addition quanta. Each frame thus indicates the cross sections for the ground state and the excited 0^+ states in the final nucleus indicated. We have neglected the phase factor e^{iG}. For comparison the Rutherford cross section at 90° is 332 mb/sr.

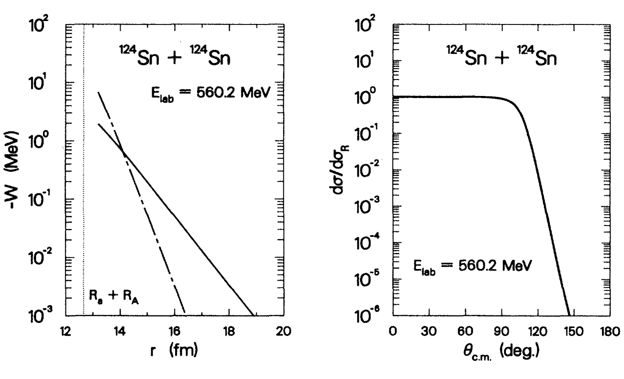

FIG. 4. Absorptive potentials and elastic angular distribution for ^{124}Sn on ^{124}Sn at 560.2 MeV. The absorptive potential $W(r)$ is calculated according to Ref. [5], and the contributions from single-particle transfer and from inelastic scattering are shown by the solid and dashed curves, respectively. The ratio of elastic to Rutherford cross sections is calculated with the real potential of Ref. [11], and Coulomb excitation is neglected.

Dawson integral and is defined in Ref. [4] [Eq. (V.10.9)].

In Fig. 3 we display the cross sections for the various states that can be reached by adding n_{-2} pair-removal modes and n_{+2} addition modes. Each frame thus refers to the ground state and excited 0^+ states in a given ejectile, except for the first frame, where the ground state is the entrance channel. Although the cross sections are large enough to make the observation of the transfer of up to three pairs feasible, it should be remembered that, at a grazing angle of about 110°, the total differential reaction cross section is much larger, making the detection of these ground state transitions quite difficult.

As an example of the collision between two pairing rotors, we consider the system ^{124}Sn + ^{124}Sn, again at

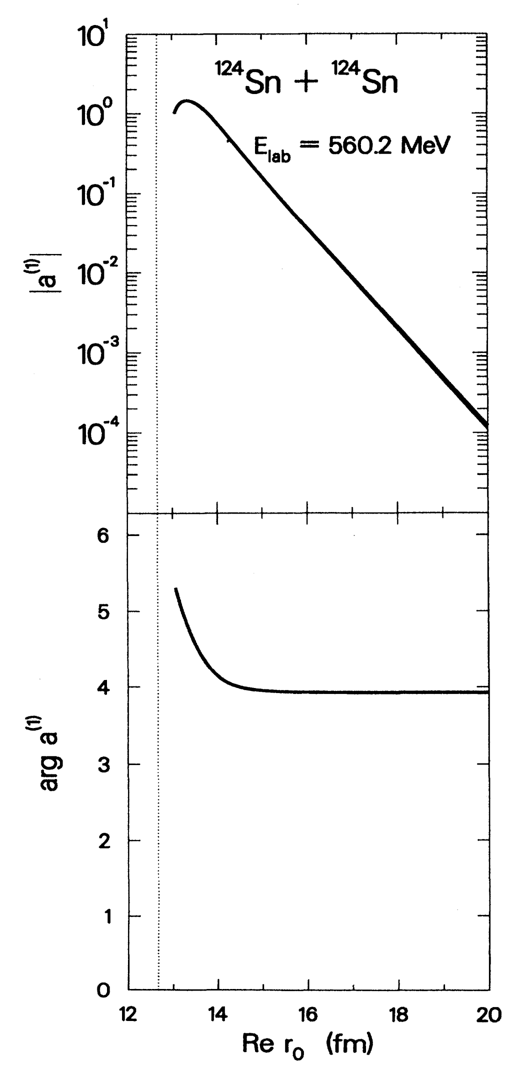

FIG. 5. Amplitude $a^{(1)}$ for pair transfer in the collision between two ^{124}Sn nuclei at 560.2 MeV. The quantity (21) is evaluated on the basis of the parametrization given in Ref. [6]. The results are given as modulus and phase in the prior as well as in the post representations (thin line) as functions of (the real part of) the distance of closest approach, which is related to the angular momentum.

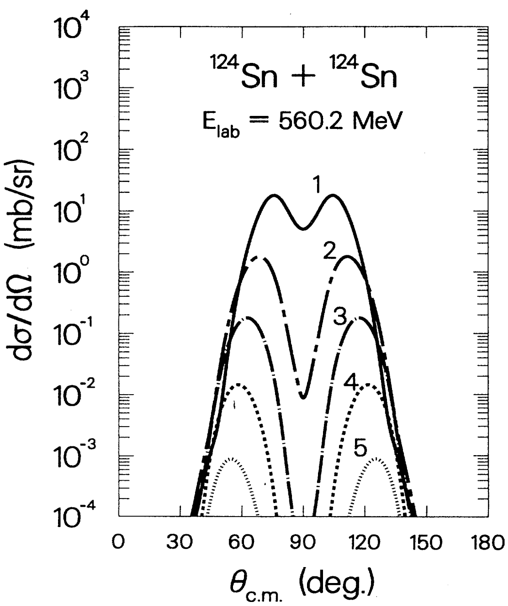

FIG. 6. Angular distributions for multipair transfer between the two superfluid ^{124}Sn nuclei in the collision of ^{124}Sn with ^{124}Sn at 560.2 MeV. The curves are labeled by the number of neutron pairs transferred in the final state. Because of the indistinguishability, the cross sections for pair addition at the scattering angle θ and the cross section for pair removal at the angle π-θ have been added, neglecting the interference effect. For comparison the Rutherford cross section at 90° is 413 mb/sr.

a bombarding energy of about 10% above the Coulomb barrier. The absorptive potential $W(r)$ was again calculated on the basis of the depopulation due to transfer reactions and inelastic processes [5], and the result is given in Fig. 4 together with the calculated cross section for elastic scattering.

To calculate the cross sections for multipair transfer, we use (23) and the expression (22) for the S matrix. The amplitude (21) can be evaluated by an expression quite similar to (26), and the results are displayed in Fig. 5. It is seen that in this case the magnitude of the first-order amplitude exceeds unity, and a characteristic inversion of the probability for one- and two-pair transfer is expected for such trajectories. In Fig. 6 we display the calculated angular distributions. In this figure we have included the fact that one cannot distinguish n-pair stripping at an angle θ from n-pair pickup at an angle $\pi - \theta$. We have, however, neglected the interference term, which would give rise to very rapid oscillations around 90°. Again the cross sections for transfer of up to four pairs are sizable, but diluted with other reactions, which in this case might include also contributions from deep-inelastic events.

It is difficult to estimate the accuracy of the above results. We judge that the main inaccuracy is associated with the estimate of the radial dependence of the neutron-pair density, where the empirical parametrization quoted in Ref. [6] was used. The form factor for ^{14}C on ^{124}Sn was compared to microscopic calculations in Ref. [7], and agreement was found to be within a factor of 2. For ^{48}Ca, proton-pair transfer compares quite accurately with experiments [6], but our estimate of the neutron-pair transfer form factor may well be uncertain by a factor of 2. The results also depend on our estimate of the absorptive potential, but it is judged that this is not the main uncertainty.

The expressions which we derived can easily be used on other systems that for experimental reasons may be more convenient.

V. CONCLUSION

In the present work we have made an estimate of the possibility of observing the multipair transfer in collisions between heavy nuclei, based on recent advances in our ability to predict cross sections for such reactions. The results exceed early estimates [12] by almost two orders of magnitude, and are so encouraging that a serious experimental effort should be made to observe this interesting effect. The main difficulty is associated with the large background of other reactions, but since almost all of these lead to products that emit gamma quanta, one might think of using an efficient gamma ball in anticoincidence to clean the particle spectra of the interesting ground-state transitions. In recent experiments [13] using this technique, the cross section for single-pair transfer in the reaction ^{118}Sn + ^{112}Sn has been measured. Our results of Fig. 6 are in reasonable agreement with these data.

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