Elastic scattering and particle exchanges between identical colliding cores

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Neutron-pair exchange and alpha exchange between two identical colliding cores, ^{32}S in the first case and ^{28}Si in the second case, are correctly described by a generalized Frahn and Venter parametrization of the elastic scattering phase shift. Possibility of a Josephson effect is discussed.

NUCLEAR REACTIONS Elastic scattering $^{34}S(^{32}S,^{32}S)$ and $^{28}Si(^{32}S,^{32}S)$; $E_{^{32}S}=77-97$ MeV; $\theta_{cm}=30°-150°$, $\Delta\theta=1°$; generalized phase shift analysis: particle exchange between identical cores.

The elastic scattering angular distributions of the ^{32}S beam on ^{34}S and ^{28}Si target nuclei had been analyzed taking into account the neutron pair exchange and the alpha exchange between the two identical colliding cores. The experimental data for the two targets had been obtained by the Strasbourg[1] group at three different incident energies —77, 90, and 97 MeV—using the ^{32}S beam of their MP tandem Van de Graaff accelerator.

To analyze these data, the most simple model was considered: To the usual total elastic scattering amplitude described by the formalism of Frahn and Venter,[2] we have added the backward angle quasielastic transfer amplitude also parametrized by Frahn and Venter.[3]

The cross section is then written[4]

$$\sigma(\theta)=|f_C(\theta)+f_N(\theta)+f_T(\pi-\theta)|^2 \ .$$

There is no spin factor since we are dealing with a complete zero spin system. $f_C(\theta)$ is the Coulomb scattering amplitude giving rise to a pure Rutherford cross section. $f_N(\theta)$ is the nuclear scattering amplitude:

$$f_N(\theta)=\frac{i}{2k}\sum_{l=0}^{\infty}(2l+1)(1-S_l)\,e^{2i\sigma_l}P_l\cos(\theta) \ .$$

The transfer amplitude is then written[3]

$$f_T(\pi-\theta)=\tau\frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)e^{2i\hat{\sigma}_l}\frac{\partial}{\partial l}\times \mathrm{Re}S_l'P_l[\cos(\pi-\theta)] \ .$$

τ is the transfer parameter proportional in some way to a spectroscopic amplitude times the ground state form factor.

The phase shifts S_l are parametrized by Woods-Saxon forms[2]:

$$\mathrm{Re}S_l=[1+\exp(l_g-l)/\Delta]^{-1} \ ,$$

$$\mathrm{Im}S_l=\mu\frac{\partial}{\partial l}[1+\exp(l_g-l)/\Delta]^{-1} \ ,$$

where l_g is the grazing wave number given by the following semiclassical relationship,[2]

$$l_g=kR\left(1-\frac{2\eta}{kR}\right)^{1/2} \ ,$$

and Δ the angular momentum width

$$\Delta=kd\left(1-\frac{\eta}{kR}\right)\left(1-\frac{2\eta}{kR}\right)^{-1/2} \ .$$

Consequently the elastic scattering amplitude is defined by three parameters: The reduced radius $r_0[R=r_0(A_T^{1/3}+A_p^{1/3})]$, the diffusivity d, and the amplitude of the phase shift imaginary part, μ. For the transfer amplitude $f_T(\pi-\theta)$, in order to obtain a better fit, we have taken a different diffusivity parameter d_T than the one of the elastic scattering. These two parameters can be slightly different since the former one corresponds to all surface reaction channels while the latter one corresponds to a particular channel.

For the transfer amplitude $f_T(\pi-\theta)$ we used the Coulomb plus the nuclear phase[5]:

$$\hat{\sigma}_l=\sigma_l^{\mathrm{Coul}}+\alpha[1+\exp(l-l_g)/\Delta]^{-1} \ .$$

If

$$\Delta\theta = \theta_{\text{Coul}} - \theta_{\text{nucl.rainbow}}$$

for $l = l_g$, than α can be expressed as $\alpha = 2\Delta\theta\Delta$.

Let us note also that the maximum of the transfer amplitude at the grazing wave is $\tau/4\Delta_T$ while the maximum of the imaginary part of the elastic scattering phase shift is $\mu/4\Delta$ also at the grazing wave.

Thus the elastic scattering cross section including the particle exchange term depends on only six quantities: r_0, d, $\mu/4\Delta$, d_T, $\Delta\theta$, and $\tau/4\Delta_T$.

An automatic search code ELTR (Ref. 6) had been written in order to reproduce the experimental elastic scattering data points. As usual, the experimental points, as well as the theoretical ones, have been divided by their pure Rutherford cross section values.

In Figs. 1 and 2 are presented the elastic scattering data. At high incident energies, 90 and 97 MeV, the backward angle rising structure is centered at $(180-\theta_C)^\circ$; θ_C is the forward angle where the elastic cross section begins to deviate from the pure Rutherford value. This behavior is a strong signature of partcle exchange between the two identical colliding cores, ^{32}S for the neutron pair exchange and ^{28}Si for the alpha exchange.[4]

In the present formalism used to reproduce the experimental data, speaking of neutron pair or alpha particle exchange is misleading; the formulas described only transfer of two or four particles without specifying anything about their relative motion.[3] Only a full optical model and distorted-wave Born approximation (DWBA) analysis including a microscopic form factor calculation would allow us to pin down the detailed mechanism. Nevertheless, due to the well known impossibility of calculating a DWBA amplitude for multinucleon transfer in absolute value,[7] such tedious analysis probably would be irrelevant.

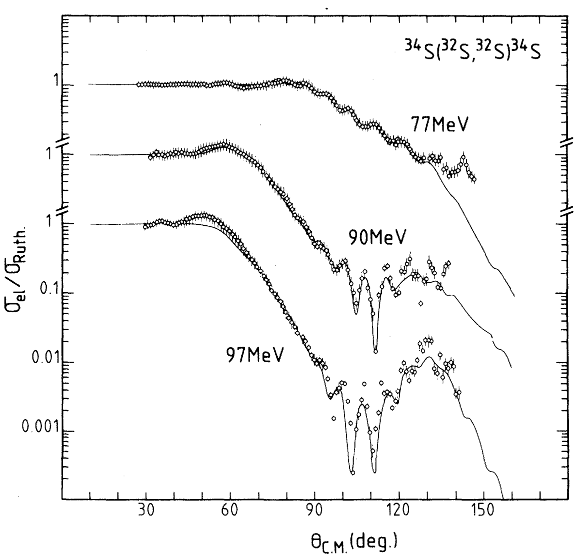

FIG. 1. Elastic scattering angular distributions of ^{32}S beam on ^{34}S target nucleus. The curves are generalized diffractional model fits obtained with the code ELTR (Ref. 6). The experimental data points are from the Strasbourg group (Ref. 1).

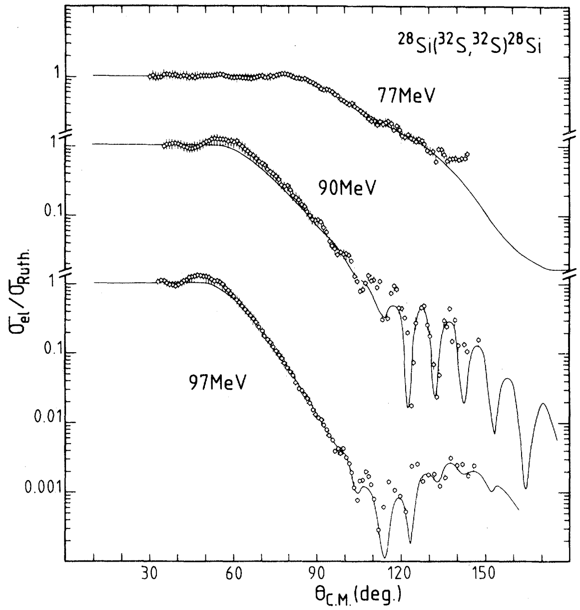

FIG. 2. Elastic scattering angular distributions of ^{32}S beam on ^{28}Si target nucleus. The curves are generalized diffractional model fits obtained with the code ELTR (Ref. 6). The experimental data points are from the Strasbourg group (Ref. 1).

In order to best fit the data, the diffractional model parameters, r_0, d, and $\mu/4\Delta$ of the usual elastic scattering had been determined by fitting the forward angle Fresnel pattern of the angular distribution; in a second step the parameters concerning the transfer amplitude d_T, $\Delta\theta$, and $\tau/4\Delta_T$ had been adjusted to reproduce the backward angles, and finally all six parameters had been readjusted to best fit the data points on the full angular range.

In Table I are presented the elastic and quasielastic diffractional model parameters used to compute the theoretical cross sections of Figs. 1 and 2. For the elastic scattering concerning the ^{32}S and ^{34}S system, the elastic parameter r_0, d, $\mu/4\Delta$ have very usual values,[5] the reduced radius r_0 is decreasing as the incident energy increases which is an expected behavior.[8] For the exchange term the transfer parameter $\tau/4\Delta_T$ is much smaller than $\mu/4\Delta$ which is responsible for all the surface reactions in an elementary formalism of direct transfer reaction.[3] In case of ^{32}S + ^{28}Si, the particle exchange parameters are not

TABLE I. Elastic and quasielastic diffractional model parameters.

Energy (MeV)	$\chi^{2\,a}$	r_0 (fm)	d (fm)	$\frac{\mu}{4\Delta}$	d_T (fm)	$\Delta\theta$ (rad)	$\frac{\tau}{4\Delta_T}$
				$^{34}S(^{32}S,^{32}S)$			
77	5.14	1.6257	0.3586	0.5106	0.4000	0.5781	0.041 80
90	5.68	1.5891	0.3776	0.4001	0.3704	0.4914	0.081 33
97	7.96	1.5882	0.5690	0.1488	0.5975	0.3277	0.038 40
				$^{28}Si(^{32}S,^{32}S)$			
77	1.968	1.6168	0.3159	0.4833	0.5000	0.4246	0.021 37
90	6.314	1.5914	0.6071	0.1325	0.4907	0.6155	0.017 88
97	5.291	1.5779	0.5639	0.1635	0.4201	0.5715	0.020 30

[a]10% error bars.

significant at 77 MeV since already a good fit can be obtained only with the elastic diffractional model alone. For the 90 and 97 MeV, it can be seen that $\tau/4\Delta_T$ is a significant part of $\mu/4\Delta$ of the imaginary part of the elastic scattering phase shift.

The general agreement shows that, for this rather heavy system, the particle exchange is an important process. It would be of great interest to perform a theoretical nuclear structure calculation of such a $\tau/4\Delta_T$ transfer parameter in order to investigate whether or not we are dealing with some supraconductivity effect for this particle exchange term.

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