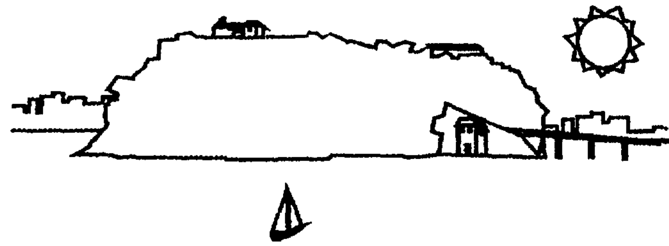

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Stripping of two protons and one alpha particle transfer reactions for 16 O+A Sm and their influence on the fusion cross section

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"STRIPPING OF TWO PROTONS AND ONE ALPHA PARTICLE TRANSFER REACTIONS FOR $^{16}O + {}^{A}Sm$ AND THEIR INFLUENCE ON THE FUSION CROSS SECTION"

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Abstract

Transfer cross section angular distribution data for the stripping of two protons and one alpha particle are studied for the $^{16}O + {}^{A}Sm$ systems (A = 144, 148, 150, 152 and 154), at near barrier energies. A semiclassical formalism is used to derive the corresponding transfer form factors. For only one channel the analysis shows evidences that the transfer reaction mechanism at backward angles , corresponding to small distances, may behave as a multi-step process leading to fusion. Simplified coupled channel calculations including transfer channels are performed for the study of the sub-barrier fusion of these systems. The influence of short distance transfer reactions on the fusion is discussed.

PACS: 125.70 Cd ; 25.70 Jj

1- Introduction

The transfer of few nucleons in reactions involving heavy ions at energies close to the Coulomb barrier has being investigated in the last years, not just by the interest of the study of this particular process, but also by the importance of its connection with other reaction mechanisms such as the fusion. There are some evidences that transfer channels with large Q-values or large cross sections may couple with the fusion and contribute to its enhancement at sub-barrier energies. However, one has to be very careful when one tries to relate fusion and transfer reactions, because they take place at different distances. Transfer reactions which occur at distances not so far from the position of the Coulomb barrier are the natural candidates to behave as doorway to fusion in a multi-step process, specially the channels which have the Coulomb barrier lowered after the first step transfer. The knowledge of the transfer form factors is, therefore, fundamental to this study. However, although there are many available data on fusion cross sections, there are few data in the literature on angular distributions of transfer channels, particularly at large backward angles, corresponding to small distances of closest approach.

Coupled channel calculations are widely used in the study of the sub-barrier fusion problem. Low-lying states collective couplings are used in all the calculations, and usually only when these couplings are not enough to explain the experimental fusion excitation function one tries to couple additional transfer channels. We were very interested in performing coupled channel calculations including transfer channels for systems where the fusion cross section had already been understood in terms of inelastic channels, in order to verify whether the additional couplings would overpredict the fusion data or give no extra enhancement.

G. Marchesseau [1] has measured the transfer reactions (^{16}O, ^{12}C) and (^{16}O, ^{14}C) on all the stable even samarium isotopes, at E_{lab} = 66 MeV (slightly lower than the Coulomb barriers). A Q-value analysis shows that the stripping of one proton (-1p), of two protons (-2p) and of the one alpha (-1α) channels are the most favorable transfer channels for those systems. Those unpublished data are important for the complete analysis of the fusion, transfer and elastic scattering processes concerning the systems ^{16}O+even Samarium isotopes. In section 2 of this paper we make considerations on the available data; in section 3 we discuss the semiclassical formalism [2,3] used to study the transfer reactions; in section 4 we show the results of the transfer data analysis and the derivation of the transfer form factors; in section 5 fusion excitation functions are studied by simplified coupled channel calculations, including those transfer channels.

2- Data Available and Q-Values Considerations

Fusion excitation functions are available for the ^{16}O + ^{A}Sm systems (A = 144, 148, 150, 152 and 154) [4,5,6], as well as elastic scattering data at near barrier energies [1,7,8,9]. Transfer reactions for the 144 and 154 samarium isotopes have been measured [9,10] with just ΔZ identification. This set of systems is a very interesting one to be studied, because the double magic projectile reacts with target nuclei which span a large range of deformation parameters.

In this paper we analyse the unpublished data [1] obtained by Marchesseau in 1978, who performed his experiments at the Tandem of Saclay, for the stripping of two protons and of one alpha particle. Marchesseau has also identified the stripping of one proton channel, but the data for the angular distribution analysis were not available and therefore we have restricted ourselves to the study of the two mentioned channels. The detector systems used to identify the transfer channels consisted of three surface barrier silicon telescopes E X ΔE, with thicknesses of 20 μm (ΔE) and 100 μm (E). The energy resolution of the order of 500 KeV was enough to separate the elastic and first inelastic peaks for the ^{144}Sm and ^{148}Sm targets, but not for the other isotopes. The angular distributions were taken up to $\theta = 170^0$. The beam energy was $E_{lab} = 66$ MeV, slightly below the Coulomb barriers of these systems, which vary from 66.9 MeV to 68.4 MeV for the ^{154}Sm and ^{144}Sm targets, respectively.

All the transfer channels of one and two particles, both pick-up and stripping reactions, for the five systems studied, have negative ground state Q-values (Q_{gg}). The matching conditions required for a heavy ion transfer reaction [11] imply that those reactions populate states in the final nuclei that are located in a Gaussian-shaped Q-window of the form $\exp[-(Q - Q_{opt})^2 / \Gamma^2]$, where the optimum Q-value is given by the expression:

$$Q_{opt} = E_{cm}[(z_f Z_f / z_i Z_i) - 1] \qquad (1),$$

where i and f stand for the entrance and exit channels, respectively. For this value the distances of closest approach for the entrance and exit channels are equal. This is equivalent of saying that

$$Q_{opt} = Q_{gg} - E^*_{opt} \qquad (2),$$

where E_{opt} is the optimum excitation energy of the final state, and the matching conditions require that

$$E^*_{opt} = Q_{gg} - Q_{opt} \geq 0 \qquad (3).$$

If one consider that a transfer channel may be a doorway to fusion, and that following the transfer of nucleons the resulting pair of nuclei will fuse, one has to take into account the variation of the Coulomb barrier in order to know whether the first step transfer process will help to enhance the fusion probability or not. Therefore, it is useful to define a quantity called effective Q-value, by the relation

$$Q_{eff} = Q_{gg} + (V^i_B - V^f_B) \qquad (4),$$

where V^i_B and V^f_B are the Coulomb barriers of the initial and intermediate systems, respectively. Transfer channels with positive Q_{eff} are good candidates to enhance the fusion cross section. For reactions with projectiles lighter than targets, the stripping of charged particles have $Q_{eff} > Q_{gg}$.

Table I shows the Q_{gg}, Q_{opt}, E^*_{opt} and Q_{eff} values for the most favorable transfer channels, concerning the matching conditions for the first-step transfer ($E^*_{opt} \geq 0$) and for the fusion following the transfer ($Q_{eff} > 0$). One can see that the values of E^*_{opt} and Q_{opt} are very similar. Due to the width of the Q-window, typically of the order of 4 MeV, channels with small negative E^*_{opt} and Q_{eff} values may also be reasonably matched. One can see that the -2p and -1α channels are the most favorable channels for the five systems. Those are the channels for which the data are analysed in this paper. The -1p is the only other favorable channel which could be considered. Figure 1 shows the experimental Q spectra obtained by Marcheseau [1], which are in agreement with the values shown in table 1.

3- Transfer Reaction Analysis

In the following, transfer reactions are studied by the use of a semiclassical formalism [2,3], from which the form factors can be derived, with the additional use of the elastic scattering data. The code SBTRANS is used [12] to perform the calculations. Due to the simplifications and approximations used in this formalism, the deduced transfer form factors should be regarded as "semi-quantitative" values.

For small values of transfer cross sections σ_{tr}, compared with Rutherford cross sections σ_R, the differential transfer cross section can be factorized in first order as

$$d\sigma_{tr}/d\Omega = P_{tr}(d\sigma_R/d\Omega) \qquad (5),$$

where the transfer probability is given by

$$P_{tr} = \left\{(1/\hbar)\int_{-\infty}^{+\infty} F(r(t))\exp[it(Q-Q_{opt})/\hbar]dt\right\}^2 \qquad (6).$$

At energies below the Coulomb barrier, the following ansatz for the form factor is made [2,3]:

$$F(r) = F_0(\varphi(r)/r)\exp[-\alpha(r-D_c)] \qquad (7),$$

where $D_c = d_c(A_1^{1/3} + A_2^{1/3})$ is the core distance, d_c is its reduced distance, α is the slope factor, F_0 is a normalization factor and $\varphi(r)$ is a smooth function which limits $F(r)$ towards a maximum close to the Coulomb barrier position.

In a general situation an absorption probability is defined as

$$P_a(\theta) = 1 - d\sigma_{el}/d\sigma_R \qquad (8).$$

This probabilty depends on the distance of closest approach $D(\theta_{cm})$, defined as

$$D(\theta_{cm}) = (z_i Z_t e^2 / 2 E_{cm})[1 + (1/sin(\theta_{cm}/2)]$$ (9),

and it can be parametrized, neglecting rainbow effects, as

$$P_a(D) = \begin{cases} 0, D > D_a \\ 1 - [(D - D_c)/(D_a - D_c)]^{s(Da - Dc)}, D_c \leq D \leq D_a \end{cases}$$ (10),

where $D_a = d_a(A_1^{1/3} + A_2^{1/3})$ is the absorption distance parameter and s is the absorption slope at D_a. The parameters d_a, d_c (reduced distances) and s can be derived from the experimental elastic scattering angular distributions.

As the orbits remain roughly outside the range of nuclear forces, only the exponential tails of the form factors are relevant to the following analysis. The form factor integral (6) is calculated along a Rutherford orbit, corrected for the influence of the nuclear potential for reduced distances smaller than 1.6 fm.

Within this simple picture, the transfer probability can be written, in terms of the distance of closest approach [2,11], as

$$P_{tr} / sin(\theta / 2) = A \exp(-2\alpha D)$$ (11).

The slope parameters α of the form factors can be extracted experimentally from the plot of the logaritm of the transfer probability versus the distance of closest approach. Those values may be calculated by the expression $\alpha = (2\mu E_B / \hbar^2)^{1/2}$, where E_B and μ are the binding energy and reduced mass, and by the introduction of many corrections which are required , for example, to take into account the dependence on the excitation energies, the Coulomb field of the aproaching nuclei and the Coulomb barrier for charged particle transfer channels.

The normalization factors F_0 are derived from the fits of the Q-integrated experimental angular distributions at small angles (or large distances of closest approach), when these reaction mechanisms are supposed to be simple one-step processes, and the first order approximation is valid.

4- Results

Figure 2 shows, as example, the plot of the elastic scattering data versus distance of closest approach for the $^{16}O + ^{144}Sm$ system. The same value of d_c = 1.48 fm was derived for the three systems for which enough data were available (144, 148 and 152 isotopes), and we have assumed the same value for the other two systems. The reduced absorption distance d_a increases with the deformation of the target, as can be seen from table 2.

The parameters α can be derived directly from the slope of ln $[P_{tr}/sin(\theta/2)]$ versus distance of closest approach, as can be seen from equation (11). Figures 3-a to 3-e show the plot for the -2p and -1α channels for the five different systems. The solid lines are the least-square fits to all the data points. Table 3 shows the derived and predicted values for the slope parameters for the ten channels studied. The predictions of the semiclassical formalism consider a sequential transfer of nucleons, and consequently use the approximations $\alpha_{2p} \cong 2\,\alpha_{1p}$, $\alpha_{2n} = 2\,\alpha_{1n}$, $\alpha_{2p2n} \cong \alpha_{2p} + \alpha_{2n}$.

One can see a good agreement between the derived and predicted values of the slope parameters for the -2p channels, except for the ^{144}Sm target, where the derived value is almost twice the experimental one. Although there is a smooth continuous rise in the value of the predicted slope parameters, the derived values do not show this trend. A possible explanation for that would be the transfer to highly excited states, where the nucleons are loosely bound, in the two most deformed Sm isotopes, leading to smaller slope parameters. Deviations from the predictions of the semiclassical theories for the slope parameters, known as "slope anomaly", as the one for the ^{144}Sm target, have been observed for two nucleon transfer of other systems [13, 14, 15], and still have to be understood.

The derived values of the slope parameters for -1α channels are not too different from the ones derived for the -2p channels, and consequently are roughly the half of the predicted values when one considers a sequential transfer of four nucleons. This shows quite clearly that the four nucleons are transfered as a cluster of one alpha particle for the five systems. The correlation between the nucleons changes drastically the binding energy in the nucleus, since the alpha particle has itself a binding energy of 28 MeV.

The experimental transfer angular distributions can be compared with the theoretical predictions obtained by the code SBTRANS and the derived values of the core distance and slope parameters. As the widths of the Q-windows are too broad and the energy resolution is limited, one can not study the transfer to isolated states, but just the overall transfer strenght. The normalization factor F_0 is obtained by fitting the experimental angular distribution at small angles (large distances) where the reaction mechanism is simple and transfer reactions are predominant.

Figures 4-a to 4-j show the experimental transfer angular distributions for the -2p and -1α chanels for the five systems studied. The full curves are the predictions of the semiclassical calculations (SBTRANS), normalized at small angles.

The angular distributions could be fitted for the whole angular range for seven of the ten transfer channels studied (-2p and -1α for the ^{148,150,152} Sm targets and -1α for the ^{144}Sm). For the two channels with the ^{154}Sm target, there are under-predictions of the data at backward angles when the extrapolated reduced core distance of 1.48 fm is used, but good fits are obtained when this value is decreased to 1.46 fm, as can be seen by the dashed curves in the figures. Finally, for the -2p channel for the ^{144}Sm target, the angular distribution can be fitted up to $\theta = 150^0$, but for more backward angles there is a "missing" experimental cross section.

One might interpret these results by saying that at large distances, transfer is a simple direct one-step process, but when there is a "missing" cross section at backward angles, part of the flux that would react as a transfer actually goes to fusion in a multi-step process. If that interpretation is correct, the channels for which this happens should increase the fusion cross section when we perform coupled channel calculations.

5- Simplified Coupled Channel Calculations

From the previous transfer data analysis, one could expect some fusion cross section enhancement only for the coupling of the -2p channel for the $^{16}O + {}^{144}Sm$ system. Table 4 shows the experimental fusion, transfer and "missing transfer" cross sections for the five systems at E_{lab} = 66 MeV. One can see that the fusion cross section is much larger, at this energy, than the transfer and "missing transfer" cross sections, the later corresponding to only 3.7% of the fusion. For the fixed E_{lab} = 66 MeV, corresponding to a smoothly increasing of the E_{cm}/V_B value as the target deformation increases, the transfer cross sections for the -2p channel increase with the target deformation, but for the -1α channels they are almost constant.

In order to study the influence of the transfer reaction process on the fusion cross section for these systems, simplified coupled channel calculations were performed, using of the code CCFUS [16]. For the systems studied, inelastic channels (quadrupole, octopole and hexadecapole vibrations and deformations) were previously found to be able to account for the observed experimental sub-barrier fusion enhancements. We have used the derived transfer form factors to couple, in addition to the inelastic channels, the -2p and -1α transfer channels.

Table 5 shows the results of the simplified coupled channel calculations, considering transfer channels, in terms of the asymptotic energy shift, defined as the shift, at the low energy limit, of the fusion excitation function when the coupling is considered. The experimental fusion shift is the value needed in the one-dimensional barrier penetration model calculation, in order to fit the data at the low energy region. One can see that the effect of the coupling is negligible when compared with the experimental fusion energy shift. These results are in agreement with our expectations, because even for the -2p channel for the $^{16}O + {}^{144}Sm$ system, where there is a "missing transfer" cross section, its value is too small compared with the fusion, in order to lead to an important fusion enhancement. However, it is important to remark that the contribution of the coupling of transfer channels for the fusion of the $^{16}O + {}^{144}Sm$ system, although small, is of the same magnitude as the ones from target vibrations.

When one couples transfer channels to fusion, one of the input parameters is the Q-value of the reaction. If one uses the Q_{gg} value, as we have done in the calculations, describer above, an under-estimation of the effect of the coupling may be obtained for those channels which have the Coulomb barrier lowered after the first-step process, such as the multi-charged particle stripping channels for projectiles lighter than the target. However, if one uses the Q_{eff} value, an over-estimation is obtained, because the barrier is lowered only after the first step has taken place. A drastic example of that effect can be seen in figure 5, for the coupling of the -1α channel on the fusion of the $^{16}O + {}^{154}Sm$ system, where an asymptotic shift of 2,35 MeV is obtained by this coupling, for a system where inelastic channel couplings could be able to account for the full experimental fusion enhancement.

6- Summary and Conclusions

Stripping transfer reactions in the ^{16}O + ^{A}Sm systems (A = 144, 148, 150, 152, 154) were studied at a bombarding energy slightly lower than the Coulomb barriers. The transfer probabilities versus distance of closest approach and the angular distributions of the two most favorable transfer channels for the five systems, the -2p and -1 channels, were analysed by a semiclassical formalism. The slope parameters of the transfer form factors, derived from the experimental data, were found to be in agreement with the semiclassical theory for the -2p channels, except for the ^{16}O + ^{144}Sm, where a "slope anomaly" is observed; for the -1 channels, the predictions which assume a sequential transfer of four nucleons do not agree with the data, showing that the a direct transfer occur for the cluster of one alpha particle. The core distances for those systems were extracted from the elastic scattering data and were used to derive the transfer form factors. The experimental transfer angular distributions could be well reproduced by the theory, except of the -2p channel for the ^{16}O + ^{144}Sm system, where a "missing cross section" was observed for large backward angles, corresponding to short distance transfer processes acting as doorway to the fusion. Simplified coupled channel calculations were performed for the transfer channels studied, and their contributions to the fusion cross section enhancements were found to be negligible, in agreement with previous calculations where the fusion behavior could be explained by the coupling of just inelastic channels. Only for the spherical ^{144}Sm target, with small fusion cross section enhancement, the contribution of transfer channels is of the same magnitude as those from inelastic channels.

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Table 1. Ground State Q-Values (Q_{gg}), Optimum Q-Values (Q_{opt}), Optimum Excitation Energies (E^{*}_{opt}) and Effective Q-Values (Q_{opt}) for the most favorable transfer channels for the ^{16}O + ^{A}Sm systems.

Target/Channel	Q_{gg}(MeV)	Q_{opt}(MeV)	E^{*}_{opt}(MeV)	Q_{eff}(MeV)
^{144}Sm				
-1p	-8.8	-6.6	-2.2	-2.3
-2p	-13.6	-13.4	-0.2	-0.3
-1α	-10.5	-13.4	+2.9	+2.2
^{148}Sm				
-1p	-8.0	-6.6	-1.2	-1.4
-2p	-11.3	-13.4	+2.1	+1.9
-1α	-9.4	-13.4	+4.1	+3.3
^{150}Sm				
-1p	-7.2	-6.6	+0.6	+0.4
-2p	-10.1	-13.5	+3.4	+3.1
-1α	-8.1	-13.5	+5.4	+4.5
+2n	-1.7	0	-1.7	-1.1
^{152}Sm				
-1p	-6.2	-6.6	+0.4	+0.2
-2p	-8.8	-13.5	+4.7	+4.4
-1α	-7.0	-13.5	+6.5	+5.6
+2n	-1.7	0	-1.7	-1.1
^{154}Sm				
-1p	-5.5	-6.6	+1.2	+0.9
-2p	-7.7	-13.5	+5.8	+5.4
-1α	-6.5	-13.5	+7.0	+6.0
+2n	-1.7	0	-1.7	-1.1

Table 2. Reduced core and absorption distances derived from elastic scattering data.

Target	d_c(fm)	d_a(fm)
^{144}Sm	1.48	1.63
^{148}Sm	1.48	1.68
^{150}Sm	(1.48)	(1.74)
^{152}Sm	1.48	1.82
^{154}Sm	(1.48)	(1.92)

Figures in brackets correspond to interpolated and extrapolated valvues.

Table 3. Slope parameter of the transfer form factor, deduced from the transfer probability versus distance of closest approach plots and predicted by the semiclassical formalism for sequential transfer.

A of the target	-2p channel		-1α channel	
	$\alpha_{the}(fm)^{-1}$	$\alpha_{exp}(fm)^{-1}$	$\alpha_{the}(fm)^{-1}$	$\alpha_{exp}(fm)^{-1}$
144	0.93	1.81	2.13	1.76
148	1.13	1.15	2.23	1.24
150	1.20	1.17	2.33	1.24
152	1.26	1.12	2.41	0.99
154	1.32	1.00	2.44	1.05

Table 4. Fusion, Transfer and "Missing Transfer" Cross Sections for the ^{16}O + ^{A}Sm Systems, at E_{lab} = 66 MeV.

Cross Section (mb)	^{144}Sm	^{148}Sm	^{150}Sm	^{152}Sm	^{154}Sm
fusion	13.6	42.0	60.0	64.0	80.0
tr.(-2p)	2.1	4.1	5.1	6.3	8.2
tr.(-1α)	3.5	3.7	3.5	3.9	4.0
"missing" (-2p)	0.5	-	-	-	-

Table 5. Asymptotic Energy Shifts on the Fusion Excitation Functions, due to the Coupling of Transfer Channels and the Total Experimental Shift.

target	ΔE(-2p) (MeV)	ΔE(-1α) (MeV)	ΔE(fusion) (MeV)
^{144}Sm	0.035	0.041	0.2
^{148}Sm	0.012	0.014	2.2
^{150}Sm	0.017	0.016	2.8
^{152}Sm	0.025	0.012	3.4
^{154}Sm	0.040	0.026	3.8

FIGURE CAPTIONS

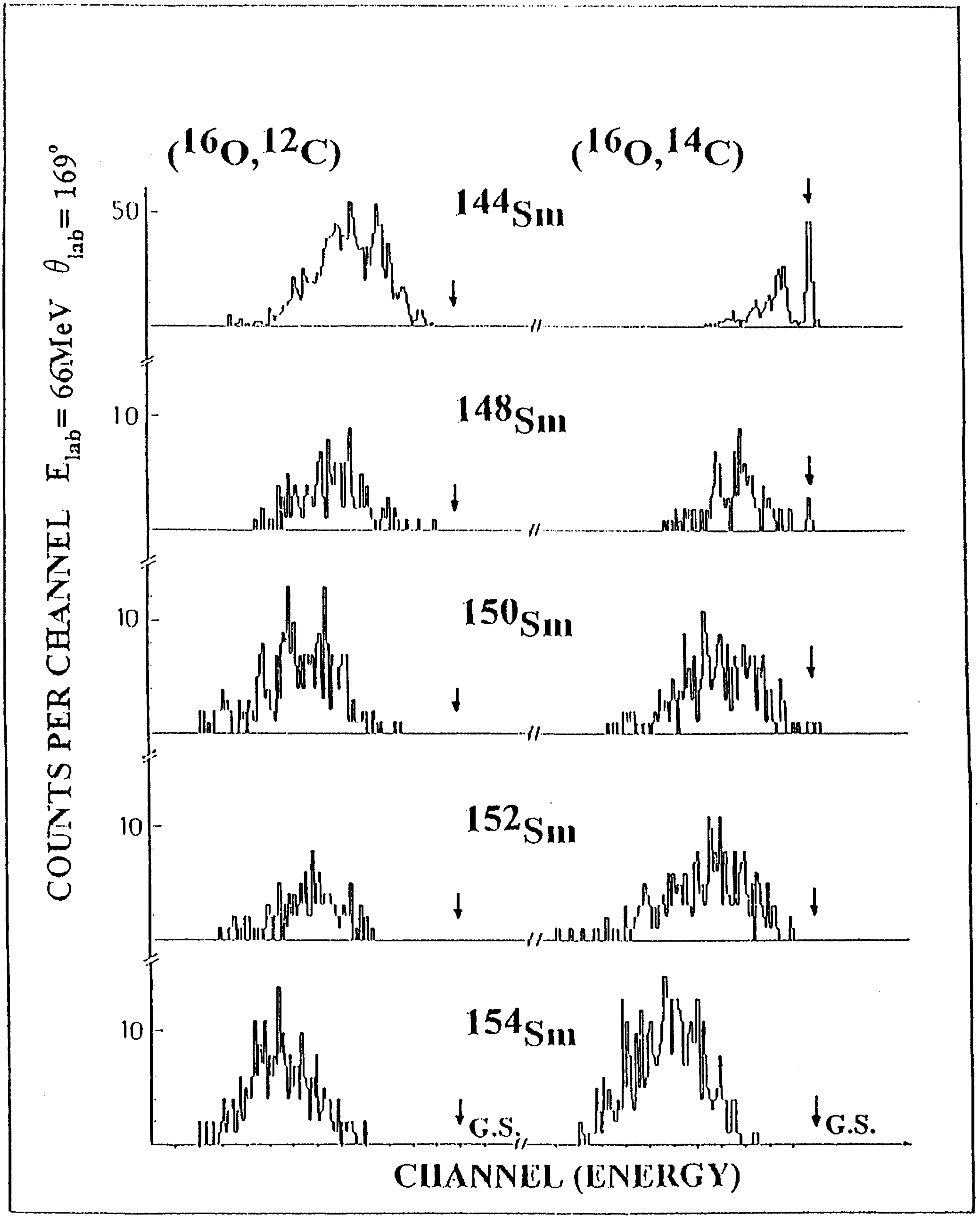
Figure 1: Q-Value Spectra for the stripping of two protons and stripping of one alpha particle, for the $^{16}O + {}^{A}Sm$ systems, at $E_{lab} = 66$ MeV, as obtained by Marcheseau [1].

Figure 2: Elastic over Rutherford differential cross sections as a function of the reduced didtance of closest approach, for the $^{16}O + {}^{144}Sm$ system at $E_{lab} = 72$ MeV. The line represents the semiclassical parametrization. Those data were obtained from ref [1].

Figure 3-a to 3-e: -2p and -1α transfer probabilities versus reduced distance of closest approaches for the five $^{16}O + {}^{A}Sm$ systems. Solid lines are the least square fits.

Figure 4a to 4j: Transfer differential cross section versus detection angle for the -2p and -1α channels for the five $^{16}O + {}^{A}Sm$ systems, at $E_{lab} = 66$ MeV. The symbols are experiemtal data and the full lines are obtained by fitting the data for the smallest angles. The dashed lines are obtained for $d_c = 1.46$ fm.

Figure 5: Simplified coupled channel calculations for the -1α transfer channel for the $^{16}O+{}^{154}Sm$ system, using the effective Q-value. The curves are the results of the uncoupled calculations and the coupling of just that channel.



(^{16}O,^{12}C)
(^{16}O,^{14}C)
COUNTS PER CHANNEL E_{lab} = 66MeV θ_{lab} = 169°
50
10
10
10
10
^{144}Sm
^{148}Sm
^{150}Sm
^{152}Sm
^{154}Sm
G.S.
G.S.
CHANNEL (ENERGY)

figure 1

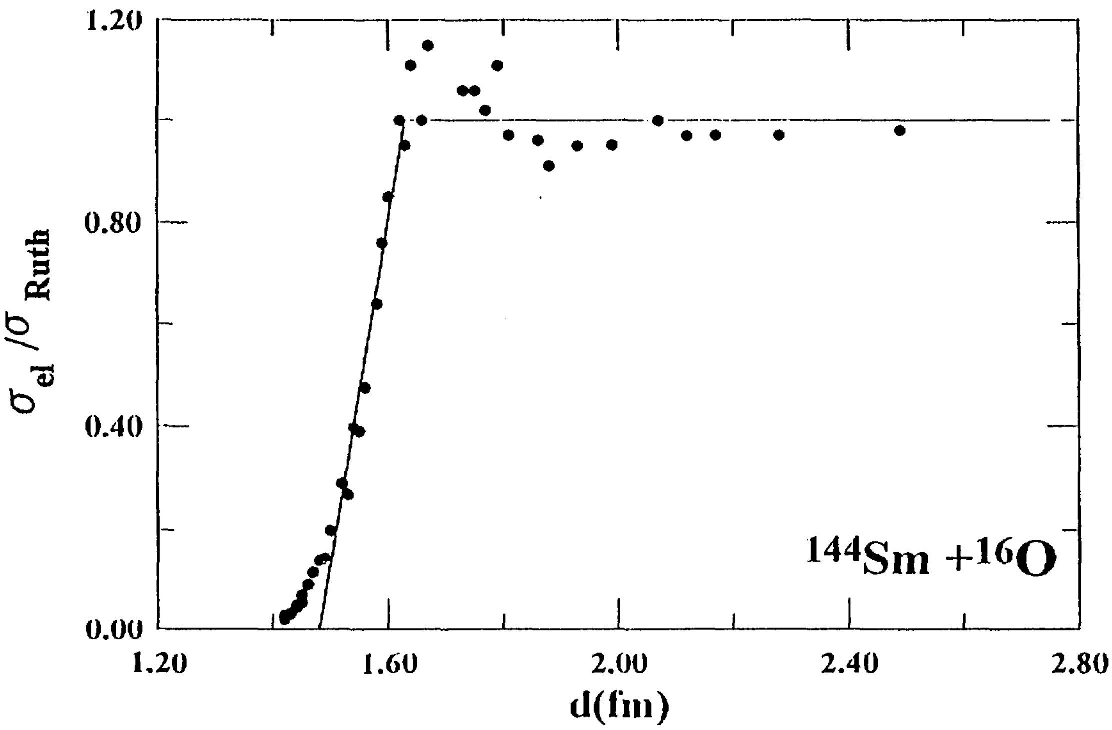
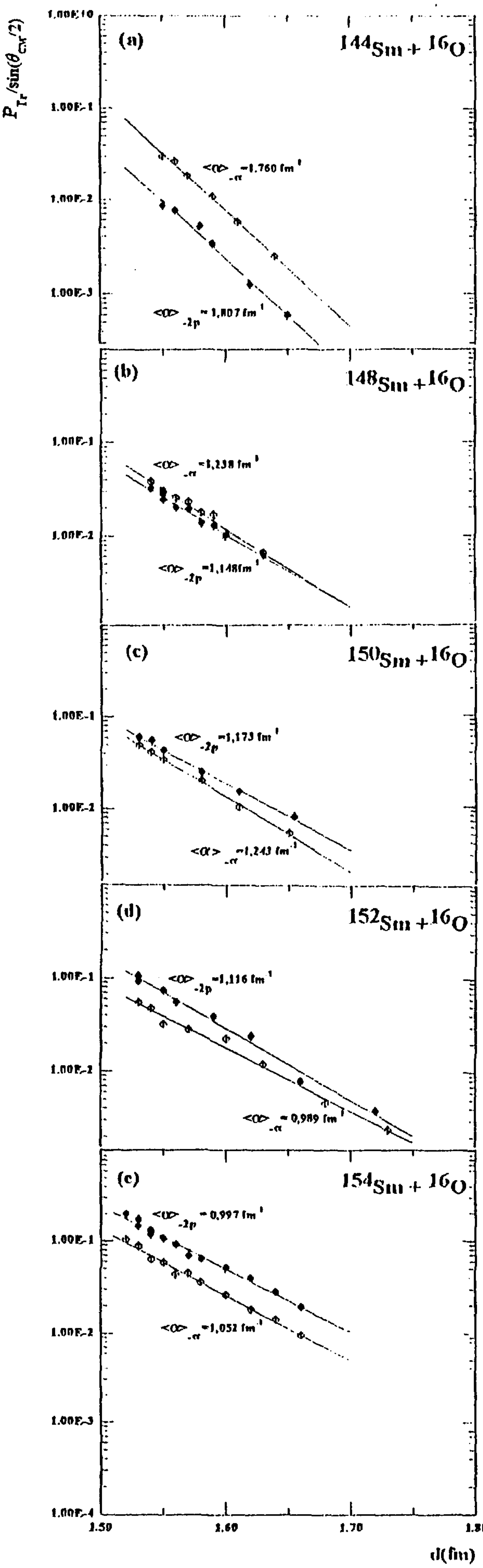
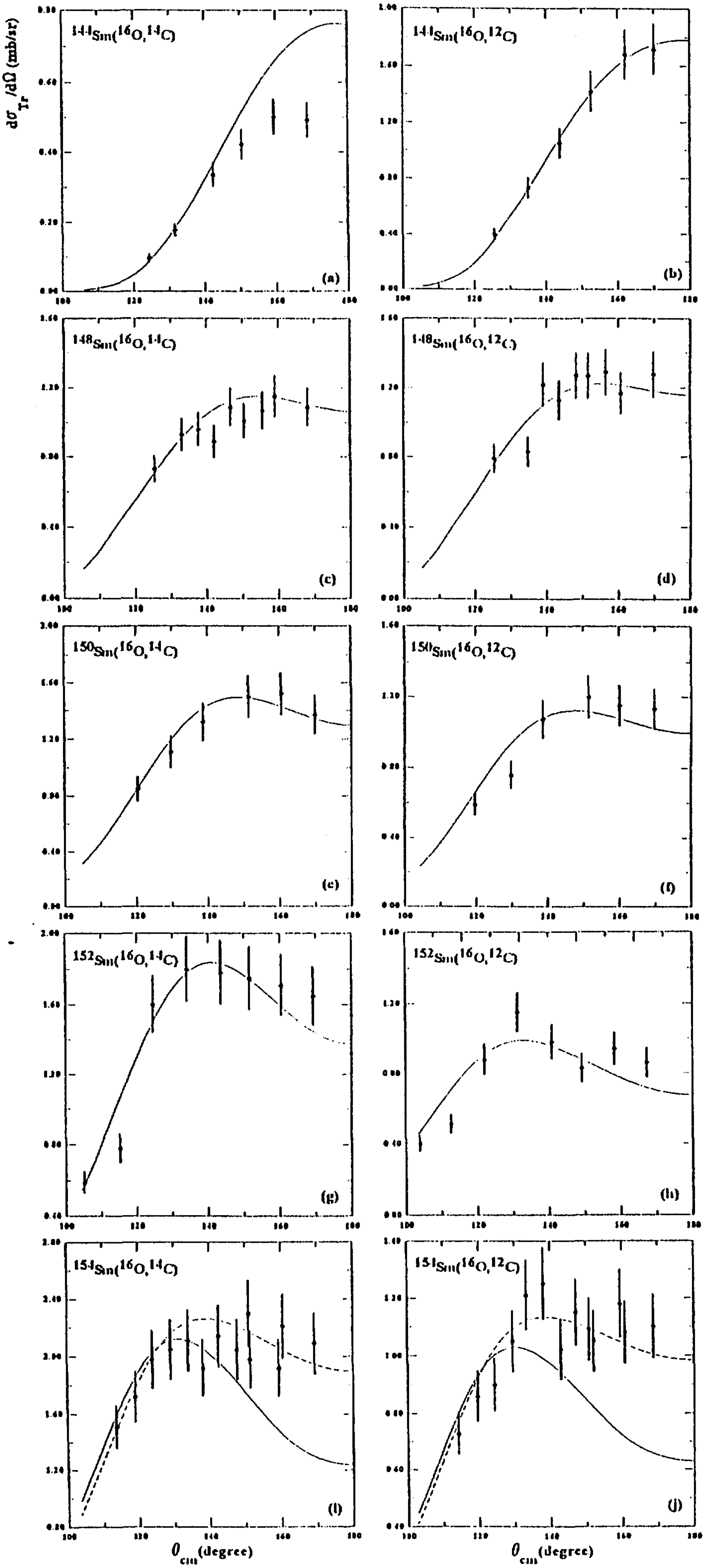

1.20
0.80
0.40
0.00
$\sigma_{el} / \sigma_{Ruth}$
$^{144}Sm + ^{16}O$
1.20
1.60
2.00
2.40
2.80
d(fm)

figure 2



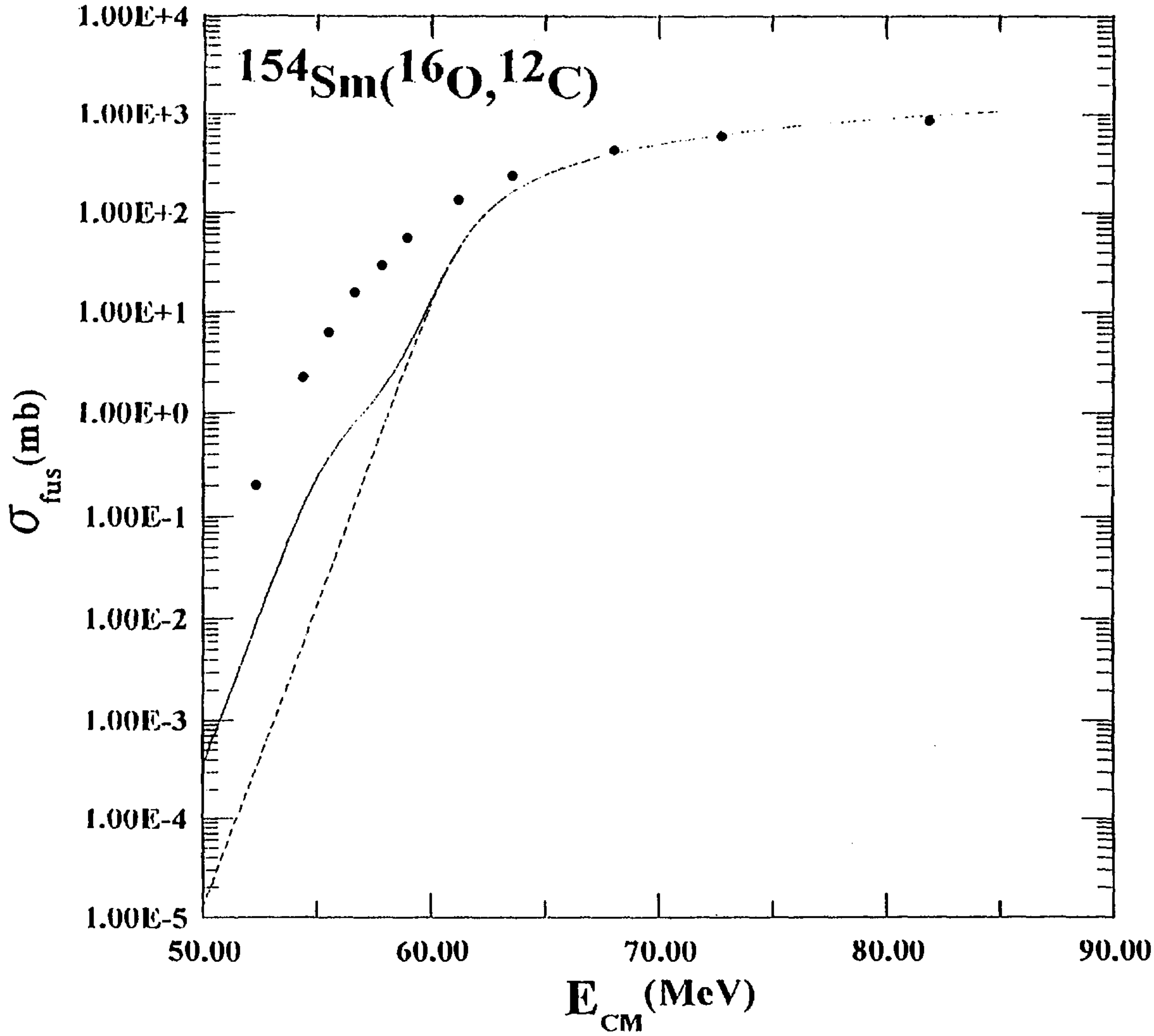
(a)
144Sm + 16O
<α>-α = 1,760 fm⁻¹
<α>-2p = 1,807 fm⁻¹
(b)
148Sm + 16O
<α>-α = 1,238 fm⁻¹
<α>-2p = 1,148 fm⁻¹
(c)
150Sm + 16O
<α>-2p = 1,173 fm⁻¹
<α>-α = 1,243 fm⁻¹
(d)
152Sm + 16O
<α>-2p = 1,116 fm⁻¹
<α>-α = 0,989 fm⁻¹
(e)
154Sm + 16O
<α>-2p = 0,997 fm⁻¹
<α>-α = 1,052 fm⁻¹
1.00E-1
1.00E-2
1.00E-3
1.00E-4
1.50
1.60
1.70
1.80
d(fm)

figure 3



$d\sigma_{Tr}/d\Omega$ (mb/sr)
$^{144}Sm(^{16}O,^{14}C)$
$^{144}Sm(^{16}O,^{12}C)$
$^{148}Sm(^{16}O,^{14}C)$
$^{148}Sm(^{16}O,^{12}C)$
$^{150}Sm(^{16}O,^{14}C)$
$^{150}Sm(^{16}O,^{12}C)$
$^{152}Sm(^{16}O,^{14}C)$
$^{152}Sm(^{16}O,^{12}C)$
$^{154}Sm(^{16}O,^{14}C)$
$^{154}Sm(^{16}O,^{12}C)$
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
θ_{cm}(degree)
θ_{cm}(degree)

figure 4



$^{154}Sm(^{16}O,^{12}C)$
1.00E+4
1.00E+3
1.00E+2
1.00E+1
1.00E+0
1.00E-1
1.00E-2
1.00E-3
1.00E-4
1.00E-5
σ_{fus}(mb)
50.00
60.00
70.00
80.00
90.00
E_{CM}(MeV)

figure 5