PRAMANA
— journal of
physics

© Printed in India

Vol. 44, No. 2,
February 1995
pp. 153 – 166

A new approach for heavy ion fusion spin distribution

S V S SASTRY, A K MOHANTY and S K KATARIA
Nuclear Physics Division, Bhabha Atomic Research Centre, Bombay 400085, India

MS received 16 June 1994; revised 3 October 1994

Abstract. The method of optical model analysis of generalized elastic scattering angular distributions (GESA) has been applied to heavy ion scattering to derive fusion spin distributions. This method is used to reproduce the coupled channel fusion spin distributions. When applied to experimental data, particularly to the fissile systems like $^{16}O + {}^{232}Th$, the method gives large mean square spin values in agreement with "anomalous" values derived from experimental fission fragment anisotropies.

Keywords. Generalized elastic scattering; optical potentials; reduced reaction cross-section; fusion spin; coupled channel calculations.

PACS Nos 25·70; 24·10

1. Introduction

The study of heavy ion reactions at low energies has created much excitement in recent years due to rich interplay between the dynamics of the reactions and the nuclear structure of the participating nuclei. Measurements on many aspects of the colliding nuclei, such as elastic, inelastic, transfer and fusion reactions have shown that these processes are correlated and attempts are being made to develop a theoretical model which will take them all into account. The common feature of all these descriptions is the realisation of importance of the couplings among different channels, either implicitly through optical models or explicitly through the coupled channels (CC) method. These couplings result in significant multi-step contributions to various reaction channels in addition to the direct one-step amplitudes that are generally evaluated by methods such as the DWBA, barrier penetration models, optical model etc. In reality, the solution of a large set of coupled channel equations is difficult and hence several approximations are made, besides limiting the number of channels that are important for a particular reaction. These approximations give rise to serious discrepancies between the theory and the experimental measurements. In fusion reaction, many models fail to explain the fusion partial wave cross-section [1] even though they account for the total fusion cross-section. Therefore, to test any theory of heavy ion reactions, it is important to understand the reaction mechanism for each partial wave and also its contribution to different reaction channels. In this context, experimental measurement of partial wave cross-sections for different reaction channels is highly desirable. In this paper, we investigate the method of obtaining partial wave cross-section for fusion channel by fitting generalized elastic scattering angular distribution (GESA). The GESA is defined as the sum of strictly elastic and appropriate non-elastic channels and the corresponding reaction cross-section is called reduced reaction cross-section [2]. Usually, the simplest of the measurements, the elastic scattering is analysed to obtain the reaction cross-section and by measuring it properly one can ensure that the total reaction cross-section contains contribution from all possible reaction channels. If angular distribution for any non-elastic channel is available, one can define a GESA by adding it to the strictly elastic angular distribution. Oeschler *et al* [2] showed that for heavy ion collisions, the reduced reaction cross-section and its partial wave distribution obtained by fitting the GESA are consistent with the total reaction cross-section for the remaining channels that are not added to the generalized elastic channel. In heavy ion scattering, the elastic channel often contains the contributions from the low lying Coulomb excitations and in [2], emphasis was put on the question whether the analysis of the sum of Coulomb excited inelastic states and elastic scattering (GESA) gives a consistent value of the reduced reaction cross-section as the flux going into the remaining channels. It was also observed that one should use an optical model fit to the GESA in order to obtain the appropriate potential for coupled channel calculations. This is in contrast to the fact that the strictly elastic scattering some times may turn out difficult to fit due to the long range Coulomb excitations. We have applied this method to obtain the partial wave cross-section for fusion channel by fitting GESA. The fusion partial wave cross-sections obtained this way contain all the effects of channel couplings. However one needs the angular distributions of all the non-fusion reaction channels. In fusion reaction, particularly for fissile targets, direct measurement of fusion partial wave cross-section based on γ-ray multiplicity measurements is difficult. Usually, indirect methods are adopted to obtain mean square spin from the studies of fission fragment anisotropies which are model dependent and many times have turned out to be anomalous. The present method is useful to obtain fusion cross-section as the reduced reaction cross-section by fitting GESA which contains all the reaction channels other than fusion.

2. The method

The total scattering amplitude which involves phase shifts δ_l and σ_l due to nuclear and Coulomb potentials is given by

$$\begin{aligned} f(x) &= \frac{1}{2ik}\sum_l (2l+1)[(e^{2i\sigma_l}-1)+e^{2i\sigma_l}(e^{2i\delta_l}-1)]p_l(x), \\ &= f_C(x)+f_n(x). \end{aligned} \tag{1}$$

Applying optical theorem to the amplitude $f(x)$, it can be shown that [2],

$$(4\pi/k)\mathrm{Im}[f_n(x=1)] = \sigma_R + 2\pi\int[\sigma_{\mathrm{el}}(x)-\sigma_{\mathrm{Ruth}}(x)]\mathrm{d}x, \tag{2}$$

where the total elastic and Rutherford cross-sections are given by

$$\sigma_{\mathrm{el}} = 2\pi\int|f(x)|^2\mathrm{d}x \quad \text{and} \quad \sigma_{\mathrm{Ruth}} = 2\pi\int|f_c(x)|^2\mathrm{d}x$$

In presence of strong Coulomb field as in heavy ion scattering, the contribution of the left hand side of (2) is very small in comparison to the total reaction cross-section σ_R and by setting it to zero, it is possible to write the total reaction cross-section as the difference of Rutherford and elastic angular distributions provided the limit of integration is taken properly (for details see ref. [2] and references therein)

$$\sigma_{\mathrm{R}} = \lim_{\varepsilon \to 0} 2\pi \int_{\varepsilon}^{\pi} [\sigma_{\mathrm{Ruth}}(\theta) - \sigma_{\mathrm{el}}(\theta)] \sin\theta \, \mathrm{d}\theta. \tag{3}$$

The above equality justifies the use of generalized elastic scattering to obtain the reduced reaction cross-section. Let (V, W) be the set of real and imaginary optical potentials that fits the strictly elastic scattering and σ_{R} the corresponding reaction cross-section. For simplicity, if we assume that there are only two reaction channels; fusion and inelastic, then σ_{R} will be the sum of σ_f and σ_{inel}. Now the GESA can be obtained by adding this inelastic angular distribution to the strictly elastic channel. Let V' and W' be another set of optical potentials that fits the GESA. The corresponding reduced reaction cross-section σ'_{R} is given by

$$\begin{aligned} \sigma'_{\mathrm{R}} &= 2\pi \int \{\sigma_{\mathrm{Ruth}}(\theta) - \sigma_{\mathrm{GES}}(\theta)\} \sin\theta \, \mathrm{d}\theta, \\ &= 2\pi \int \{\sigma_{\mathrm{Ruth}}(\theta) - [\sigma_{\mathrm{el}}(\theta) + \sigma_{\mathrm{inel}}(\theta)]\} \sin\theta \, \mathrm{d}\theta. \end{aligned}$$

The reduced reaction cross-section σ'_{R} will now be less than σ_{R} and using (3), it can be shown that

$$\sigma_{\mathrm{R}} - \sigma'_{\mathrm{R}} = 2\pi \int \sigma_{\mathrm{inel}}(\theta) \sin\theta \, \mathrm{d}\theta = \sigma_{\mathrm{inel}}. \tag{4}$$

Therefore, we can identify, σ'_{R} as the fusion cross-section and (V', W') as the corresponding optical potential for fusion. It will be in general different from bare potentials and will contain long range polarization contribution. Therefore, the reaction partial wave distribution obtained with this set of optical potentials will correspond to the fusion partial wave distribution. Now the difference of the two reaction partial wave distributions obtained with two sets of potentials (V, W) and (V', W') will give the partial wave distribution for inelastic channel. In a simple situation, where we have only elastic and inelastic angular distributions, we define the GESA as $\mathrm{d}\sigma_{\mathrm{el}}/\mathrm{d}\Omega + \mathrm{d}\sigma_{\mathrm{inel}}/\mathrm{d}\Omega$. By fitting optical model to GESA, we are trying to find the nuclear part of the scattering amplitude f_l, (absorbing all multiplicative factors) that satisfies the equation given by,

$$\left| f_c(x) + \sum_l f_l'^{\mathrm{el}} p_l(x) \right|^2 = \left| f_c(x) + \sum_l f_l^{\mathrm{el}} p_l(x) \right|^2 + \sum_m \left| \sum_{ll'} f_{ll'm} p_{l'm}(x) \right|^2 .$$

The f'_l values derived in this manner correspond to the pseudo-optical potentials (V', W') as mentioned above.

The above discussion is based on the assumption that, one can neglect the term on the LHS of (2) in comparison to the reaction cross-section. This term as a function of angular momentum is highly oscillatory, but the total sum i.e. $(4\pi/k)\mathrm{Im} f_n(x = 1)$ extends to large l values in heavy ion scattering and is quite small in the presence of a strong coulomb field. In this paper we studied systems for which $Z_T Z_P \geqslant 450$ and the above sum is less than 0·1% of the total reaction cross-section and therefore it

Table 1. Im $[f_n(x=1)]$ compared to σ_R as a test for validity of GESA method in heavy ion case.

System	E_{lab}(MeV)	σ_R(mb)	$4\pi/k\,\text{Im}[f_n(x=1)]$
$^{16}O + {}^{28}Si$	40	995	118
	50	1122	158
	60	1302	−336
	70	1419	460
$^{16}O + {}^{208}Pb$	78	88·9	$0{\cdot}704 \times 10^{-4}$
	86	472	$-0{\cdot}222 \times 10^{-4}$
	90	673	$0{\cdot}808 \times 10^{-4}$
	98	1024	$-0{\cdot}118 \times 10^{-1}$
	110	1449	0·302

can be neglected. Table 1 gives an estimate of this quantity compared with the total reaction cross-section at different energies for a light ion case ($^{16}O + {}^{28}Si$) and a heavy ion case ($^{16}O + {}^{208}Pb$).

3. Results and discussion

First we test the validity of the GESA method for obtaining fusion l-distribution for a simple two channel case. The coupled channel calculations for $^{32}S + {}^{130}Te$ system have been carried out with rotational coupling to the 2^+ state of ^{130}Te with a Q value of 100 KeV. The coupling parameters are taken from ref. [2]. The coupled channel (CC) code ECIS [3] has been used to generate elastic and inelastic angular distributions and also the l-distributions for both reaction, inelastic and fusion channels. The GESA is generated by adding these elastic and inelastic angular distributions. The CC fusion l-distribution is compared with the reduced reaction l-distribution obtained from the optical model analysis of GESA using the optical code SNOOPY [4]. As shown in ref. [2], it might be difficult to reproduce the reaction l-distribution for strictly elastic scattering using optical model, as one is trying to fit an angular distribution resulting from long ranged absorption due to Coulomb excitations with a short ranged imaginary potential. On the other hand, such problems are less serious in the case of GESA.

Figure 1(a) shows the angular distributions at two typical bombarding energies (much below, and around the Coulomb barrier). The corresponding partial wave distributions are shown in figure 1(b). As seen from figure 1(b), the CC fusion l-distribution is in good agreement with the reduced reaction l-distribution.

We have carried out this analysis for this case over a wide range of energies (108 MeV to 139·5 MeV), from much below to much above the Coulomb barrier and found this method satisfactory (figure 1c). The corresponding mean square spin of fusion is shown in figure 1(d). The good agreement between GESA estimates and CC results in figures 1(c, d) over wide energy region show the usefulness of the present method.

In the following, we study the sensitivity of GESA parameters on fusion spin distributions as different sets of parameters can be used to get the same quality of fit to GESA. This test is carried out at 128 MeV for different sets of optical model parameters (OMP) that reproduce the GESA of ECIS within 10% error, figure 2(a)

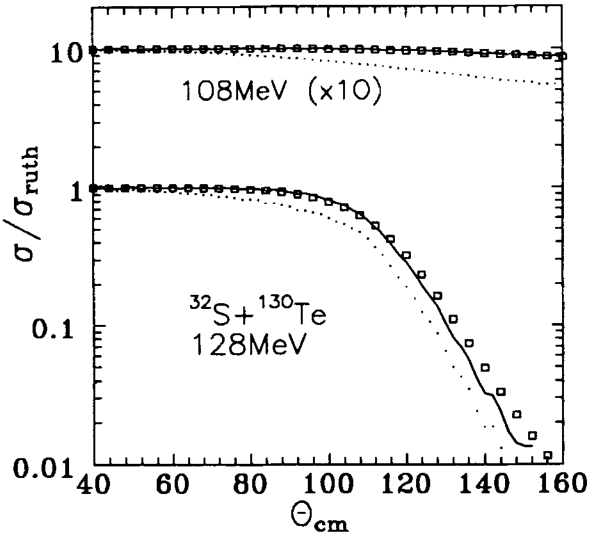

Figure 1a. $\sigma/\sigma_{\mathrm{Ruth}}$ vs θ_{cm} for strictly elastic scattering (dotted curve) and GESA (solid curve) for $^{32}S + ^{130}Te$ system at $E_{\mathrm{lab}} = 108$ and 128 MeV obtained from ECIS. The open squares represent the optical model fits to GESA.

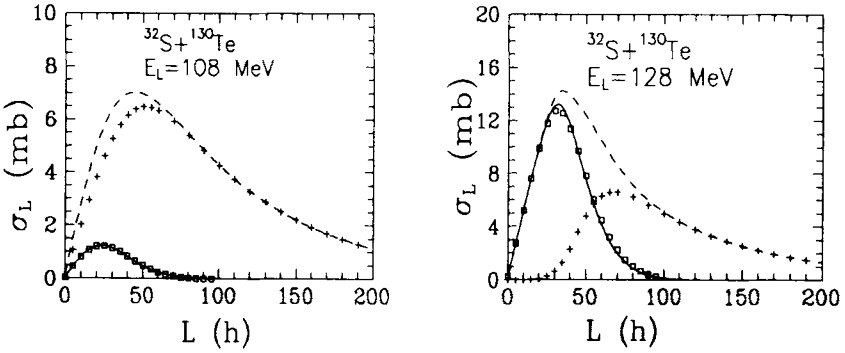

Figure 1b. σ_l vs l for $^{32}S + ^{130}Te$ system at $E_{\mathrm{lab}} = 108$ MeV and 128 MeV. The dashed, solid curves and plus symbols represent l-distribution for total reaction, fusion and 2^+ inelastic state obtained from ECIS. The open squares are the fusion l-distribution obtained from the optical model fit to GESA.

shows OM fits to GESA with different sets of OM parameters as listed in table 2. Figure 2(b) shows the corresponding l-distributions. It can be concluded from figures 2(a, b) that fusion spin distribution is not very sensitive to optical parameters as long as they give acceptable fit to GESA. It is also interesting to note that though the OM parameter sets (see table 2) are different, the imaginary parts have same strength at strong absorption radius (R_s) as shown in figure 3(b), and real part has same strength at barrier radius (R_b) as seen in figure 3(a). Together, they determine the absorption of flux into the fusion channel. These features are very similar to those of OM potentials derived from strictly elastic scattering data.

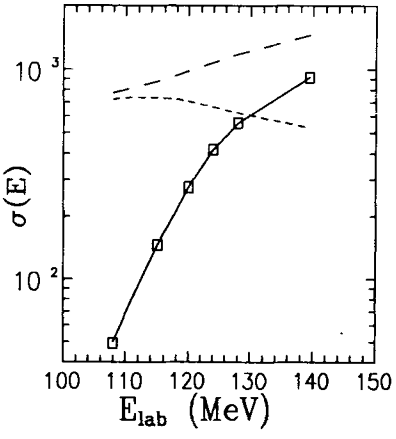

Figure 1c. Cross-sections for different reaction channels vs lab energy obtained from ECIS. The long and short dashes represent the CC results for total reaction and the inelastic channel. The CC fusion is shown by solid curve, obtained as the difference of long and short dashed curves. The squares represent the results of the GESA method.

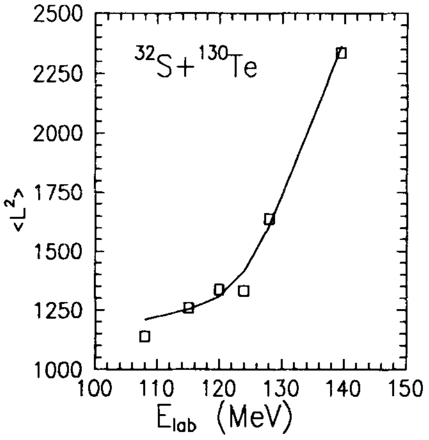

Figure 1d. Fusion $\langle L^2 \rangle$ versus lab energy with symbols as in figure 1c.

Table 2. Five sets of OMP which fit GESA data as shown in figure 2.

SET	V_0	r_0	a_0	W_0	r_i	a_i	χ^2/N	σ	$\langle L^2 \rangle$
A	100	1·217	0·5	100	1·24	0·52	3·619	544	1415
B	100	1·217	0·5	70	1·22	·59	2·045	562	1510
C	100	1·217	0·5	50	1·17	0·705	3·457	570	1658
D	100	1·217	0·5	30	1·21	0·705	4·581	558	1638
E	50	1·180	0·8	30	1·21	0·705	2·289	589	1652

^{32}S + ^{130}Te at $E_{\text{lab}} = 128{\cdot}0$ MeV; $r_c = 1{\cdot}250$ fm, $N = 71$ and 10% error on data taken for calculating χ^2/N. σ_F(ECIS) = 555·8 mb and $\langle L^2 \rangle_F$(ECIS) = 1607 $\hbar^2$

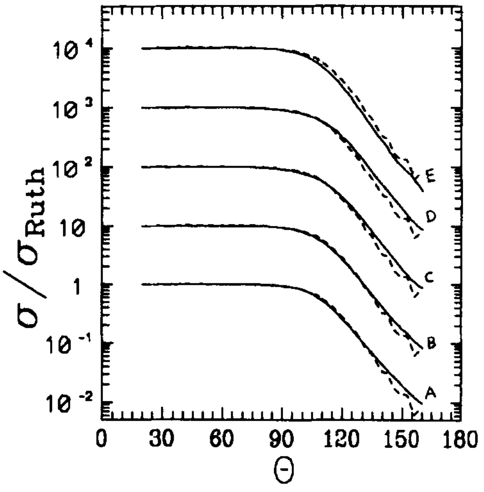

Figure 2a. Optical model fits (solid lines) to GESA obtained from ECIS (dashed lines) for the OMP sets listed in table 2.

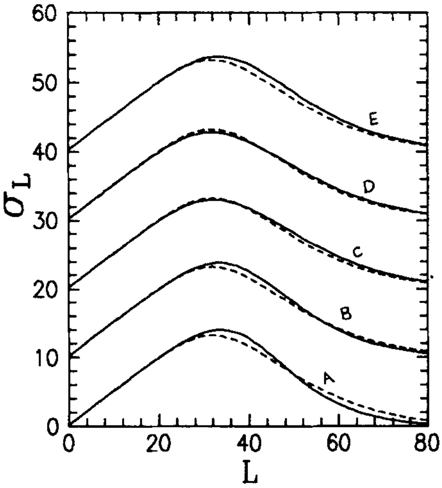

Figure 2b. The reduced reaction spin distribution corresponding to figure 2a.

In the above discussion only two reaction channels were considered, however, this method can be generalised even if more channels are present. In order to verify this, we carried out CC calculations for the $^{16}O + ^{152}Sm$ system at 72 MeV lab energy including the 2^+ and 4^+ states of Sm. The coupling parameters are taken from [5] which fit the experimental angular distributions for 2^+ and 4^+ inelastic states. In this case the GESA is the sum of elastic, 2^+ and 4^+ inelastic states. As before, the CC l-distribution for fusion is obtained as the difference of the l-distributions for total reaction and total inelastic channels obtained from the ECIS. Figure 4 shows that the reduced reaction l-distribution obtained from SNOOPY and the CC fusion l-distribution are in good agreement.

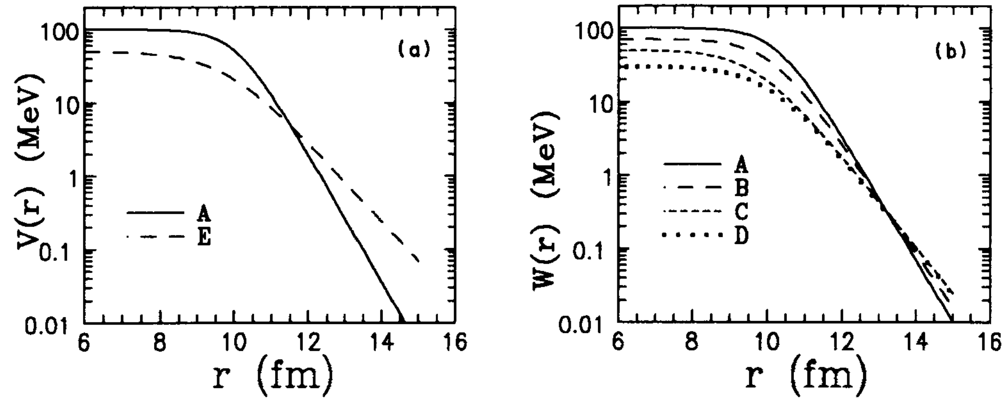

Figure 3a, b. Real part (3a) and Imaginary part (3b) of OMP of table 2 as a function of radial separation showing the agreement of imaginary strengths at strong absorption radius.

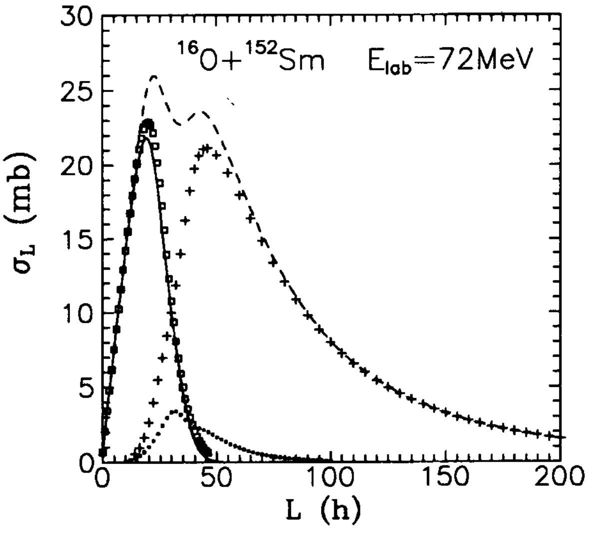

Figure 4. Same as figure 1(b), but for $^{16}O + ^{152}Sm$ system at $E_{lab} = 72$ MeV. The dashed, solid, plus symbols and the dotted curves represent the *l*-distributions for total reaction, fusion, 2^+, 4^+ inelastic states. The squares are the fusion *l*-distribution obtained from the optical model fit to GESA.

The reduced reaction of the model calculations for above cases of $^{32}S + ^{130}Te$ and $^{16}O + ^{152}Sm$ has been identified with fusion channel, since the model space consists of elastic, inelastic channels only. In heavy ion reactions, several inelastic as well as transfer channels contribute significantly to reaction and therefore the results of these cases cannot be compared with experimental fusion data. Thus, the accuracy of the method to obtain fusion depends on the relative contribution of the left out channels.

In general, for heavy ion reactions, single step as well as multi-step particle transfers following the inelastic excitations contribute significantly to the total reaction cross-section. Therefore, to verify the validity of the present method for fusion partial wave distribution in the presence of particle transfer, the coupled channels results for $^{16}O + ^{208}Pb$ system at 80 MeV have been analysed using the present method. The Coupled channel calculations were carried out using the code FRESCO [6]. The potentials and coupling parameters are taken from [6]. As before, the fusion l-distribution can be obtained using an optical model fit to the GESA, generated by adding the FRESCO angular distributions for elastic, inelastic and transfer channels. In this case the reduced reaction can be identified with true fusion since the coupling scheme includes all channels that contribute significantly to reaction.

Figure 5(a) shows the CC angular distributions for the strictly elastic channel and the GESA. Figure 5(b) shows the l-distributions for the total and reduced reaction cross-sections obtained by fitting the strictly elastic scattering and the GESA. The difference between the total and the reduced reaction (fusion) l-distributions gives the

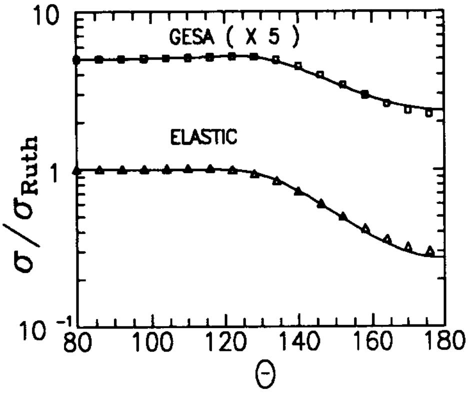

Figure 5a. $\sigma/\sigma_{\text{Ruth}}$ versus θ_{cm} for strictly elastic scattering (lower solid curve) and GESA (upper solid curve) obtained from FRESCO for $^{16}O + ^{208}Pb$ system at $E_{\text{lab}} = 80$ MeV. The optical model fits are shown by triangles (elastic) and squares (GESA).

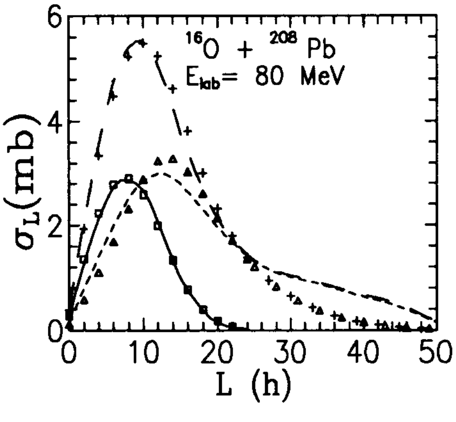

Figure 5b. σ_l versus l for $^{16}O + ^{208}Pb$ system at $E_l = 80$ MeV. The long dashed, continuous and the dashed lines represent the reaction, fusion and the transfer cross-sections obtained from FRESCO. The corresponding results from optical model fits to GESA are shown by plus symbols, squares and triangles (see text).

l-distributions for the inelastic plus transfer channels. However, for this system, the inelastic cross-section at this energy is negligible and the reaction comprises of mainly transfer and fusion channels. The coupled channel *l*-distributions for reaction, fusion and transfer channels are also shown for comparison. It can be seen that the reduced reaction *l*-distribution reproduces well the coupled channel fusion *l*-distribution. However, the reaction *l*-distribution obtained fitting strictly elastic scattering, does not agree well with the coupled channel reaction at higher *l* values. As a result, the transfer of *l*-distribution obtained from the optical model fit does not agree well with the coupled channels results for higher *l* values. In case of fusion, the coupled channel contribution to fusion from the non-elastic processes comes mostly from the low *l* values (see cc fusion *l*-distribution in figure 5(b)). Therefore, the GESA can be used to obtain the fusion *l*-distributions. On the basis of these studies, one can conclude that the present method is able to reproduce the fusion *l*-distribution derived from coupled channels calculations reliably.

This method has been applied to the experimental angular distributions of $^{16}O + ^{208}Pb$ system at 90 MeV, and to $^{16}O + ^{232}Th$ system at several energies for which complete measurements on elastic, inelastic and transfer channels are available [7–10]. The $\langle L^2 \rangle$ values experimentally determined from fission angular distributions for these systems, turn out to be anomalously large [8, 10]. The CC calculations for fusion also underpredict the $\langle L^2 \rangle$ values [11], showing the importance of higher order coupling processes leading to fusion.

In case of $^{16}O + ^{208}Pb$ system at 90 MeV due to large errors in the experimental data, the inelastic and transfer angular distributions are smoothed by a polynomial fit before being used to generate GESA in two ways. Initially, the total inelastic angular distribution is added to elastic data (case-I) and then both inelastic and transfer angular distributions are added to elastic data (case-II). The optical model reduced reaction *l*-distributions corresponding to these cases are shown in figure 6(a). The *l*-distribution for inelastic channels can be obtained as the difference of *l*-distribution for the total reaction and *l*-distribution for case-I. Similarly, the transfer *l*-distribution can be obtained as the difference of *l*-distribution for case-II and that

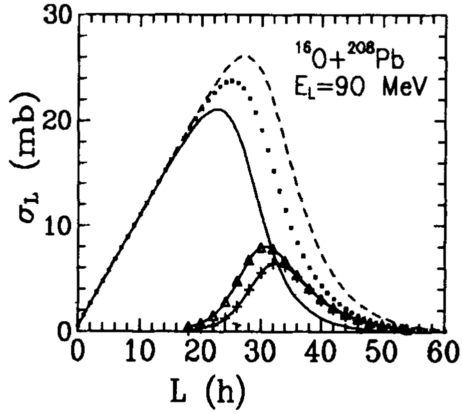

Figure 6a. σ_l versus l for $^{16}O + ^{208}Pb$ system at $E_l = 90$ MeV. The dashed, dotted, solid lines represent *l*-distributions for the three cases explained in the text. The plus symbols and the triangles represent total inelastic and transfer *l*-distributions respectively.

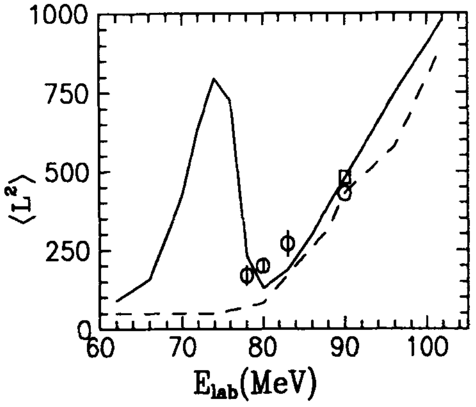

Figure 6b. Fusion mean square spin versus energy obtained by different methods. The results of FRESCO and BPM calculations are shown by solid and dashed curves. The result of GESA method obtained at 90 MeV is shown by square symbol. The experimental data are shown by circles.

for case-I. The reduced reaction l-distribution of case-II can be identified as true fusion l-distribution because the GESA for this case includes both inelastic and transfer channels. At 90 MeV, total reaction cross-section is about 670 mb and the total angle integrated cross-sections for inelastic and transfer are 92 ± 20 mb and 109 ± 5 mb. Therefore, fusion cross-section obtained by eliminating these non-elastic channels (with total cross-section of 201 ± 25 mb) from total reaction, is expected to be 469 ± 25 mb. The optical model fit to GESA of case-II predicts reduced reaction cross-section of 454 mb and average and the mean square l values are $20{\cdot}2\hbar$ and $481\,\hbar^2$. The experimental fusion cross-section is 450 ± 25 mb and mean square l value is $433\,\hbar^2$. The corresponding values from coupled channel calculations [6] are 466 mb, $20{\cdot}6\,\hbar$ and $488\,\hbar^2$ and from barrier penetration model (BPM as defined in [6]) are 448 mb, $19{\cdot}5\,\hbar$ and $433\,\hbar^2$. Thus, we have shown that the fusion cross-section and the l-distribution obtained from GESA method are consistent with the results of coupled channel method and the experimental measurements. At very high energy these values are more or less independent of the choice of any particular model as the transmission probability for fusion is nearly unity. As seen from figure 4, the inelastic l-distribution has a long tail due to the long range Coulomb excitations and such a behaviour is also expected in figure 6(a). This discrepency arises due to the fact that the optical model fit is not able to predict the large l behaviour of total reaction. Figure 6(b) shows the fusion mean square spin versus energy obtained by different methods. It is seen from the figure that the present method agrees well with the other methods. The fusion mean square spin from CRC method is observed to increase with decreasing energy and results in a peaking behaviour at deep sub-barrier energies. However, the exhaustive experimental data are not available at such deep sub-barrier energies and this aspect is under further study.

Figure 7(a) shows, for $^{16}O + ^{232}Th$ system, the reaction cross-section, fusion cross-sections at five bombarding energies obtained by this method and also the experimental fusion data. In order to obtain fusion, only available transfer angular distributions are added to the elastic channel, as the experimental elastic data already contains the contribution from the low lying excited states. The figure also shows the fusion obtained from Wong's model [12] (with deformation parameter $\beta_2 = 0{\cdot}22$,

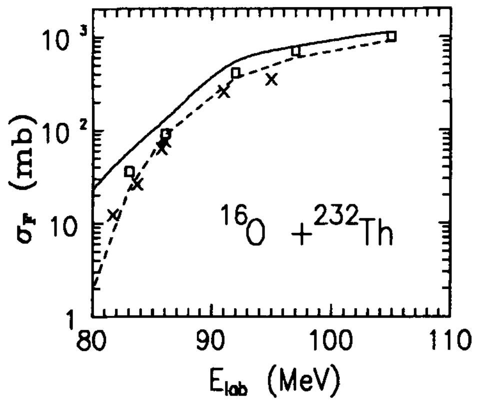

Figure 7a. Fusion and reaction cross-section versus energy for $^{16}O + ^{232}Th$ system. The reaction cross-section is shown by solid curve. The fusion cross-sections obtained by GESA method at five bombarding energies is shown by squares (interpolated by long dashes in figure 7(b)) and the experimental fusion data are shown by crosses. The dashed curve represents the fusion obtained from Wong's model.

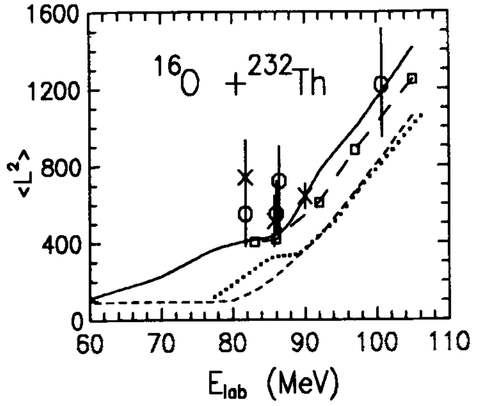

Figure 7b. Mean square spin values versus energy for different cases shown in figure 7(a). The crosses and circles with error bars are the experimental $\langle L^2 \rangle$ data. The dotted curve is the CC calculations [11].

$V_0 = 79{\cdot}7$ MeV, $\hbar\omega = 4{\cdot}96$ MeV and $R_0 = 12{\cdot}3$ fm). Figure 7(b) shows the corresponding mean square spin values for different cases shown in figure 7(a). As seen in figure 7(b), the mean square values obtained for fusion are much higher than Wong's model prediction as well as the CC calculations. At high energy, the Wong's model and CC calculations give same $\langle l^2 \rangle$ for fusion, which is less compared to the present method. This discrepancy with the present method at high energy is expected as we have not added all the transfer channels to the GESA and the reduced reaction cross-sections so obtained are also much higher than the experimental fusion cross-section (see figure 7(a)). For example, at $E_{lab} = 105$ MeV, the quasielastic reaction cross-section is about 1124 mb ($\langle L^2 \rangle = 1413\,\hbar^2$). By adding available transfer angular distributions for a few channels with total angle integrated cross-section of 120 mb, we get the reduced reaction cross-section about 1005 mb ($\langle L^2\rangle = 1249\,\hbar^2$). However, at this energy, the total measured transfer cross-section is around 220 mb and fusion cross-section is about 914 mb. Therefore, if we include all transfer channels (i.e. contribution of another 100 mb more), it is possible to get the reduced reaction cross-section which will be quite close to the experimental fusion cross-section. The corresponding $\langle L^2\rangle$ value will also agree with Wong or CC results.

Figures 8(a, b) show the l-distributions for different reaction channels at 105 and 83 MeV for the case of $^{16}O + ^{232}Th$. The dashed curve corresponds to the l-distribution obtained fitting quasi elastic data and the solid line for GESA data. At above barrier energy of 105 MeV the transfer l-distribution shows localisation in the L space around $L \simeq 50\,\hbar$. However, it is interesting to note that at 83 MeV the l-distribution for different reaction channels are very much similar to each other and does not show any localisation in L space. Therefore, if we include more transfer

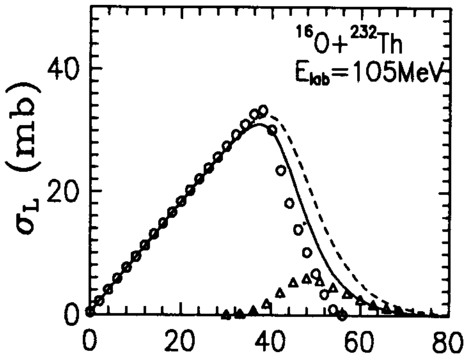

Figure 8a. σ_l versus l for $^{16}O + ^{232}Th$ system at 105 MeV. The dashed and the solid curves represent the l-distribution for reaction (without inelastic) and fusion obtained from optical model fits to GESA. The difference between the solid and dashed curves is shown by triangles, which represent the l-distribution for transfer channel. The circles are obtained from the Wong model fit to fusion excitation function.

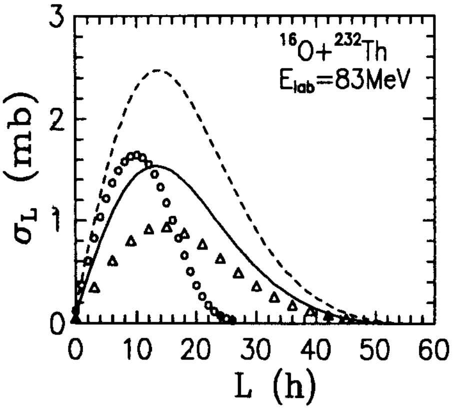

Figure 8b. Same as figure 8(a), but for $E_{lab} = 83$ MeV.

channels to get reduced reaction cross-section same as fusion cross-section, the shape of the l-distribution will not change. This is also evident from figure 7(b) where $\langle L^2 \rangle$ versus energy shows a plateau at energies around the Coulomb barrier and the values for the fusion and the reaction become the same. In other words, transfer reactions compete with the fusion process at all l values. As a result, the fusion $\langle L^2 \rangle$ values increase and approach that of reaction $\langle L^2 \rangle$ values at near barrier energies. The $\langle L^2 \rangle$ values obtained by the present method are in agreement with experimental data.

Summary

It is shown that the GESA method can be used to obtain the fusion spin distributions from the experimental, elastic and non-elastic angular distributions. The validity of this method has been verified in the presence of couplings to inelastic as well as transfer channels. When applied to fissile systems, the method gives large mean square spin, in agreement with the measured "anomalous" values. Further, the analysis shows that the fusion competes with transfer processes for all partial waves at low energy, whereas at high energy, the transfer exhibits localisation in l-space. These results are model independent as one uses only the experimental angular distributions for appropriate reaction channels.

Acknowledgements

We are thankful to Dr S S Kapoor for his keen interest in this work; Dr P Singh, Dr S Kailas, Dr K V Bhagwat and Prof. C V K Baba for several useful discussions during the course of this study. We are thankful to Dr I J Thompson for the FRESCO code.

References

[1] R Vandenbosch, *Annu. Rev. Nucl. Part. Phys.* **42**, 447 (1992)
[2] H Oeschler, H L Harney, D L Hillis and K S Sim, *Nucl. Phys.* **A325**, 463 (1979)
[3] J Raynal, *Phys. Rev.* **C23**, 2571 (1981)
[4] SNOOPY Computer program by P Schwandt, Indiana University, Cyclotron centre report (1988)
[5] R G Stokstad and E E Gross, *Phys. Rev.* **C23**, 281 (1981)
[6] I J Thompson, M A Nagarajan, J S Lilley and M J Smithson *Nucl. Phys.* **A505**, 84 (1989)
[7] F Videbaek, R B Goldstein, L Grodzins and S G Steadman, *Phys. Rev.* **C15**, 954 (1977)
[8] T Murakami, C C Sahm, R Vandenbosch, D D Leach, A Ray and M J Murphy, *Phys. Rev.* **C34**, 1353 (1986)
[9] J S Karp, S G Steadman, S B Gazes, R Ledoux and F Videbaek, *Phys. Rev.* **C25**, 1838 (1982)
[10] J P Lestone, J R Leigh, J O Newton and J X Wei, *Nucl. Phys.* **A509**, 178 (1990)
[11] H Esbensen and S Landwone, *Nucl. Phys.* **A467**, 136 (1987)
[12] C Y Wong, *Phys. Rev. Lett.* **31**, 766 (1973)