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Fusion cross section for the system ^{6}Li + ^{28}Si at $E \sim 36$ MeV

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Abstract. The fusion cross section for the system ^{6}Li + ^{28}Si has been measured at $E \sim 36$ MeV. Combining this with the data available at lower energies, the nucleus-nucleus real potentials have been determined for a range of interaction distances.

Keywords. ^{6}Li + ^{28}Si system; $E = 36$ MeV; fusion; break up; real potential from fusion.

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1. Introduction

For a number of heavy ion systems, the ion-ion potentials determined from the analysis of fusion excitation function data agreed over a range of interaction distances with the ones deduced from the analysis of elastic scattering data (Kailas and Gupta 1986). In the case of ^{6}Li + ^{28}Si system this comparison could not be extended to smaller interaction distances for want of higher energy fusion cross section data. As the fusion data for this system was available only up to $E \sim 25$ MeV (Hugi *et al* 1981), it was decided to measure the fusion cross section at a convenient higher energy of about 36 MeV.

For this weakly bound projectile, the technique of Hugi *et al* (1981) has been employed for the measurement of the fusion cross section. Using this method it is possible to separate more reliably the direct and the compound nuclear parts of the interaction and hence determine more accurately the fusion cross section. The experimental details are given in § 2. The analysis procedure and the results of the measurement are given in § 3. The discussion of the results form the content of § 4 and the conclusions are given in § 5.

2. Experimental procedure

The experiment was performed with a 36 MeV ^{6}Li beam from the University of Washington tandem accelerator. Typical beam intensities were in the range of 10 to 100 enA. A detector grade Si crystal of about 2·8 mg/cm^2 thickness was used as the target. The energy spectra of emitted protons, deuterons and α particles were measured with $\Delta E - E$ Si telescopes. The detector telescopes accepted protons with energies between 5 and 19 MeV, deuterons with energies between 5 and 25 MeV and α particles with energies from 6 to 37 MeV. The particle spectra were measured at several angles between 8° and 155°. The angular resolution of the counters was better than $\pm 0{\cdot}8°$. The cross sections were normalized to the elastic scattering yields monitored at a fixed angle. They were also independently determined making use of target thickness, beam intensity and solid angle values. The error on the absolute normalization of cross section is of the order of $\pm 5\%$. No prominent elastic peaks corresponding to scattering from lighter contaminants like O and C were observed and it was estimated that their amounts would be less than 100 $\mu g/cm^2$. Further by measuring the elastic yield from a carbon target of known thickness and comparing with the spectrum from the Si target corresponding to the expected position of scattering from C, the amount of C present in the Si target has been estimated to be of the order of 20–40 $\mu g/cm^2$.

No correction was made from the observed yields for possible contributions from O/C. The spectra were however corrected for the distortion introduced by the thick target.

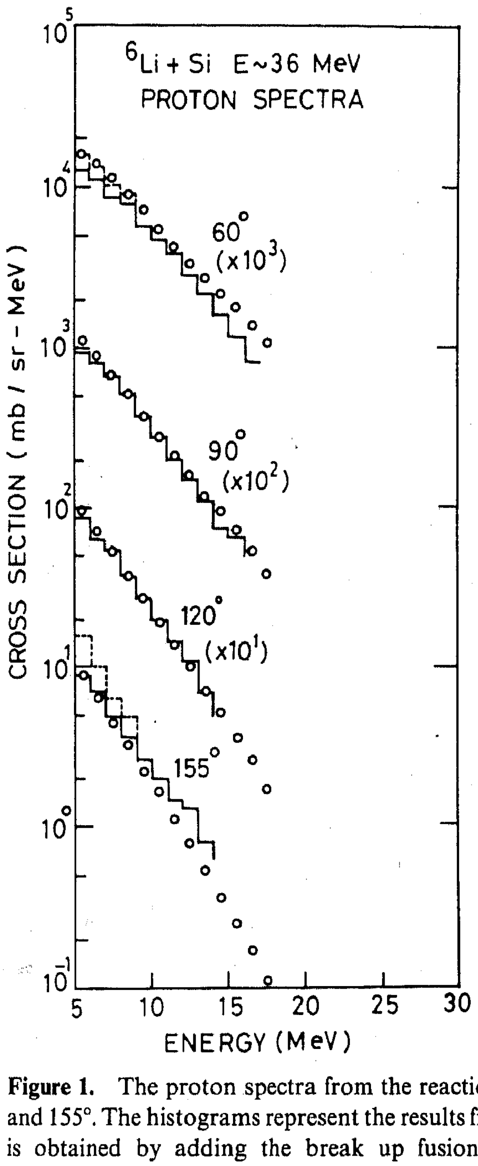

Figure 1. The proton spectra from the reaction $^{28}Si(^6Li, p)$ measured at $\theta = 60°, 90°, 120°$ and 155°. The histograms represent the results from PACE calculation. The dashed histogram is obtained by adding the break up fusion component as discussed in the text. The cross-sections, the angles and the energies are in the laboratory system.

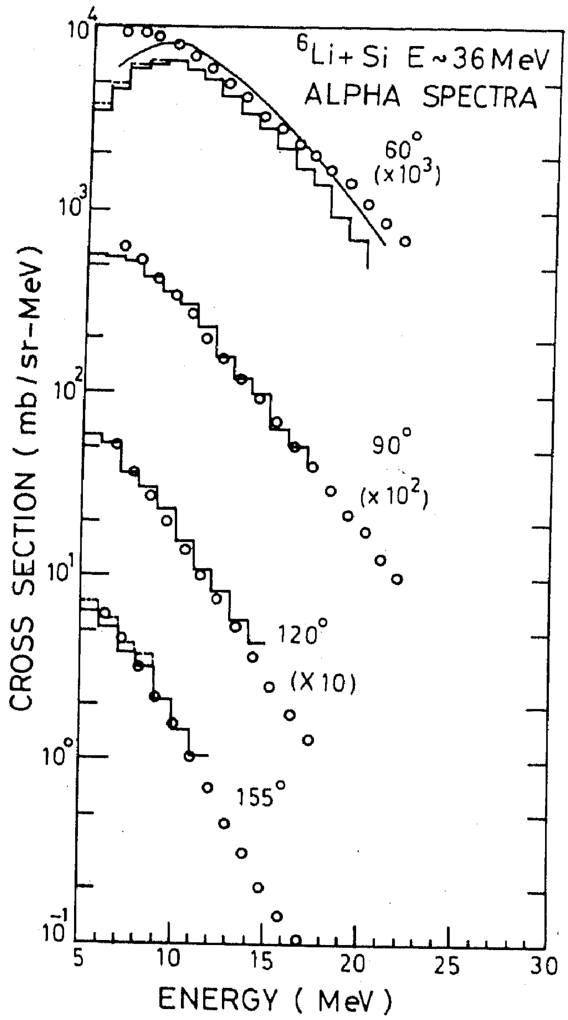

Figure 2. The alpha spectra from the reaction ^{28}Si(^{6}Li, α) measured at $\theta = 60°, 90°, 120°$ and $155°$. The histograms represent the results from PACE calculation. The dashed histogram is obtained by adding the break up fusion component as discussed in the text. The continuous line for $\theta = 60°$ spectrum is obtained by adding the α break up contribution to the evaporation spectrum calculated using the code PACE. The cross sections, the angles and the energies are in the laboratory system.

The energy calibration of the particle spectra was accomplished by making use of ^{241}Am alphas, elastic/inelastic scattering of proton from ^{12}C, elastic scattering of ^{6}Li from Si and proton recoils from the reaction ^{1}H(^{6}Li, ^{1}H) ^{6}Li. The measured proton and alpha spectra integrated over 1 MeV energy bins at $\theta = 60°, 90°, 120°$ and $155°$ are shown respectively in figures 1 and 2. The spectra in the forward angles are dominated by the break up (Tabor *et al* 1982; Utsunomiya *et al* 1983) of the projectile into fragments like deuterons, alphas and other particles. In figure 3 the spectra of alphas and deuterons measured in the forward angles are shown and the characteristic break up bumps at (1/3) E (Li) in the case of deuterons and at (2/3) E (Li) in the case of alphas can be clearly seen respectively in the deuteron and alpha spectra. It is found that the break up yield exponentially decreases with increase of scattering angle and the centroid of the break up peak changes with θ approximately as $\cos^2(\theta)$.

Using these characteristic features the break up cross section can be reliably estimated.

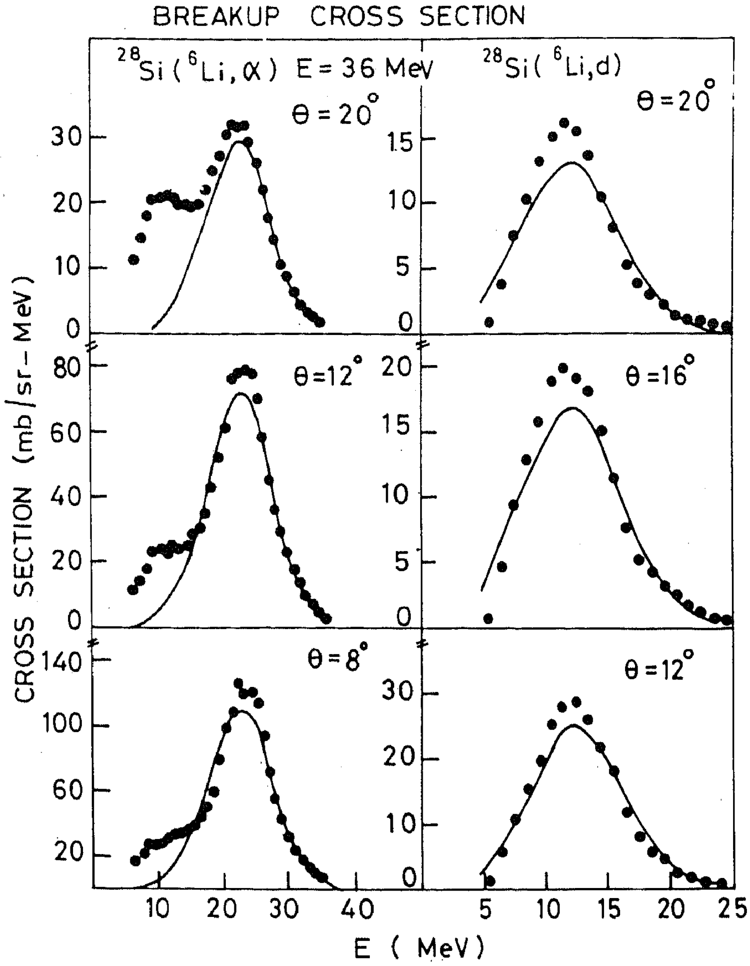

Figure 3. The alpha and the deuteron spectra measured from the reaction ^{6}Li + ^{28}Si in the forward angles of 8° to 20°. The break up peaks dominate the spectra. The fits to the break up region are shown as continuous lines. The spectra and the angles are in the laboratory system.

3. Analysis and results

3.1 *Break up cross section*

The spectra in the forward angles, though dominated by break up process on the higher energy side, have a distinctive component on the lower energy side mainly arising from the compound nuclear evaporation process. Hence a proper analysis of the spectra should include both these contributions. The spectra have been analyzed making use of the expression

$$Y = \underset{\text{(EVAPORATION)}}{Y_{\mathrm{EV}}} + \underset{\text{(BREAKUP)}}{Y_{\mathrm{BU}}}$$

$$= N_{\mathrm{EV}}(E - V_c)^{1/2} \exp\left[-\frac{E + E_0 - V_c + 2\sqrt{E_0(E - V_c)}\cos(\theta)}{T} \right]$$

$$+ \frac{N_{\mathrm{BU}}}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(E - E_{\mathrm{BU}})^2}{2\sigma^2} \right] \qquad (1)$$

V_c = Coulomb energy $= (Z_T Z_P e^2 / r_c(A_T^{1/3} + A_P^{1/3})(A_T + A_P/A_T)(r_c = 1{\cdot}44)$ where T and P stand for target and projectile (ejectile). The various parameters N_{EV}, E_0, T, N_{BU}, E_{BU}, σ were suitably varied to determine the break up yields at various θ values. The average E_{BU} values of alpha and deuteron break up peaks were at 22·4 and 12·3 MeV respectively. The average σ values of alpha and deuteron peaks were found to be 5·1 and 4·0 MeV respectively.

In figure 3 the fits due to break up part alone are shown and they reproduce well the break up region of spectra. The break up cross sections so determined have been fitted in the forward angular region by an exponential function of the form $a \exp(-b\theta)$ (a, b are adjustable parameters) and then angle integrated to obtain the total break up cross section. The alpha and the deuteron break up cross sections have been determined to be 500 ± 80 and 200 ± 30 mb respectively. As the break up proton has an energy centred at (1/6) E (Li) ~ 6 MeV which strongly overlaps with the proton evaporation region, it has not been possible to determine reliably the proton break up cross section. The ^3He and ^3H break up peaks are also seen in their respective spectra but their cross sections are not very large. The alpha and the deuteron break up cross sections obtained for $^6Li + ^{28}Si$ system compare favourably with the corresponding values of 376 ± 38 and 259 ± 26 mb obtained for $^6Li + ^{27}Al$ system (Tabor *et al* 1982). For the $^6Li + ^{28}Si$ system the total break up cross section (fragments $\alpha + d$) is ~ 700 mb. This is about 40% of the total reaction cross section deduced from the fit to the elastic scattering data.

3.2 *Fusion cross section*

In order to determine the fusion cross section, the procedure of Hugi *et al* (1981) has been followed in the present work. They determined the fusion cross section by first measuring the proton and the alpha spectra at several angles, followed by a statistical model analysis of the data. For the statistical model analysis we considered the data in the θ range 90° to 155°. The Monte carlo statistical model code PACE (Gavron 1980) has been used for the analysis. The fusion cross section σ_{FUS} is given as

$$\sigma_{FUS} = \pi \lambda\!\!\!^{-2} \sum (2l + 1)\, T_l \tag{2}$$

with $T_l = [1 + \exp((l - l_{max})/\Delta)]^{-1}$. Δ is a diffuseness parameter. In the present work we have taken $\Delta = 1$ (deduced from σ_l versus l plot). The variable l_{max} is determined by the total fusion cross section. In the present case we varied σ_{FUS} such that we obtained best fit to the proton and alpha spectra measured for angles from $\theta = 90°$ to 155°. The transmission coefficients for the light particle emission (n, p, α) were determined using the optical model potentials of Perey and Perey (1976) and Huizenga and Igo (1962). The level density $\rho(E_x, J)$ used for E_x above 5 MeV is given as

$$\rho(E_x, J) = \rho_0(U)(2J + 1) \exp\{2[a(U - E_{rot}(J))]^{1/2}\} \tag{3}$$

where $U = E_x - P$, P = Pairing energy and Erot (J) = rotational energy. We took $\rho_0(U)$ from Gilbert and Cameron formula (1965). The deexcitation process is followed by a Monte carlo procedure. The level density parameter 'a' changes the shapes of the particle spectra and the absolute magnitudes are decided primarily by l_{max} (Jarczyk *et al* 1978) or equivalently σ_{FUS} the quantity we are interested in determining. After preliminary searches on the statistical model parameters we made extensive calculations with $a = A/8$, moment of inertia as given by the rigid body estimate and the optical model parameters as discussed above. By adjusting σ_{FUS} cross section and hence l_{max} we obtained fits to the particle spectra. This has yielded σ_{FUS} values in the range 850 to 950 mb. In spite of using 10^5 cascades in the Monte carlo calculations, we could not get statistically significant cross sections for higher energy regions of the spectra. Hence the comparison of the theory and the experiment could not be extended beyond the energies shown in figures 1 and 2. The histograms in these figures represent the calculations made using PACE code.

4. Discussion on σ_{FUS} measurement and extraction of ion-ion potential

Even though a very good fit to the evaporation region of the particle spectra was possible for angles beyond 90°, the calculation was discrepant with the data at smaller θ values. The reasons for this discrepancy were explored. Firstly, the influence of break up contributions in the evaporation region as well as in the higher energy region was considered. Extrapolating the angular distribution of break up process observed for angles up to 30° to larger angles gave an estimate of this process at other angles. The break up peak centroid was also adjusted for θ variation. For example for $\theta = 60°$ in the case of alphas the centroid energy is close to 10 MeV and with $\sigma = 5{\cdot}1$ MeV, we determined the energy spectrum due to break up process. This when added to the evaporation yield as calculated by PACE gave the continuous line as shown in figure 2. This clearly demonstrates the importance of break up contributions in forward angles spectra.

There is also yet another contribution which needs to be considered. This is the process of break up fusion (Utsunomiya *et al* 1983; Belery *et al* 1987) in which one of the fragments from the projectile after break up fuses with the target giving rise to light particles from the evaporation process. An estimate of the contribution of light particles due to break up fusion-alpha and deuteron break up with the resulting deuteron fusing with the Si target giving rise to protons and alphas is made as follows. It is seen that from break up $\sigma_\alpha > \sigma_d$. This difference may be due to the fact that the alpha particles can be produced in more ways than the deuterons (Utsunomiya *et al* 1983). We make the simple assumption that the difference arises due to the fact these deuterons $(\sigma_\alpha - \sigma_d)$ are perhaps absorbed by the target by break up fusion process as discussed above. As break up is a direct reaction it takes place preferentially on the surface of the target nucleus. For an approximate value of $\sigma_{FUS} \simeq 900$ mb, we can deduce $l_{FUS} = 13{\cdot}2$. $((\sigma_{FUS}/\pi\lambda^2) = (l_{FUS} + 1)^2)$. As the deuteron has the same velocity as ^{6}Li, the angular momentum of deuteron will scale as $(2/6) l_{FUS} \sim 5$. Starting with $E_d = 12$ MeV $(2/6\, E_{Li})$ interacting with Si target we made a statistical model calculation assuming $\sigma_{FUS}(d) \simeq 300$ mb. $(\sigma_\alpha - \sigma_d = 500\text{–}200)$. Further we assigned all this cross section to $1 = 5$. $(\sigma_{FUS}(d) = \sigma_l(l = 5))$. The proton and the alpha evaporation cross sections calculated by this procedure when added to the evaporation calculation made for the Li beam interacting with Si results in the dashed histograms shown in figures 1 and 2. As can be seen from the figures, this extra contribution arising due to break up fusion leads to better agreement with the data for alphas. However in the case of protons, there is a good agreement between theory and experiment at $\theta = 60°$, but not at $\theta = 155°$. The calculations over predict considerably the proton data at 155°.

In the present statistical model code we have not included the decay of the compound nucleus with the emission of deuterons. The evaporation cross section for this channel is about 50 mb. Inclusion of this channel in the calculation with σ_{FUS} fixed at the value mentioned above (~ 900 mb) will lead to some reduction in the values of alpha and proton cross section spectra. Hence in order to make the theory agree with experiment we will have to increase σ_{FUS} a little.

From the above discussion it is clear that if direct break up and break up fusion components are properly taken into account there could be an improved agreement with the data. We could also make a rough estimate of break up fusion contribution for the case where we assume 300 mb missing deuteron cross section ($\sigma_\alpha - \sigma_d$) is due to deuteron fusing with the Si target (as discussed above). From a statistical model calculation we can estimate for Li + Si system with $\sigma_{FUS} = 900$ mb, the proton multiplicity M_p to be 1·3. For d + Si system with $\sigma = 300$ mb the M_p is 0·5. Therefore the percentage of protons from deuteron fusion is $(300 \times 0{\cdot}5)/(900 \times 1{\cdot}3) \times 100 = 13$. It can be concluded that the break up fusion is not negligible and it could be 10 to 15% and the present data are consistent with this estimation. We estimate the fusion cross section for Si + Li system to be 900 ± 90 mb. This is in good agreement with the Bass model estimate which is 880 mb. Adding the fusion cross section of 900 mb with the break up cross section ($\alpha + d$) we get the total cross section to be 1600 mb which compares favourably with the reaction cross section value of 1750 mb.

The main motivation for measuring the fusion cross section at $E = 36$ MeV is to combine this with the other fusion cross section values measured at lower energies to determine V_N(Li + Si real potential) versus R (interaction distance) by the procedure discussed by Bass (1977) and Kailas and Gupta (1986). We refitted the fusion excitation function for the Li + Si system using the expression

$$\begin{aligned} \sigma_{FUS} &= 10\pi\rho(\rho - D)\,\text{mb} \\ \rho &= mE + b\,\text{fm} \\ D &= \frac{1{\cdot}44 Z_{Li} Z_{Si}}{E}\,\text{fm} \\ m &= (\text{fm/MeV}) \\ b &= (\text{fm}). \end{aligned} \tag{4}$$

The best fit parameters are $m = -0{\cdot}101 \pm 0{\cdot}022$ and $b = 9{\cdot}566 \pm 0{\cdot}486$. The fit to the fusion data is shown in figure 4a. The V_N and R values deduced starting with these parameters are shown by the continuous line in figure 4b. The dashed line is the one obtained from an analysis of elastic scattering data. It is found that the potentials obtained by both the methods agree very well up to an interaction distance approximately equal to sum of the half density radii ($R \sim 5$ fm). At smaller values of R($R < 4{\cdot}5$ fm), the two potentials differ considerably. As there is considerable overlap of target and projectile at smaller distances, the potentials determined at these distances may have large uncertainties and it may not be very meaningful to compare the potentials at distances very much smaller than sum of the half density radii of the interacting ions. It may be mentioned that with the excitation function data available earlier (up to 25 MeV) we could make a reliable comparison of the potentials (deduced by the two methods) only up to $R \sim 6$ fm. The present additional measurement at $E \simeq 36$ MeV has made it possible to extend the comparison of the potentials to smaller distances.

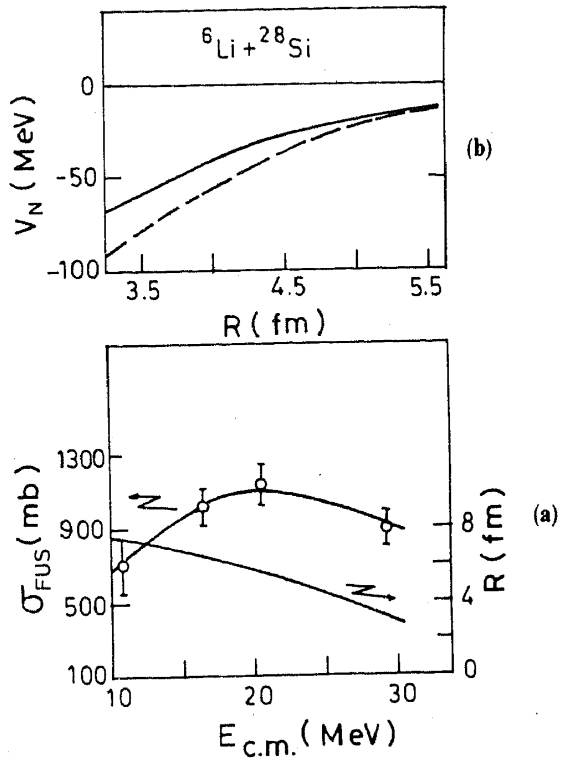

Figure 4a. The fusion excitation function for the system ^{6}Li + ^{28}Si and the fit to the data using the prescription discussed in the text. The highest energy point is from the present work and the rest are from Hugi *et al* (1981). The deduced R values are as indicated. (bottom).
Figure 4b. The real potential values V_N plotted as a function of the interaction distance R. The dashed line is obtained from analysis of elastic scattering data. The continuous line is obtained from analysis of fusion excitation function data. (top)

5. Conclusion

In the present work we have reported the measurement of the fusion cross section for the system ^{6}Li + ^{28}Si at a bombarding energy of 36 MeV. Combining this with the other values available at lower energies we have deduced the real potential values at several values of R. It is found that there is a good agreement between the potentials determined from analysis of fusion and elastic scattering analyses, thereby confirming our earlier observations.

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