Interplay of static and dynamic effects in $^6\text{He}+^{238}\text{U}$ Fusion

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Abstract
We investigate the influence of the neutron halo and the breakup channel in $^6\text{He}+^{238}\text{U}$ fusion at near-barrier energies. To include static effects of the $2n$-halo in $^6\text{He}$ nuclei, we use a single-folding potential obtained from an appropriate nucleon-$^{238}\text{U}$ interaction and a realistic $^6\text{He}$ density. Dynamical effects arising from the breakup process are then included through coupled-channel calculations. These calculations suggest that static effects dominate the cross section at energies above the Coulomb barrier, while the sub-barrier fusion cross section appears to be determined by coupling to the breakup channel. This last conclusion is uncertain due to the procedure employed to measure the fusion cross-section.

1 Introduction

The recent availability of radioactive beams has made possible to study reactions involving unstable nuclei [1]. Several of the light neutron and proton rich nuclei exhibit halo structures, with a compact core plus one or two loosely bound nucleons. For example, $^{11}\text{Li}$ and $^6\text{He}$ are two-neutron, borromean halo nuclei, while $^{11}\text{Be}$ and $^{19}\text{C}$ are one-neutron halo nuclei. The isotope $^8\text{B}$ has been confirmed to have a one-proton halo, while $^{17}\text{F}$ is a normal nucleus in its ground state but becomes a one-proton halo in its first excited state.

Reactions induced by these nuclei are important in processes of astrophysical interest, among others. We ask the question of how the above systems fuse, in particular how the fusion induced by these nuclear species behaves as a function of bombarding energy, especially near the Coulomb barrier.
The main new ingredient in reactions induced by unstable projectiles is the strong influence of the breakup channel. One important feature of these loosely bound systems is that they exhibit the so-called soft giant resonances (pygmy resonances), the most notorious of which is the soft dipole resonance, very nicely confirmed in $^6$He by Nakayama et al. [2].

In the case of not too unstable projectiles, the effect of the breakup channel in the fusion cross section at sub-barrier energies is, as in the case of stable beams, to enhance it. At slightly above-barrier energies, however, the situation is qualitatively different from the case where only stable nuclei are involved. The contribution from the breakup channel to the fusion reaction is strongly influenced by the low probability that all fragments are captured. Thus, in this case, the fusion cross section is partitioned into a complete and one or more incomplete fusion contributions.

Recently, nuclear reactions involving the neutron-rich nucleus $^6$He have attracted considerable attention [3]. In particular, very interesting experimental data on the fusion of He isotopes with $^{238}$U have been obtained [4]. These data show an enhancement of several orders of magnitude of the $^6$He+$^{238}$U fusion cross section with respect to that of $^4$He+$^{238}$U. The physical process leading to this result has not yet been established. A natural candidate is the coupling with the breakup channel. This led us to develop a simple theoretical model to estimate statical and dynamical effects of the breakup channel on the complete and incomplete fusion cross section in the $^6$He+$^{238}$U collision. The extension of the model to study fusion induced by other radioactive beams is straightforward.

The paper is organized as follows. Section 2 describes the calculation of the static effects brought about by the presence of a nuclear halo. The coupling to the breakup channel is performed, by means of schematic coupled-channels calculations, in section 3. Our conclusions are presented in the last section.

## 2 Static effects from the 2n-halo

The weakly bound neutrons in $^6$He are expected to influence the fusion cross section in two ways. Firstly, by the static effect of barrier lowering due to the existence of a halo. Secondly through the coupling with the breakup channel. In this section we consider the first of these effects.
Owing to the two weakly bound neutrons in $^6$He, the nuclear density has a long-range tail and so does the real part of the optical potential describing the $^6$He-target collision. In this way, the potential barrier is lowered and the fusion cross section is enhanced. In order to account for this effect, we use a single folding model to describe the real part of the nuclear $^6$He-$^{238}$U interaction. This potential is given by the expression

$$V_N(r) = \int v_{n-T}(r - r') \rho(r') \, d^3r'. \quad (1)$$

Above, $v_{n-T}(r - r')$ is a phenomenological interaction between a nucleon and the $^{238}$U target nucleus and $\rho(r')$ is a realistic $^6$He density, containing the contribution from the halo. The nucleon-$^{238}$U interaction is obtained from studies of the collision of low-energy neutrons with heavy target nuclei in the actinide region. It can be written (discarding the spin-orbit part) [5]

$$v_{n-T}(x) = -V_0 \, f_r(x), \quad (2)$$

with

$$V_0 = \left[50.378 - 27.073 \, \left(\frac{N - Z}{A}\right) - 0.354 \, E_{Lab}\right] \, (MeV) \quad (3)$$

and

$$f_r(x) = \frac{1}{1 + \exp \left[\left(\frac{x - R}{a_r}\right)\right]}, \quad (4)$$

with the parameters $R_r = 1.264 \, A^{1/3} \, \text{fm}$ and $a_r = 0.612 \, \text{fm}$. The total optical potential is then given by

$$U(r) = V_N(r) + V_C(r) - iW(r). \quad (5)$$

Above, $V_C(r)$ is the usual Coulomb interaction in nuclear collisions,

$$V_C(r) = \begin{cases} \frac{Z_P Z_T e^2}{r} & \text{for } r \geq R_C = 1.2 \left(\frac{A^{1/3}}{A} + \frac{A^{1/3}_p}{A_p}\right) \\ \frac{Z_P Z_T e^2}{2R_C} \left(3 - \frac{r^2}{R_C^2}\right) & \text{for } r < R_C. \end{cases} \quad (6)$$
and $W(r)$ is a volumetric strong absorption potential with small values for both its radius and diffusivity. We use the parametrization

$$W(r) = W_0 f_i(r),$$

with $W_0 = 50$ MeV and $f_i(r)$ a Wood-Saxon shape as in eq.(4) with

$$R_i = 1.0 \left( A_P^{1/3} + A_T^{1/3} \right) \text{ fm}, \quad a_i = 0.10 \text{ fm}.$$  

As a test, we applied the above procedure to $^4\text{He} + ^{238}\text{U}$ fusion. The nuclear potential was evaluated by eq.(1) using a Gaussian density. We write

$$\rho(r) = C \exp \left( -r^2/\gamma^2 \right)$$

and choose the parameters $C$ and $\gamma$ as to give the correct normalization and experimental r.m.s. radius. That is

$$\int \rho(r) d^3r = A; \quad \int r^2 \rho(r) d^3r = r_{rms}^2.$$  

In the present case, we set $A = 4$ and $r_{rms} = 1.49$ fm [6]. The fusion cross section obtained with our optical model calculation with the single folding potential is shown in figure 1 (thin solid line), in comparison with the data of Trotta et al. [4] and the data of Viola and Sikkland [7]. The agreement is very good. Since the calculation contains no free parameter, this agreement indicates that the procedure is reasonable.

We now consider $^6\text{He} + ^{238}\text{U}$ fusion. Firstly, we disregard the existence of the $^6\text{He}$ halo and repeat the above procedure. We parametrize the density as in eq.(9) and scale the density and r.m.s. radius to $^6\text{He}$. That is, we set in eq.(10) $A = 6$ and $r_{rms} = (6/4)^{1/3} \times 1.49$ fm. This density is then used in eq.(1) and the folding potential is determined. The fusion cross section calculated with this potential is shown in figure 2 (dashed line), in comparison with the data [4]. The agreement is poor throughout the considered energy range. We now take into account the existence of the $^6\text{He}$ halo, replacing the gaussian of eq.(9) by a realistic parametrization [6] of the $^6\text{He}$ density, based on the symmetrized Fermi distribution of ref. [8]. It leads to the r.m.s. radius $r_{rms} = 2.30$ fm. Using this density in eq.(1), we obtain a potential which includes contributions from the $^4\text{He}$-core and also from the
2n-halo. The resulting fusion cross section is represented by a solid line in figure 2. We note that the agreement with the data at above barrier energies ($E_{c.m.} > V_B \simeq 22.3$ MeV) is considerably improved. Since the Coulomb barrier height is reduced by the attractive contribution from the halo, the cross section becomes larger. However, at sub-barrier energies the agreement remains very poor. The theoretical prediction for the fusion cross section is still several orders of magnitude smaller than the experimental data.

3 Coupled channel effects

It is well known that the coupling between channels enhances the fusion cross section at sub-barrier energies [9]. Therefore, coupled-channel effects should be taken into account in a theoretical description of the fusion process. However, in the case of coupling to the breakup channel the situation is more complicated since the breakup channel involves an infinite number of continuum states. A possible treatment of the problem, used in refs. [10, 11], is to use continuum discretization to reduce it to a finite number of channels. The situation is still more complicated in the breakup of $^6$He, since it breaks up into three particles. In the present work we schematically replace the breakup channel by an effective channel [12]. This state has energy equal to the breakup threshold and carries the full strength of the continuum. This procedure is justified when breakup occurs through a low-lying long-lived resonance (with a half life much larger than the collision time), as it seems to be the case with $^6$He [2]. Since the kinetic energy of the relative motion between the $^4$He-core and the neutron pair is neglected, this approximation tends to overestimate the importance of the coupling to the breakup channel. Therefore the simplified model of the present work should provide an upper limit for the fusion cross section.

The starting point of the coupled channel method is the Schrödinger equation for the colliding system,

$$H\Psi(r, \xi) = E\Psi(r, \xi),$$  \hspace{1cm} (11)

where $r$ is the projectile-target vector, $\xi$ stand for the relevant intrinsic coordinates, $E$ is the total energy in the center de mass frame and $H$ is the total Hamiltonian of the system. One then performs the channel expansion
of the wave function
\[ \Psi(r, \xi) = \sum_{\alpha} \psi_{\alpha}(r) \phi_{\alpha}(\xi), \quad (12) \]

where \( \phi_{\alpha}(\xi) \) denotes an intrinsic state with energy \( \epsilon_{\alpha} \) and \( \psi_{\alpha}(r) \) is the relative motion wave function in channel-\( \alpha \). Substituting this expansion in eq.(11), we obtain the coupled-channel equations
\[ (E_{\alpha} - H_{\alpha}) \psi_{\alpha}(r) = \sum_{\beta} V_{\alpha\beta}(r) \psi_{\beta}(r). \quad (13) \]

Above, \( E_{\alpha} = E - \epsilon_{\alpha} \) and \( H_{\alpha} = T + U_{\alpha}(r) \), where \( U_{\alpha}(r) \) is the optical potential in channel-\( \alpha \). The channels are coupled through an interaction \( V(r, \xi) \), with matrix-elements in channel space given by
\[ \nu_{\alpha\beta}(r) = \int d\xi \phi_{\alpha}^*(\xi) v(r, \xi) \phi_{\beta}(\xi). \quad (14) \]

For practical purposes, it is convenient to carry out angular momentum expansions. The wave function is then written as (see e.g. [13])
\[ \Psi^{(+)}(\alpha \nu_0 k_0; r) = \frac{1}{(2\pi)^{3/2}} \sum_{J M \ell_0} 4\pi \langle J M | l_0(M - \nu_0) I_0 \nu_0 \rangle Y_{\ell_0}(M - \nu_0) (\hat{k}_0) \]
\[ \times \sum_{\alpha \ell} Y_{\alpha \ell}^{\pi, J M}(\xi) \frac{u_{\alpha \ell, \ell_0}(k_{\alpha}, r)}{k_0 r} \quad (15) \]

and using this expansion in eq.(11) one obtains the angular momentum projected coupled channel equations
\[ [E_{\alpha} + \frac{\hbar^2}{2\mu} \left( \frac{d^2}{dr^2} - \frac{l (l + 1)}{r^2} \right) - V_{\alpha l}(r)] u_{\alpha l, \ell_0}(k_{\alpha}, r) = \sum_{\alpha' \ell'} V_{\alpha l, \alpha' \ell'}(r) u_{\alpha' \ell', \ell_0}(k_{\alpha'}, r). \]

In the present calculation, \( \alpha \) takes only the values 0 (elastic channel) and 1 (effective breakup channel). For the energy of the breakup channel we used \( \epsilon_1 = 0.975 \text{ MeV} \), which corresponds to the breakup energy. As said above, this means we neglect the kinetic energy of the relative motion of the fragments after breakup.
We initially consider the coupling interaction as the electric dipole term in the multipole expansion of the electromagnetic interaction between the projectile and the target. This is based on the idea that, in order to break a very weakly bound nucleus, only a small perturbation is needed. The fact that the breakup cross section for those nuclei is very large, suggests that this process is important.

In the case of a electric dipole interaction, the coupling matrix elements are [13]

\[
\mathcal{V}^{J}_{l,l_0}(r) = A \ i^{l-l_0} \ i_l \ i_{l_0} \sqrt{\frac{4\pi}{3}} \frac{1}{r^2} \begin{pmatrix} l & 1 & l_0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} J & 1 & l \\ 1 & l_0 & 0 \end{pmatrix},
\]

(17)

with

\[
A = eZ_T \sqrt{B(E1, 0 \rightarrow 1)} (-)^{J+1}
\]

(18)

Above, \( \begin{pmatrix} l & 1 & l_0 \\ 0 & 0 & 0 \end{pmatrix} \) and \( \begin{pmatrix} J & 1 & l \\ 1 & l_0 & 0 \end{pmatrix} \) are the usual 3J and 6J symbols [14]. Note that the above matrix-elements are fully determined, except for the value of the reduced transition probability \( B(E1, 0 \rightarrow 1) \).

Solving the coupled channel equations, one obtains the fusion cross section by the formula\(^1\)

\[
\sigma_F = (2\pi)^3 \ \frac{k_0}{E} \sum_{\alpha=0}^{1} \langle \psi_\alpha^{(+)} \vert W_\alpha \vert \psi_\alpha^{(+)} \rangle.
\]

(19)

The method of the present work was used to evaluate the fusion cross section in the \(^6\)He+\(^{238}\)U collision. We used the optical potential discussed in the previous section, which include the static effects of the halo. The coupling matrix-elements were given by eqs.(17) and (18), with the \( B(E1, 0 \rightarrow 1) \) given by the cluster model [1],

\[
B(E1, 0 \rightarrow 1) = \frac{3\hbar^2 e^2}{16\pi \epsilon_1 \mu_{2n-4He}}.
\]

(20)

\(^1\)The constant \((2\pi)^3\) in the expression for \(\sigma_F\) arises from the normalization factor \((2\pi)^{-3/2}\) adopted for \(\psi_\alpha^{(+)}\).
Above, $\epsilon_1$ is the energy binding the dineutron to $^4$He in the $^6$He nucleus and $\mu_{2n-^4He}$ is the corresponding reduced mass. Taking the numerical value of eq.(20), we obtain $B(E1, 0 \rightarrow 1) = 1.37 \, e^2 \, \text{fm}^2$.

Recently Hagino et al. [10] have shown that the effects of the nuclear coupling may extend quite far in the case of weakly bound nuclei. In order to estimate the additional dynamic effects arising from the nuclear interaction, we must include the coupling due to the nuclear potential. Since we use an effective channel to describe breakup states, the calculation of the nuclear form factor is a complicated task. For the estimates of the present work, we considered the nuclear interaction potential associated to $^6$He breakup to be the difference between the sum of the nuclear potentials between $^{238}$U and $^4$He and the dineutron, and between $^{238}$U and the $^6$He projectile, i.e.

$$V_{\text{int}}^N(r, x) = V_{^4\text{He}}(r + x/3) + V_{2n}(r - 2x/3) - V_{^6\text{He}}(r).$$

Above, $x$ is the vector going from the di-neutron to the $^4$He cluster, $V_{2n}$ is twice the potential of eq.(2) and $V_{^4\text{He}}$ and $V_{^6\text{He}}$ are the folding potentials of the previous section. We carry out the angular momentum expansion

$$V_{\text{int}}^N = \sum_{\lambda, \mu} Y_{\lambda\mu}(\hat{r}) Y_{\lambda\mu}^*(\hat{x}) \, V_{\lambda}^N(r, x),$$

and keep only the dipole term ($\lambda = 1$). In this way, the nuclear form factor is

$$F_{\lambda=1}^N(k; r) = \int_0^\infty dr \, \phi_0(x) \, V_{1}^N(r, x) \, u_1(k, x),$$

where $\phi_0(x)$ is the radial function associated to the bound state of the $2n-^4$He system and $u_1(k, x)$ the $l = 1$ continuum radial wavefunction for the same system, with energy $E_k = \hbar^2 k^2 / 2\mu_{2n-^4He}$. Both functions are calculated using the radial Schrödinger equation associated to the internal coordinate $x$. The depth of the $V_{2n-^4He}$ potential was set in order to have the second S-state with energy $E_0 = -0.975 \, \text{MeV}$ (to be consistent with Pauli Principle we discarded the first S-state). Owing to the normalization of $u_1(k, x)$, the above form factor vanishes in the $k \rightarrow \infty$ limit. However, the absolute strength of $F_{\lambda=1}^N$ should be treated as a free parameter, since the final state is an effective channel. In this way, we adopt the form factor

$$F_1^N(r) = F_0 \, f(r),$$

8
with

\begin{equation}
\frac{f(r)}{f(0)} = \lim_{k \to \infty} \left[ \frac{F_{\lambda=1}^N(k;r)}{F_{\lambda=1}^N(k;0)} \right].
\end{equation}

To estimate the strength \(F_0\), we adopt the following procedure. Firstly, we evaluate the Coulomb form factor as we evaluated the nuclear one. Instead of using \(B(E1, 0 \to 1) = 0.59 \, e^2 \, \text{fm}^2\), we calculate reduced matrix elements of the dipole term in the Coulomb coupling using the analog of eq.(23). The resulting Coulomb and nuclear dipole form factors are shown in figure 3. Since the dipole term of the nuclear coupling cannot be written as a product of a function of \(r\) times a function of \(x\), as can the Coulomb coupling to a good approximation, the shape of the nuclear form factor depends on the energy of the continuum state in the \(x\)-space. However, the shape of the nuclear form factor does not change much as \(k \to 0\). Although both form factors go to zero in this limit, they decrease by a common factor. In figure 3, we show the Coulomb and the nuclear form factors for a very low energy in the continuum. We see that the ratio of these form factors changes strongly with the radial distance. The Coulomb form factor dominates at large separations while the nuclear form factor is larger at small separations. They have approximately the same strength at \(r \simeq 16 \, \text{fm}\). In the present calculation, we use the experimental \(B(E1, 0 \to 1)\) value and choose the parameter \(F_0\) such that the ratio between the nuclear and the Coulomb form factors is maintained.

Figure 4 shows the \(^{6}\text{He} + ^{238}\text{U}\) total fusion data in comparison to the static (dashed line) calculation of the previous section, and two coupled channels calculations. The thin line is the coupled channel calculation restricted to Coulomb breakup. We notice that the cross section at high energies is little affected by the inclusion of the breakup channel. Although the sub-barrier cross section is larger than that found in the previous section, it remains much smaller than the experimental values.

The solid line is the calculation including also the nuclear coupling. We notice that it also changes little the cross section at high energies, and although the nuclear coupling affects more the fusion cross section at sub-barrier energies, the slope remains much larger than that suggested by the data. Changing the strength or diffuseness parameters of this coupling does not change this behavior.

It should be pointed out that the coupling with excited states of \(^{238}\text{U}\) is not likely to be relevant for this issue, since they were not necessary for the
description of the $^4\text{He}+^{238}\text{U}$ fusion data, considered in section 2. As our calculation should provide an upper limit for the cross section, the experimental fusion cross section at the lowest energies cannot be explained through our calculations. However, one should keep in mind that in the calculations presented here we have not included effects due to coupling to other channels other than breakup, and in particular the transfer channels. As transfer close to the optimal Q-value may be quite important at sub-barrier energies [15], coupling to those channels, which should not affect much the $^4\text{He}+^{238}\text{U}$ fusion, is expected to influence strongly sub-barrier $^6\text{He}+^{238}\text{U}$ fusion. This could also be the case for the $^6\text{He}+^{209}\text{Bi}$ total fusion cross section, where the data [16] show a similar trend as sub-barrier energies.

4 Conclusions

We have investigated static and dynamic effects on the $^6\text{He}+^{238}\text{U}$ fusion cross section. Static effects of the halo were taken into account through the use of an appropriate optical potential. This potential was obtained by the single folding model, with a nucleon-target interaction which is able to reproduce the $^4\text{He}+^{238}\text{U}$ fusion cross section and from a realistic $^6\text{He}$ density. Dynamical effects were considered in a simplified coupled channel calculation, in which the breakup channel was represented by a single state with energy $\epsilon_1 = 0.975$ MeV (the threshold for $^6\text{He}$ breakup), concentrating all the low energy dipole strength. From our calculations we concluded that the static effects dominate the behavior of the fusion cross section at energies above the Coulomb barrier. The dynamic coupling to the breakup channel is important mostly below the barrier. It may be separated into the Coulomb and nuclear contributions. Although the breakup process takes place at large distances, we have shown that the coupling with the breakup channel cannot reproduce the main trends of the data in the sub-barrier region. We believe that demonstrates that a full description of the $^6\text{He}+^{238}\text{U}$ fusion cross section at sub-barrier energies requires the inclusion of neutron-transfer channels. We point out that a similar enhancement of the sub-barrier fusion cross section has also been observed in the collision of $^6\text{He}$ with $^{209}\text{Bi}$.

After the completion of this paper we have learned [17] that the data of Trotta et al. [4] have been reanalyzed and new data with a different experimental set up have been taken. The new set of data seems to indicate that
the large enhancement at sub-barrier energies is due to transfer-fission, rather than fusion-fission events. This is consistent with our previous remarks.

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References

[1] C.A. Bertulani, L.F. Canto and M.S. Hussein, Phys. Rep. 226, 281 (1993); C.A. Bertulani, M.S. Hussein and G. Münzenberg, “Physics of Radioactive Beams” (Nova Science, New York, 2001); M. S. Hussein, L.F. Canto and R. Donangelo, Nucl.Phys. A722, 321c (2003).

[2] S. Nakayama et al. Phys. Rev. Letters 85, 262 (2002).

[3] T. Aumann et al., Phys.Rev.C59, 1252 (1999).

[4] M. Trotta et al., Phys. Rev. Lett. 84, 11 (2000).

[5] D.G. Madland and P.G.Young, Los Alamos Report No. LA7533-mb (1978) (unpublished).

[6] G. D. Alkhazov et al., Phys. Rev. Lett. 78, 2313 (1997).

[7] V.E. Viola and T. Sikkeland, Phys. Rev. 128, 767 (1962).

[8] Yu. N. Eldyshev, V.N. Lukyanov. and Yu. S. Pol, Sov. J. Nucl. Phys. 16, 282 (1973).

[9] C.H. Dasso, S. Landowne and A. Winther, Nucl. Phys. A432, 495 (1985).
[10] K. Hagino, A. Vitturi, C.H. Dasso and S. Lenzi, Phys. Rev. C61, 037602 (2000).

[11] A. Diaz-Torres and J.J. Thompson, Phys. Rev. C65, 024606 (2002).

[12] A.M.S. Breitschaft et al., Ann. of Phys. 243, 420 (1995).

[13] G.R. Satchler, “Direct Nuclear Reactions”, Oxford University Press, 1983.

[14] A.R. Edmonds, “Angular Momentum in Quantum Mechanics”, Princeton University Press, Princeton, New Jersey, 1974.

[15] E. Switkowski, R.M. Wieland and Aa. Winther, Phys. Rev. Lett. 33, 840 (1974).

[16] J.J. Kolata et al., Phys. Rev. Letters 81, 4580 (1998)

[17] M. Trotta, private communication.
Figure captions

Figure 1: $^4\text{He} + ^{238}\text{U}$ fusion cross sections. The data of refs.[4] (solid squares) and ref.[7] (open squares) are compared with the calculations of the present work. The barrier energy is indicated by an arrow. For further details see the text.

Figure 2: Coulomb coupling to the breakup channel for the $^6\text{He} + ^{238}\text{U}$ fusion cross section. Experimental results [4] are compared with a static calculation similar to that of figure 1, with just a scaling of the potential $^4\text{He}$ (dashed line), and taking into account the fact that $^6\text{He}$ is a halo nucleus (full line).

Figure 3: Coulomb and nuclear dipole form factors (a) and their ratio (b). See text for details.

Figure 4: Total fusion data of $^6\text{He}$ incident on $^{238}\text{U}$ in comparison to the static calculation, including the $^6\text{He}$ halo, of figure 2 (dashed line), a coupled channel calculation including only the Coulomb interaction (thin full line), and also including nuclear effects (thick full line). See text for details on these two last calculations.
Figure 1

\( ^4\text{He} + ^{238}\text{U} \)
Figure 2

Data of Trotta et al. without static effect

with static effect

\[ \sigma_F (\text{mb}) \]

\[ E_{\text{c.m.}} \ (\text{MeV}) \]
Figure 3

Form factors

- **Coulomb**
- **Nuclear**

**arbitrary units**

(a)

**$F_N(r) / F_C(r)$**

(b)
Figure 4

$\sigma_F (\text{mb})$

$E_{\text{c.m.}} (\text{MeV})$

$^6\text{He} + ^{238}\text{U}$

- Data of Trotta et al.
- Only static effect
- Coulomb coupling
- C+N coupling

$V_B = 20.4 \text{ MeV}$

$1 \times 10^4$

$1 \times 10^3$

$1 \times 10^2$

$1 \times 10^1$

$1 \times 10^0$