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STATIC AND DYNAMIC DEFORMATION EFFECTS IN THE FUSION CROSS SECTION OF LIGHT HEAVY IONS AT SUB-BARRIER ENERGIES*

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A B S T R A C T

The static and dynamic deformation effects on the sub-barrier fusion cross section of light heavy ions are investigated by performing a coupled channel calculation for the system $^{12}C + {}^{16}O$. It is found that dynamic effects are negligible whereas static effects could be important.

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It is a common practice in sub-barrier light-heavy ion data analysis, particularly in the case of fusion, to utilize spherically symmetric potentials[1]. Althought the quality of the fits obtained is often quite good there are, however, several systems, e.g. $^{12}C + ^{12}C$, $^{16}O + ^{12}C$, where this type of analysis has always presented difficulties. Here we will discuss the static and dynamic effects that the deformed shape of nuclei such as ^{12}C induces on the fusion cross section at sub-barrier energies.

In so far as ^{12}C is considered to be oblately deformed the fusion process will depend on the relative orientation of the two nuclear surfaces as the corresponding densities start overlapping. In the case of the fusion of a spherical nucleus (1) with a deformed nucleus (2) the sum of the nuclear radii is given by:

$$R(\theta) = r_0\left[A_1^{1/3} + A_2^{1/3}\left(1+\sqrt{\frac{5}{4\pi}}\beta_2 P_2(\cos\theta)\right)\right] \tag{1}$$

where is the angle subtended between the symmetry axis of (2) and the line connecting the centers of (1) and (2), A_1 and A_2 are the mass numbers of the two nuclei, β_2 the quadrupole deformation parameter of (2) and P_2 the second degree Legendre polynomial.

Considering the specific case of ^{16}O impinging over $^{12}C(\beta_2 = -0.47)$ the largest and smallest spatial extentions of the fusing system are given by:

$$\begin{aligned} R_> &= R\left(\frac{\pi}{2}\right) \\ R_< &= R(0) \end{aligned} \tag{2}$$

leading to a relative change in the barrier height, as compared to the spherical case

$$\frac{\Delta E_b}{\overline{E_b}} = \frac{\frac{1}{R_<} - \frac{1}{R_>}}{\frac{1}{\overline{R}}} \sim 25\% \tag{3}$$

The above result is a clear indication of possible static effects due to the deformation of ^{12}C effecting the sub-barrier fusion cross section.

Besides this static effect there might be dynamical effects due to coupling to inelastic channels. Consideration of the coupling to the 2^+ excited state in ^{12}C has been made by Imanishi [2] several years ago. The importance of this coupling in explaining several features of the fusion cross section of $^{12}C + {}^{12}C$ and $^{16}O + {}^{12}C$ was emphasized by this author.

In order to study both static and dynamic effects on the fusion cross section we have performed coupled-channel calculations on the system $^{16}O + {}^{12}C$ involving both the ground and the first excited (E_{2^+} = 4.43 MeV) states of ^{12}C, using the code CHUCK[3]. The optical potential used was a deformed, surface-transparent; Wood-Saxon potential. The diffuseness, a_w, of the imaginary part of this potential was restricted to values satisfying the condition[4]

$$a_W \leq \frac{\hbar}{\sqrt{8\mu E_b}} \tag{4}$$

In equation (4) μ is the reduced mass of the fusing system and E_b the Coulomb barrier height.

These calculations were performed for the experimental value of the deformation parameter of ^{12}C, β_2=-0.47 [5], as well as for β_2 = 0.0 and β_2 = -0.6, for the purpose of comparison and later discussion. Other parameters entering the calculation are given in the caption of figure (1).

Our results are shown in figure (1). In figure (1a) the modulii of the $\ell=0$ wave amplituted are plotted as a function of the certer-of-mass energy E_{CM}, where as in figure (1b) we exhibit $\sigma_{Fusion}(E_{CM})$. It is immediately seen that an increase in the deformation parameter β_2 yields a corresponding increase in σ_{Fusion}.

In view of the fact that the inelastic cross section resulting from our coupled channel calculation was found to be quite small ($\sim 10^{-5}$— 10^{-8} mb), such an increase in σ_{Fusion} should be attributed exclusively to the static deformation effects. Such an increase in σ_{Fusion} can be mocked up in the strength of the absorptive potential or in a lowering and/or narrowing of the Coulomb barrier. The latter possibilities are connected to the choice of the real part of the optical potential. In figure (2) we show a calculation with a larger value of W_0 indicating also an increase in σ_{Fusion}.

A natural way to take the effects of the static deformation into account is to average the nuclear optical potential $U(r,\theta)$ over all orientations:

$$\bar{U}(r) = \int_0^{\pi/2} U(r,\theta)\sin\theta \, d\theta \tag{5}$$

In the present paper $U(r,\theta)$ is given by the deformed Wood-Saxon form

$$U(r,\theta) = -\frac{V_0}{1+\exp\left[\frac{r-R(\theta)}{a_R}\right]} - \frac{iW_0}{1+\exp\left[\frac{r-R(\theta)}{a_W}\right]} \tag{6}$$

where $R(\theta)$ is given by equation (1).

In the limiting case where the diffuseness parameter is very small, as it is usually the case with that of the imaginary part of the potential used in sub-barrier fusion data analysis, the average potential $\bar{U}(r)$ acquires an effective diffuseness:

$$a_{eff} \simeq 1.2\, A_2^{1/3}\, |\beta_2|\ [fm] \tag{7}$$

If the diffuseness parameter is not small the averaging procedure indicated in equation (5) will also result in an increase in the diffusivity of the potential although a_{eff} will not be given by such a simple expression as that of equation (7).

In conclusion we mention that the static effects of the deformation on σ_{Fusion} were found to be important even for light systems. This is in accordance with the recent work of Stokstad et al. In particular it was shown that the diffuseness of the optical potential should be increased to account for these effects. On the other hand, dynamical effects resulting from the coupling to inelastic channels were shown to be negligible[7]. We should remark that this is not in conflict with the conclusions reached by Imanishi[7] since this author treated the excited state in ^{12}C as a closed channel, in order to explain the oscillatory behaviour of the fusion cross section of $^{12}C + ^{12}C$.

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FIGURE CAPTIONS

Figure 1 - 1a) The $\ell=0$ reflection function plotted vs.the center of mass energy for three different values of the deformation parameter the parameters of the optical model potential used in the coupled channel calculation (Code CHUCK) are V_o = 50 MeV, a_R = 0.4 fm $r_{o,R}$ = 1.4 fm, W_o = 8 MeV, a_w = 0.1 fm, $r_{o,W}$ = 1.4 fm.

1b) The fusion cross section plotted vs. E_{CM} for the three different values of β_2 ; the optical model parameters as in Figure 1a.

Figure 2 - Same as Figure 1b but with W_o = 20 MeV.

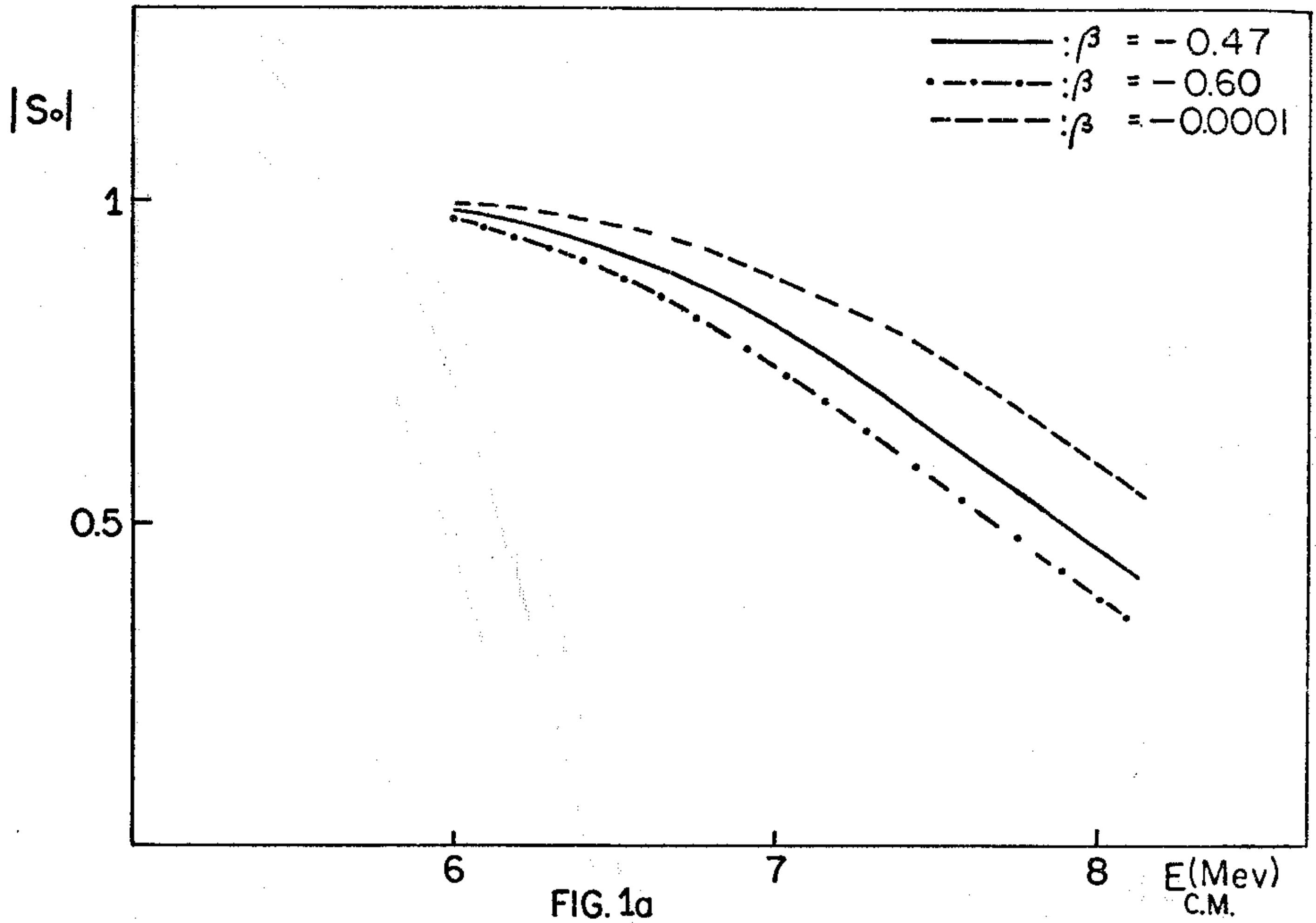

FIG. 1a

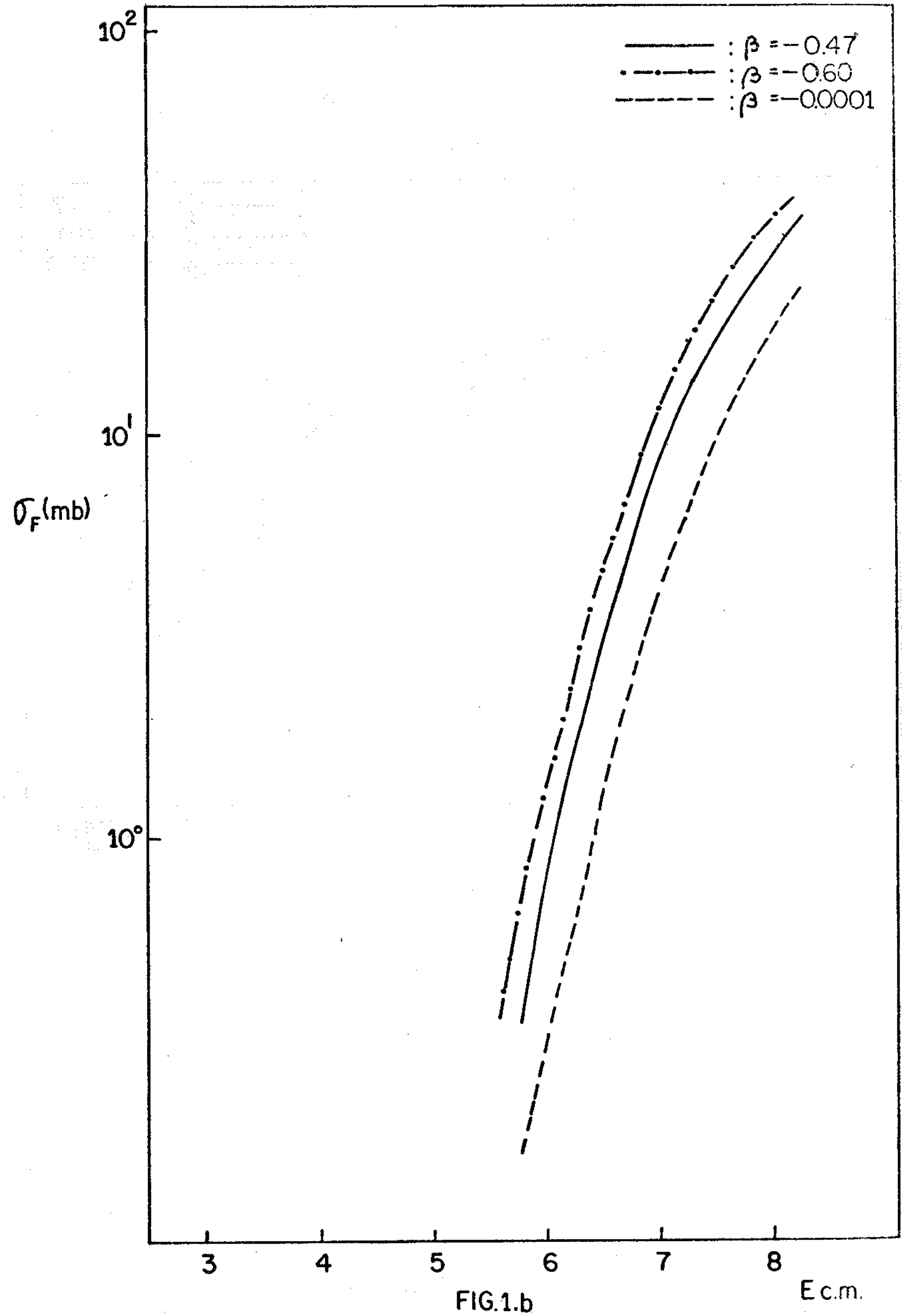

FIG.1.b

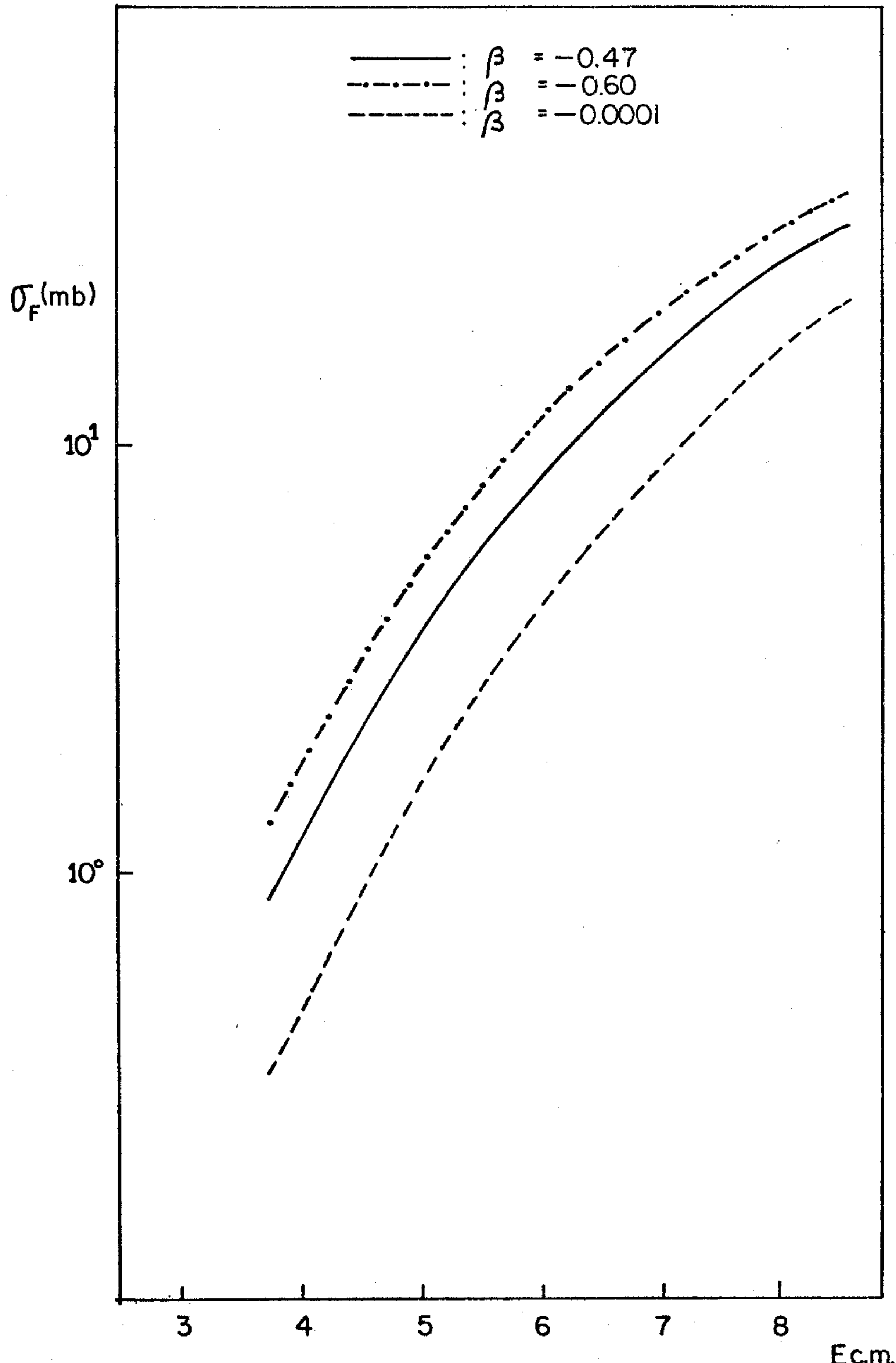

FIG. 2