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DISCLAIMER

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FUSION OF $^{16}O + {}^{144}Sm$ AT SUB-BARRIER ENERGIES

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Abstract:

Fusion cross sections have been measured for the system $^{16}O + {}^{144}Sm$ at bombarding energies in the range 63 MeV $\leqslant E_{lab}(^{16}O) \leqslant$ 72 MeV by observation of delayed X-rays emitted by the evaporation residues. Comparison of the present results for the magic nucleus ^{144}Sm with those already existing for the fusion of ^{16}O with other samarium isotopes shows that the enhancement of the cross sections at sub-barrier energies can be explained in terms of a one-dimensional barrier-penetration model that incorporates the quadrupole deformation parameter, β_2. There is no need to invoke the neck degree of freedom.

NUCLEAR REACTIONS: $^{16}O + {}^{144}Sm$. $E(^{16}O) = 63\text{-}72$ MeV.

Measured σ_{fusion} by off-line observation of X-rays from evaporation residues. One-dimensional barrier-penetration analysis including effects of deformation.

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In the last few years there has been considerable experimental and theoretical interest in studying the influence of the nuclear structure on heavy-ion fusion cross sections at energies near and below the Coulomb barrier[1]. The effects of nuclear static deformation have been demonstrated in measurements of fusion of ^{16}O + $^{148,150,152,154}Sm$[2]. Recently there has been a dramatic increase in the theoretical effort devoted to the understanding of dynamic effects such as the excitation of vibrational or rotational states of the target nucleus during the collison[3-9]. It has also been shown that the zero-point motion of collective surface vibrations is important[10]. Specific correlations of enhanced fusion cross sections with neutron excess[11,12] and transfer of two nucleons[13] have been reported. Additional degrees of freedom, such as the formation of a neck, have also been suggested[14,15] as playing an important role for fusion with heavier projectiles[16].

In this letter we present results for the fusion of two spherical nuclei, the doubly-magic nucleus ^{16}O and the neutron magic-nucleus ^{144}Sm, at energies near and below the Coulomb barrier. Due to the particular nature of the projectile and target, deformation effects (both static and vibrational) are minimized. Therefore, this work provides an important piece of data to complete the analysis of the influence of nuclear deformation in the even-even samarium isotopes[2,3]. Moreover, the conflicting claims by Jahnke et al.[15] (that the neck degree of freedom is already apparent in the fusion of ^{16}O + ^{144}Sm) and Reisdorf et al.[17] (that the fusion of ^{40}Ar + ^{144}Sm does not require this effect) are resolved by a new measurement and analysis of ^{16}O + ^{144}Sm using a different experimental method than in ref. 15.

The experiment was performed at the Instituto de Fisica da Universidade de Sao Paulo. Beams of ^{16}O delivered by the 8 UD Pelletron with laboratory energies from 63 to 72 MeV were used to bombard a 94 $\mu g/cm^2$ ^{144}Sm target isotopically enriched to 88.6%. Evaporation residues were trapped in a stack of three aluminized mylar foils, which were glued together to form a single catcher foil and were placed about 3 mm behind the target. Silicon surface-barrier detectors were placed at ±45° to the beam for monitoring the Rutherford scattering. The beam intensity was recorded as a function of time during the bombardments. Following bombardments of about 120 minutes, the catcher foils were removed from the scattering chamber and placed in front of a 5 cm^3 Ge planar X-ray detector having an energy resolution of 480 eV (FWHM) and a photopeak efficiency of 8.5% in the range 40-60 KeV. The K_α and K_β lines of the X-rays of Tm, Er, Ho and Dy were well resolved. The absolute efficiency of the Ge detector was determined using a set of calibrated sources that were carefully mounted in the same geometry as the catcher foils.

Figure 1 shows the experimental count rates for the decay of holmium and dysprosium residues produced at bombarding energies of 65 MeV and 72 MeV. Taking into account the contribution from different decay chains, the time dependence of the K_α X-ray yields for parent and daughter activities can be calculated using the known half-lives and the absolute X-ray intensities. The total number of K_α X-rays produced per decay of each isotope in each mass chain was obtained from the normalized decay schemes in the Nuclear Data Sheets[18] and in the Table of Isotopes[19]. In comparing the experimental data with the calculated intensities, the contributions of each isotope were taken as adjustable parameters in a least-squares procedure. The values obtained in this way were finally used in the calculation of the fusion cross sections for the $^{16}O + {}^{144}Sm$ reaction.

The full curves in Fig. 1 illustrate results at two different bombarding energies for simultaneous fits of the activities for the third and fourth generations of the decay chains. Effects explicitly taken into account in the deduction of the cross sections are: i) the time dependence of the beam intensity, ii) the presence of isomeric states with half-lives of several minutes in the decay chains of some of the evaporation residues, and iii) summing effects due to the simultaneous detection of more than one photon. Corrections to the Ho and Dy K_α X-ray yields from the fusion of ^{16}O with the 11.4% of other Sm isotopes present in the target were based on the measured[2] (or interpolated) cross sections for these isotopes. These corrections were relatively small because the X-ray energy and decay half-life enable one to discriminate experimentally against the products of fusion with the heavier isotopes. No corrections need be made for fusion of the projectile with the light contaminants in the target because these residues pass through the catcher foil. (Corrections for contaminants, both light and heavy, are more of a problem if neutron yields are measured, as in the experimental method used by Jahnke et al.[15]). Fission of the compound nucleus and α-particle emission were estimated to be negligible effects. Furthermore, it can be shown that proton decay does not affect the calculated activities of the Er and Ho isotopes. Taking into account the sources of random and systematic uncertainties, an overall error of around 9% in the fusion cross sections was calculated. In order to check the experimental technique, a measurement with a 64 MeV ^{16}O beam and a ^{154}Sm target was performed. The result of this measurement (see Fig. 2) was in agreement with that of Ref. 2.

The measured fusion cross sections for the system $^{16}O + ^{144}Sm$ are presented in Fig. 2 as a function of laboratory bombarding energy. The measurements for $^{16}O + ^{148,150,152,154}Sm$ are taken from Ref. 2. At the highest bombarding energies, the values of σ_{fus} are similar for all the systems, while at sub-barrier energies there is a clear enhancement for the fusion of ^{16}O with the more deformed isotopes relative to the spherical ^{144}Sm.

Since ^{154}Sm is a well-deformed nucleus, the simplest approach to discuss the systematic behavior of the fusion cross sections at sub-barrier energies for the different isotopes is to use a one-dimensional barrier-penetration model that includes explicitly the effect of deformation.

For this purpose we use Wong's model[20], in which σ_{fus} is evaluated in terms of four parameters: the interaction-barrier height V_B, its radial position R_B, its curvature $\hbar\omega$ and the quadrupole deformation of the target nucleus β_2. The parameters V_B and R_B govern the fusion cross sections at energies above the interaction barrier, whereas β_2 and $\hbar\omega$ control the behavior of the excitation function at sub-barrier energies. Although Wong's model is derived on the basis of a static deformation, the value of β_2 represents, quite generally, a range of interaction-barrier heights arising from effective variations in the radius of the target nucleus due to either changing orientation or zero-point vibrational configurations.

The analysis of the data proceeded as follows: the values of V_B and R_B were obtained from a least-squares fit to the corresponding experimental points for all the different samarium isotopes at energies above the barrier [Fig. 3(a)]. The adjustable parameters in this minimization procedure were the radius parameter r_B and the effective radius parameter r_e, which are defined by

$$R_B = r_B\,(A_1^{1/3} + A_2^{1/3})\ \mathrm{fm}$$

$$V_B = \frac{1.44\ Z_1Z_2}{r_e(A_1^{1/3} + A_2^{1/3})}\ \mathrm{MeV} \qquad (1)$$

The results of the fit are shown in Fig. 3(a) in terms of the (dimensionless) reduced cross section $\tilde{\sigma}$ and reduced inverse center-of-mass energy $1/\tilde{E}_{cm}$, defined by $\tilde{\sigma} = \sigma_{fus}/[\pi\ (A_1^{1/3} + A_2^{1/3})^2\ \mathrm{mb}]$ and $1/\tilde{E}_{CM} = Z_1Z_2(A_1^{1/3} + A_2^{1/3})^{-1}\ \mathrm{MeV}/E_{CM}$. The fitted values are r_B = 1.32 fm and r_e = 1.54 fm, in excellent agreement with the systematics of Kovar, et al.[21].

Using the appropriate values of R_B and V_B given by [1], and taking ħω and β_2 as free parameters, a theoretical excitation function for ^{16}O + ^{144}Sm was fitted to the experimental points. We obtained $\beta_2 = 0.00\pm0.03$ and ħω = (3.9 ± 0.2) MeV. The corresponding value of β_2 obtained from elastic and inelastic scattering of protons[26] is 0.055. The nuclear interaction potentials of Blocki[22], Christensen and Winther[23], Bass[24], and Siwek-Wilczynska and Wilczynski[25] yield values of ħω = 4.4, 4.7, 3.7 and 3.7 MeV, respectively. A significantly larger value of ħω = (6.8 ± 0.9) MeV was deduced by Jahnke et al. [15], and was considered evidence for the influence of a neck degree of freedom. The difference between their value of ħω and the one deduced in the present work arises from differences in the measured fusion excitation functions.

In the analysis of the ^{16}O + ^{148,150,152,154}Sm systems, the results from ^{16}O + ^{144}Sm were taken as a reference by adopting the same value of ħω = 3.9 MeV and leaving β_2 as the only free parameter. The assumption of a constant ħω as a function of the target mass is supported by the results of calculations using realistic potentials. The resulting fits of the excitation functions are included in Fig. 2 (solid curves), and the deduced values of β_2 as a function of the target mass are shown in Fig. (3b). Similar β_2-values were obtained in Ref. 3 for ^{150,152,154}Sm, where ^{148}Sm was taken as the reference nucleus. For comparison, Fig. (3b) also shows the values of β_2 obtained from elastic and inelastic scattering of protons on ^{144,148,150,152,154}Sm [26] and of α-particles on ^{148,152,154}Sm [27]. (All values of β_2 presented here are normalized to a target nucleus radius given by 1.2 $A^{1/3}$fm.) The overall consistency of i) the values of β_2 obtained from sub-barrier fusion with those obtained from elastic and inelastic scattering, and ii) the fitted value of $\hbar\omega$ with the value from realistic (frozen) nuclear potentials, thus provides no evidence for the influence of degrees of freedom other than deformation on the fusion cross section for oxygen with the Sm isotopes. Similar conclusions were obtained by Reisdorf et al.[17] based on the analysis of ^{40}Ar + ^{144,148,154}Sm.

In conclusion, we have measured the cross sections for fusion of ^{16}O on ^{144}Sm at energies near and below the barrier. The effects of deformation are minimized due to the magic and semimagic nature of the projectile and the target, respectively. The ^{16}O + ^{144}Sm system was used as a reference to obtain the shape of the interaction barrier, which was consistent with the shape given by theoretical static nuclear potentials and from analysis of other experimental data. The quadrupole nuclear-deformation parameters for the deformed samarium isotopes were then deduced and found to be consistent with previous results. The systematic enhancement of σ_{fus} observed for ^{16}O on Sm isotopes, which span the region from spherical to well-deformed nuclei, can be explained in terms of a one-dimensional barrier-penetration model when these deformation parameters are included. Therefore, we found no need to include an extra degree of freedom, such as the formation of a neck, for these systems.

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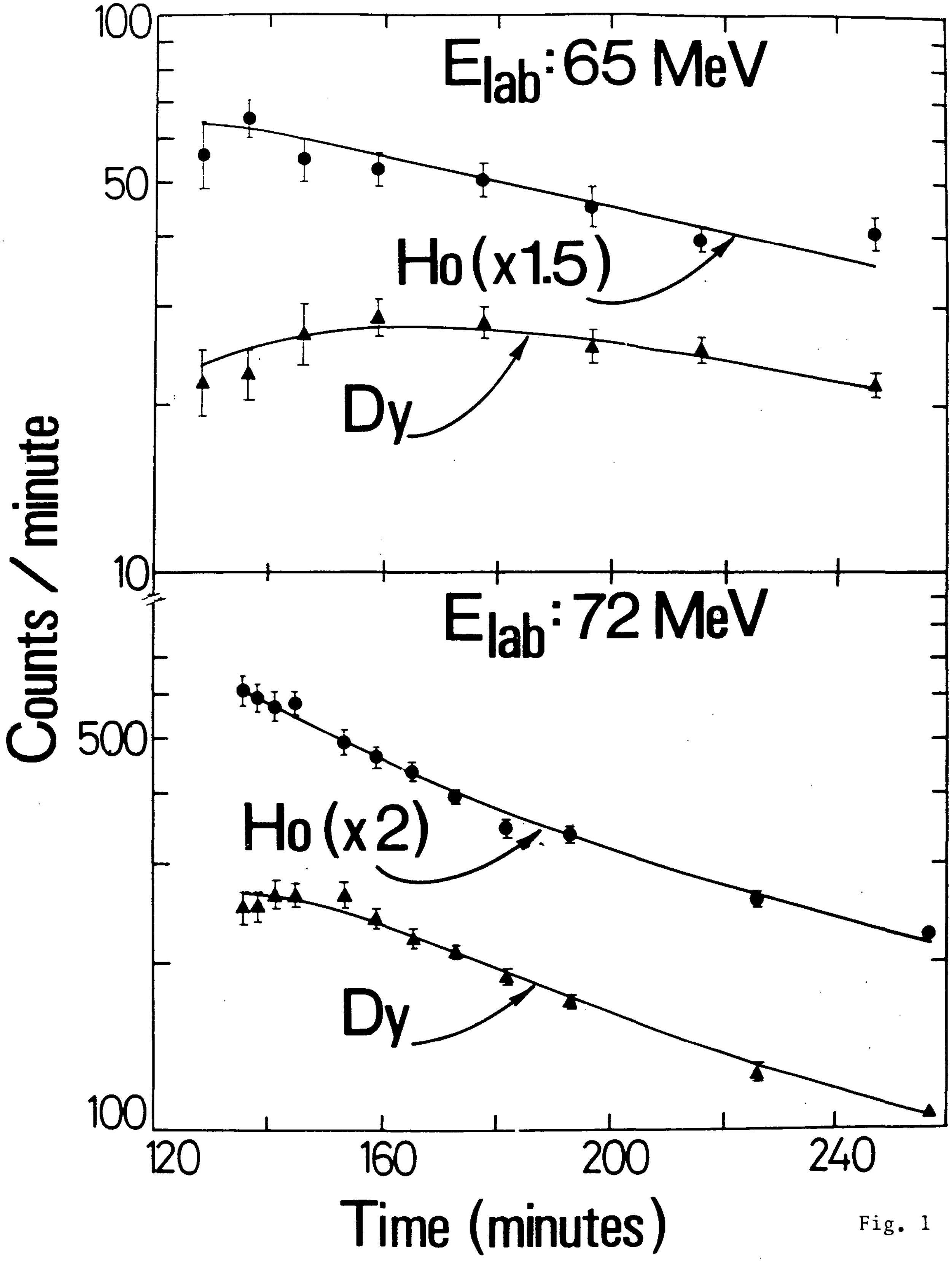
Figure Captions

Figure 1: The K_α X-ray count rates from holmium and dysprosium as a function of the time after the start of bombardment of ^{144}Sm by ^{16}O at E_{Lab} = 65 MeV and 72 MeV. The curves are simultaneous fits to the data using known half-lives and absolute K_α X-ray intensities.

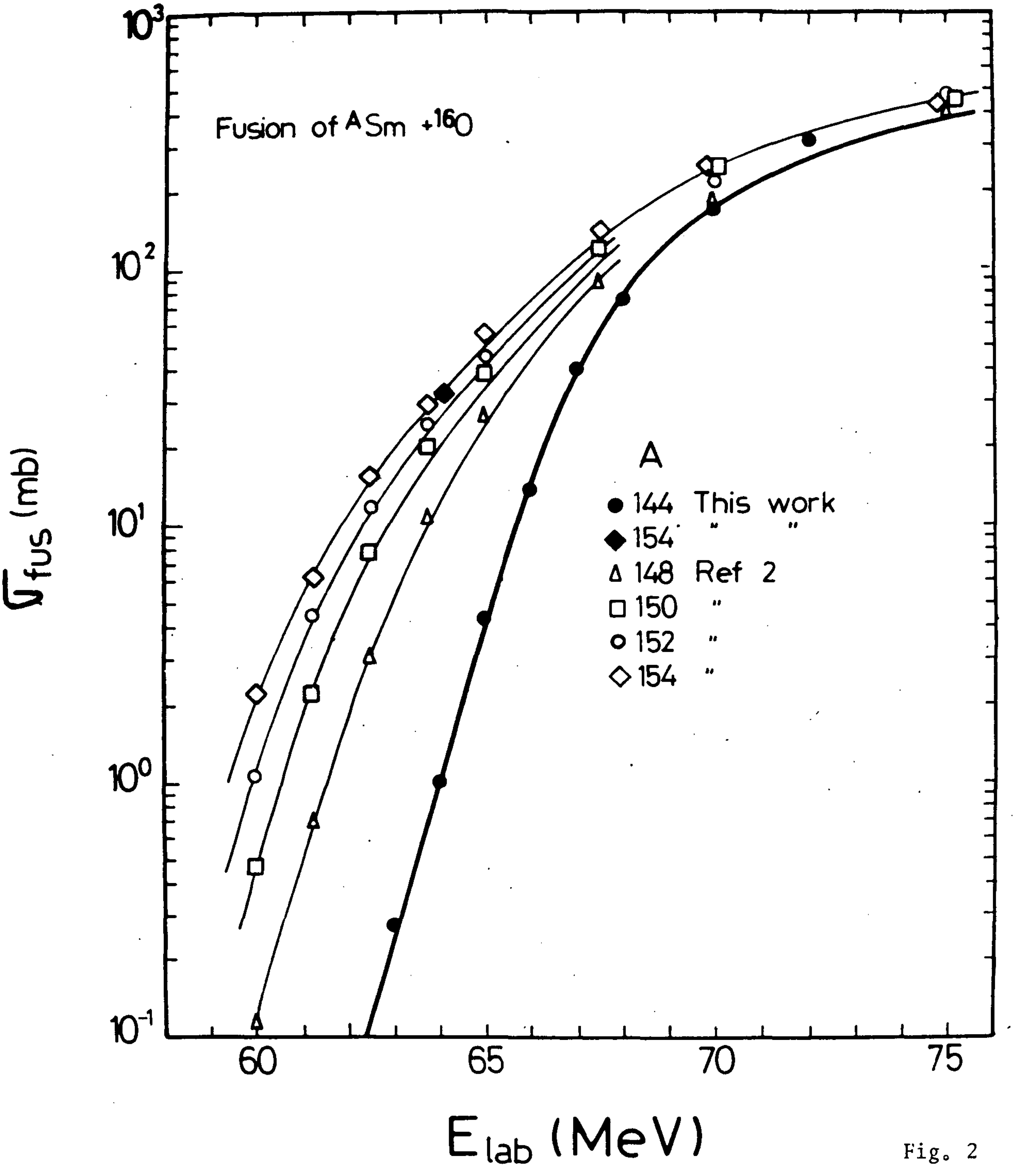
Figure 2: Fusion cross sections as a function of bombarding energy. The solid curves are fits to the data using Wong's model with parameters given in the text.

Figure 3: (a) Extraction of the parameters r_B and r_e from a fit to the high-energy points for the fusion of ^{16}O with various samarium isotopes (see text). (b) Comparison of the values of β_2, obtained from fitting σ_{fus}, with those deduced by other methods (see text).



100
50
10
Elab: 65 MeV
Ho (x1.5)
Dy
Elab: 72 MeV
500
100
Ho (x 2)
Dy
Counts / minute
120
160
200
240
Time (minutes)

Fig. 1


Fusion of $^{A}Sm + ^{16}O$
σ_{fus} (mb)
10^3
10^2
10^1
10^0
10^{-1}
60
65
70
75
E_{lab} (MeV)
A
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◆ 154 " "
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Fig. 2

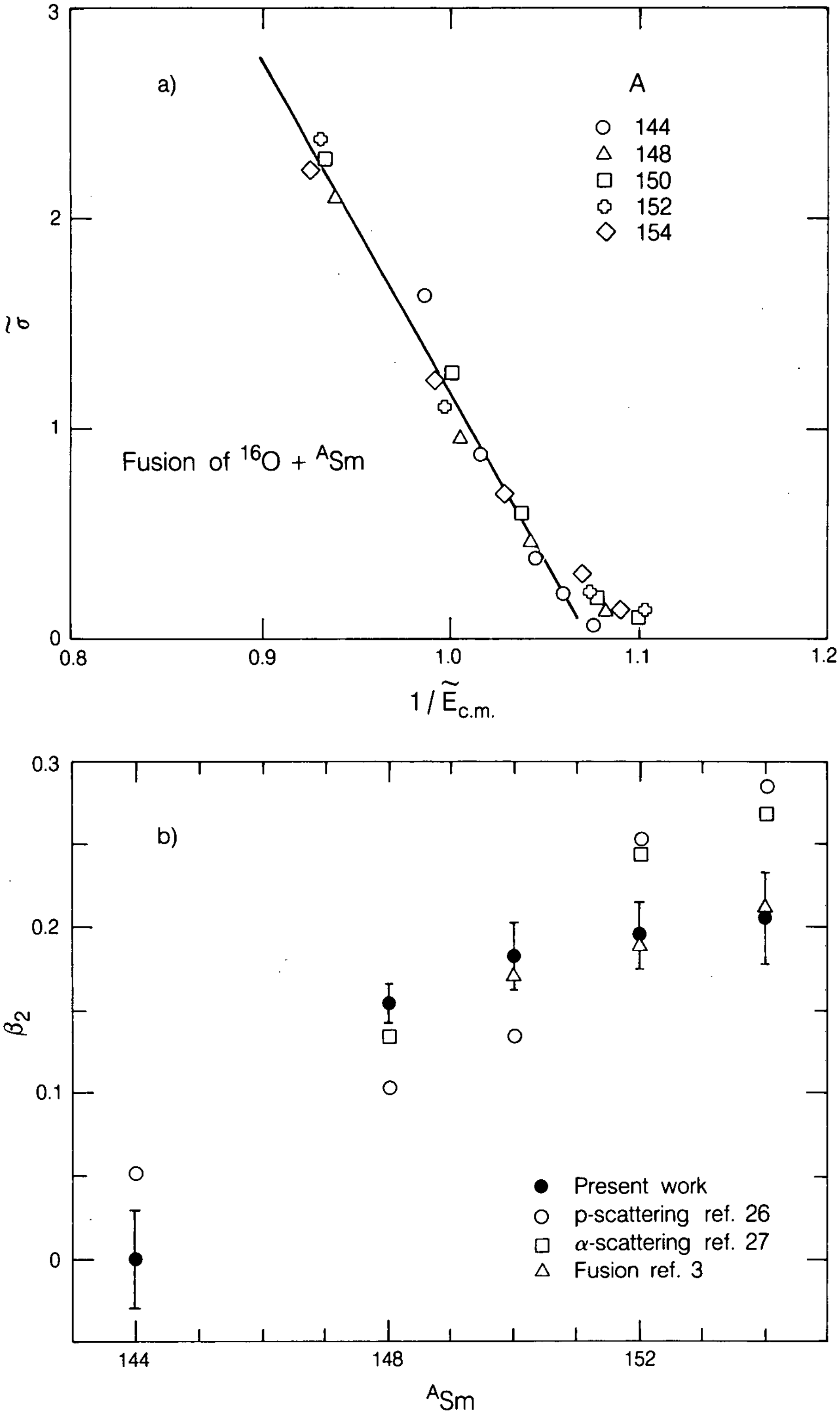

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Fig. 3.