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On Reaction Times for "Quasi-fission" and on the Critical Distance Concept in Heavy-Ion Fusion Reactions

Franz Plasil

Institut de Physique Nucléaire, Orsay, France
and Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA *

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In this contribution, I wish to deal briefly with two unrelated aspects of heavy-ion reactions : reaction times for the quasi-fission process (sometimes also refered to as strongly damped collisions or deep inelastic scattering) and the concept of critical distance as applied to the description of heavy-ion fusion.

I. Reaction Times for "Quasi-fission".

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On comparing recent quasi-fission results of the Orsay group^{1}) with those obtained by the RAMM group at Berkeley^{2}), one is struck by what appears to be an important difference in the way in which the mass distributions vary with the angle at which they are observed. The results of Pêter, Ngô and Tamain^{1}) are for the reaction ^{197}Au+^{63}Cu at a laboratory bombarding energy of 365 MeV. At this energy, which is only about 10% higher than the interaction barrier, they obtained light-fragment mass-distributions at seven laboratory angles ranging from 26° to 96°. The overall angular distribution is peaked at a c.m. angle of 100°, which is somewhat forward of the grazing angle. At the peak of the angular distribution, and at angles backward of the peak, the light-fragment mass-distributions were found to be rather

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narrow, and peaked at a few a.m.u below the 63 a.m.u. of the Cu projectile. At more forward angles, however, the peak of the mass distribution shifts toward heavier masses, and at 50° in the center-of-mass, for example, the mass distribution is considerably broader, with a peak near 80 a.m.u. Thus a tendancy toward mass equilibrium is observed at angles that are smaller than the peak of the angular distribution, while at the peak of the angular distribution, and at angles in back of it, no such tendancy is observed.

In contrast, the results of Wolf et al$^{2)}$ are for the system of ^{209}Bi+^{84}Kr at a bombarding energy of 600 MeV, which is well above the interaction barrier. The overall angular distribution is peaked at about 60° in the center-of-mass, which is close to the grazing angle. In this work, only two mass distributions are given, one at 34° (∿ 52°c.m.) and the other at 59° (∿ 86° c.m.). At 52° c.m., close to the peak of the angular distribution, the light fragment mass distribution is peaked at the projectile mass of 84 a.m.u., and there is essentially no yield at symmetric mass divisions (147 a.m.u). At 86° c.m, however, the light-fragment mass distribution is peaked near 110 a.m.u, and there is a considerable yield at symmetry. Thus in this case, a tendancy toward mass equilibrium is found at a larger angle than that which corresponds to the peak of the angular distribution.

If we assume that a tendancy toward mass equilibrium implies longer reaction times, then the curious conclusion is that longer reaction times correspond to angles smaller than the angular-distribution-peak angle in the Au+Cu case, but that they correspond to angles larger than the angular-distribution-peak angle in the Bi+Kr case. By considering reaction times as obtained from rotation times, it will be shown that the above conclusion is reasonable, and that the two sets of results are not in contradiction to each other.

Two extreme cases were considered : (a) the stick-on-contact case, and (b) the Rutherford orbit case. In case

(a) the projectile nucleus follows a Rutherford trajectory in the field of the target nucleus until the two nuclei come in contact with each other, at which point they stick to each other and rotate about their center-of-mass until the angle of re-emission is reached. In case (b), the Rutherford orbit for the projectile is calculated assuming no interaction with the target nucleus, and the time required for the system to rotate from its Rutherford deflection angle to the observed emission angle is estimated. Case (b) is similar to Huizenga's method of estimating reaction times$^{3)}$, and it will be seen that the two cases yield the same qualitative conclusions. They represent opposite extremes in that in the one case no energy damping is considered, while in the other case instantaneous total damping is assumed. In both cases an effective radius parameter $r_0 = 1.362$ fm was used. It was obtained from elastic scattering data obtained by the Orsay group.

The results are given in figures 1 and 2. The figures show curves for various values of angular momentum ℓ, as a function of the c.m angle, and of the reaction time in units of 10^{-21} secs. If we consider the Au+Cu case, the quasi-fission angular distribution was found to peak at 100° c.m and the cross section is such that ℓ-waves between about 50 and 75 are involved for events that show no tendancy toward mass equilibrium. These conditions define the hatched region in the top part of fig.I. If we now assume that for a greater mass exchange deeper penetration and hence lower ℓ-waves are required, we obtain at the observed c.m. angle of 50° the dotted region, in which a tendancy toward equilibrium is observed. It can be seen that there is a considerable time difference between the two regions. Times at the peak of the angular distribution are of the order of 2×10^{-21}secs, while those at 50° c.m are in the range of $7\text{-}11\times10^{-21}$secs.

The bottom part of fig.1 illustrates the Bi+Kr case. The peak of the angular distribution is at about 60° c.m and partial waves are in the range of 100-200. This defines the hatched area which corresponds to times of $1\text{-}2\times10^{-21}$sec. The angle where some mass exchange is observed is 86°c.m, and the partial waves are below about 50. This defines the dotted region, with times in the range of $6\text{-}9\times10^{-21}$secs. It can be seen that the times associated with the two different regions in the two reactions are consistent with each other. Furthermore, in the Au+Cu case, at an angle below the peak of the angular distribution, for $\ell=25$, the reaction time would be too close to that at the peak of the distribution, and a substantial amount of mass exchange would not be expected.

In fig.2 similar curves are shown for the Rutherford-orbit case. The various hatched and dotted regions correspond to those of fig.1. It can be seen that the qualitative conclusions are the same as those from fig.1.

To conclude, what appeared at first sight to be an inconsistancy in the experimental data, may be understood by considering rotation times for the specific reactions involved.

II. Critical Distance Concept (work done with J. Péter, C.Ngô and B. Tamain)

Several calculations have been performed in efforts to understand the growing body of data on heavy-ion fusion cross sections. Most of these calculations involve dynamics, and they have achieved various degrees of success. As yet, however, no simple method exists that would allow the experimenter to predict to within, say, 20%, the heavy-ion fusion cross section for any given system. One of the simplest methods to systematize heavy-ion fusion data is by means of the critical distance concept of Galin et al [4]). It was shown that, for a large number of systems, the point where the bombarding energy is equal to the ion-ion potential for the highest partial wave ℓ_{cr} that contributes to the experimental fusion cross section is located at a distance R_{cr} such that $r_{cr} = 1 \pm 0.1$ fm, where $R_{cr} = r_{cr}(A_1^{1/3}+A_2^{1/3})$.

This result implies that it is necessary to push the ions together to the rather small distance characterized by $r_{cr} \approx$ 1 fm in order to achieve fusion.

The nuclear part of the potential used by Galin et al was obtained in the framework of energy density formalism. This potential was later successfully applied by Ngô et al 5) in a systematization of interaction barriers. Furthermore, studies have shown that up to a distance of $(A_1^{1/3}+A_2^{1/3})$ fm (i.e in the region of interest) the energy density formalism potential gave essentially identical results to contact potentials and folding potentials. Thus a certain degree of confidence was generated in the validity of the potential used.

If we invoke the sudden approximation, which is an underlying assumption in the critical distance treatment, we have

$$E_{c.m} = V(R_{cr}) + \frac{\ell_{cr}(\ell_{cr}+1)\hbar^2}{2\mu R_{cr}^2} \qquad (1)$$

where $V(R_{cr})$ is the sum of the nuclear and of the Coulomb potential at R_{cr}, μ is the reduced mass and $E_{c.m}$ the bombarding energy.

Thus

$$E_{c.m} \approx V(R_{cr}) + \frac{1}{r_{cr}^2}\,\frac{\ell_{cr}^2\,\hbar^2}{2(A_1^{1/3}+A_2^{1/3})}\,\frac{A_1+A_2}{A_1A_2}$$

A plot of $E_{c.m}$ versus $\frac{\ell_{cr}^2(A_1+A_2)}{A_1A_2(A_1^{1/3}+A_2^{1/3})^2}$ should be linear and should have a slope characteristic of r_{cr}. Plots of this type were made for many reactions where excitation functions for fusion were available. Straight lines were indeed found, with an average slope given by r_{cr} = 1.04 ± 0.09 fm.

Fusion cross sections σ_{fus} were calculated from

$$\sigma_{fus} = \pi R^2{}_{cr}\left(1 - \frac{V(R_{cr})}{E_{c.m}}\right)$$

which follows from equation 1 and from

$$\sigma_{fus} = \pi\lambdabar^2(\ell_{cr}+1)^2 = \frac{\pi(\ell_{cr}+1)^2\hbar^2}{2\mu E_{c.m}}$$

Values of $V(R_{cr})$ were obtained from the energy density formalism potential and r_{cr} was varied from 1.0 fm to 1.08 fm. Plots of $\sigma_{exp}/\sigma_{calc}$ versus the mass of the compound nucleus were made, and the plot of r_{cr} = 1.0 fm is shown in fig.3. The result is a disapointing scatter of points, with no obvious trend. Experimental results tabulated by Lefort, Le Beyec and Péter 6) were used, supplemented by recent results. It is clear that predictions made in this way cannot be trusted to 20%. Part of the problem may be due to inaccuracies in the nuclear potential and part of the problem may be due to errors or inaccuracies in the experimental data, but probably the greatest problem lies in the fact that cross sections are extremely sensitive to the precise value of r_{cr} (since it enters as a square in the expression for σ, and since $V(R_{cr})$ is a steep function of R_{cr}), and small variations in r_{cr} produce large variations in σ.

The conclusion is that the critical distance concept cannot, at this point, be applied to obtain reliable predictions of fusion cross sections. What the actual meaning of the critical distance is beyond a requirement that the ion densities overlap substantially for fusion to take place, remains an open question.

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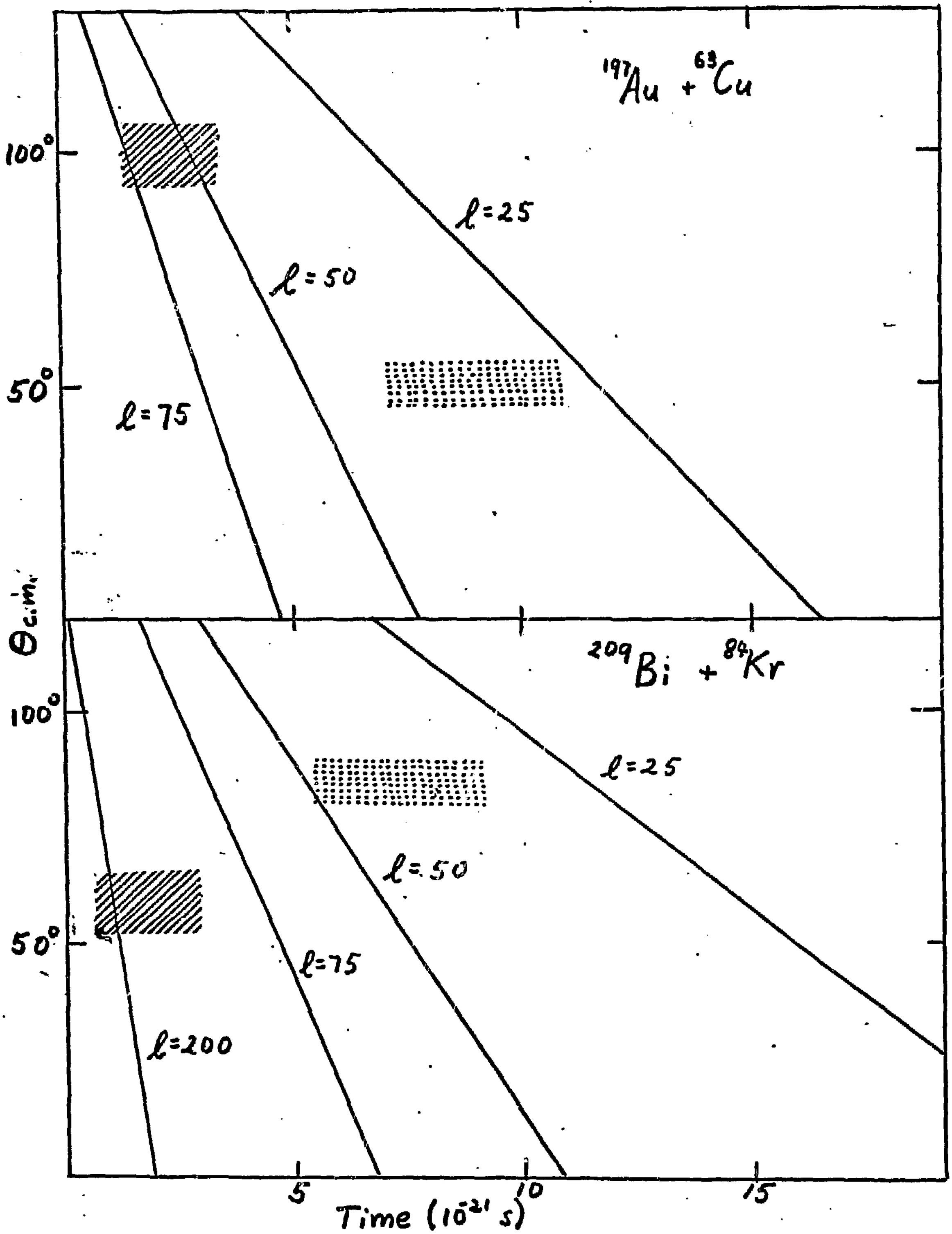

Fig.1. Center-of-mass angle versus interaction time for various partial waves for the reactions $^{197}Au+^{63}Cu$ at 365 MeV and $^{209}Bi+^{84}Kr$ at 600 MeV. Target and projectile nuclei were assumed to stick on contact and then rotate to the appropriate center-of-mass angle. The hatched regions correspond to the peaks in the angular distributions where little mass exchange has taken place. The dotted

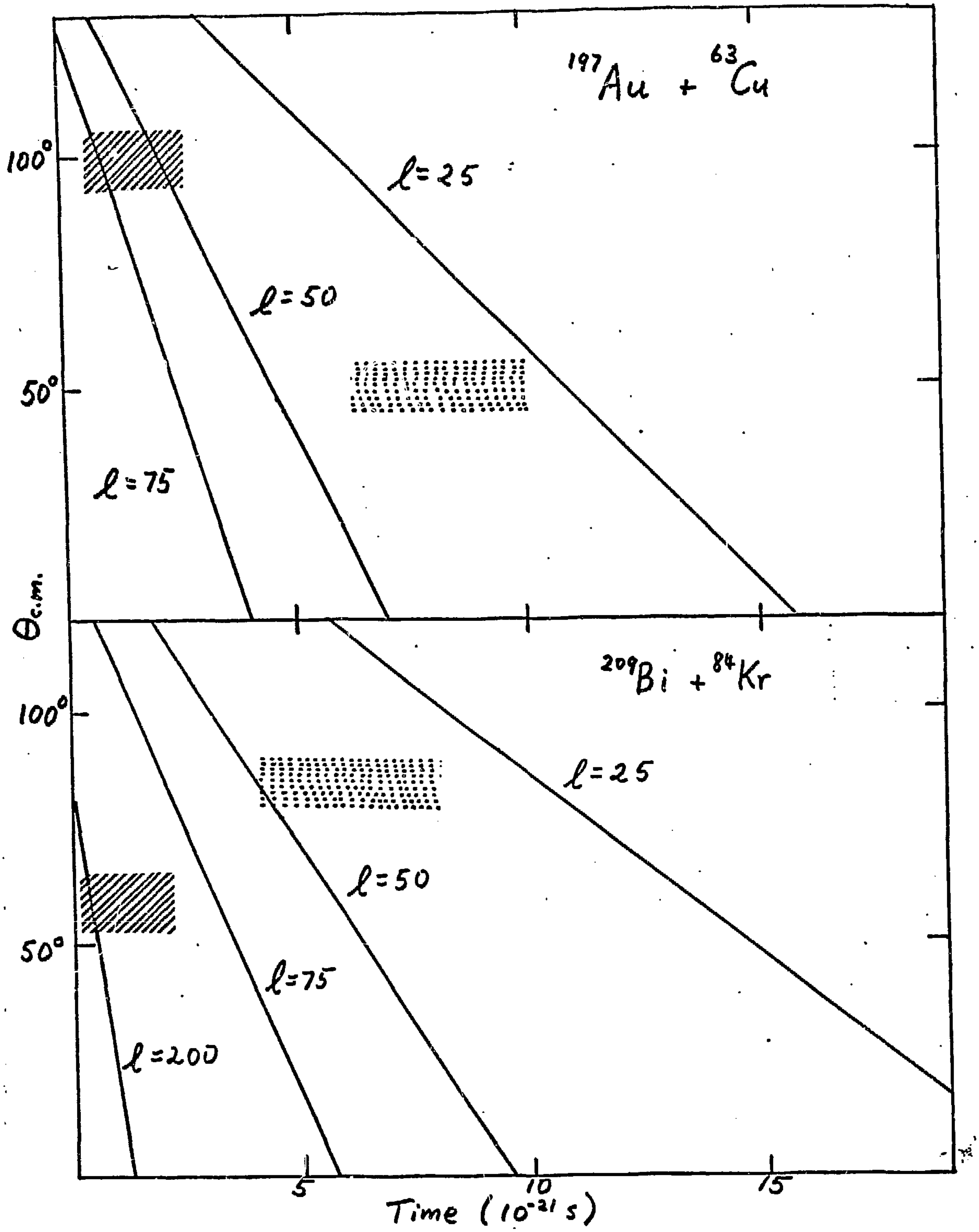

Fig.2. Same as fig.1, but on the assumption that the projectile nucleus follows a complete unperturbed Rutherford orbit, and that rotation takes place between the Rutherford exit angle and the appropriate

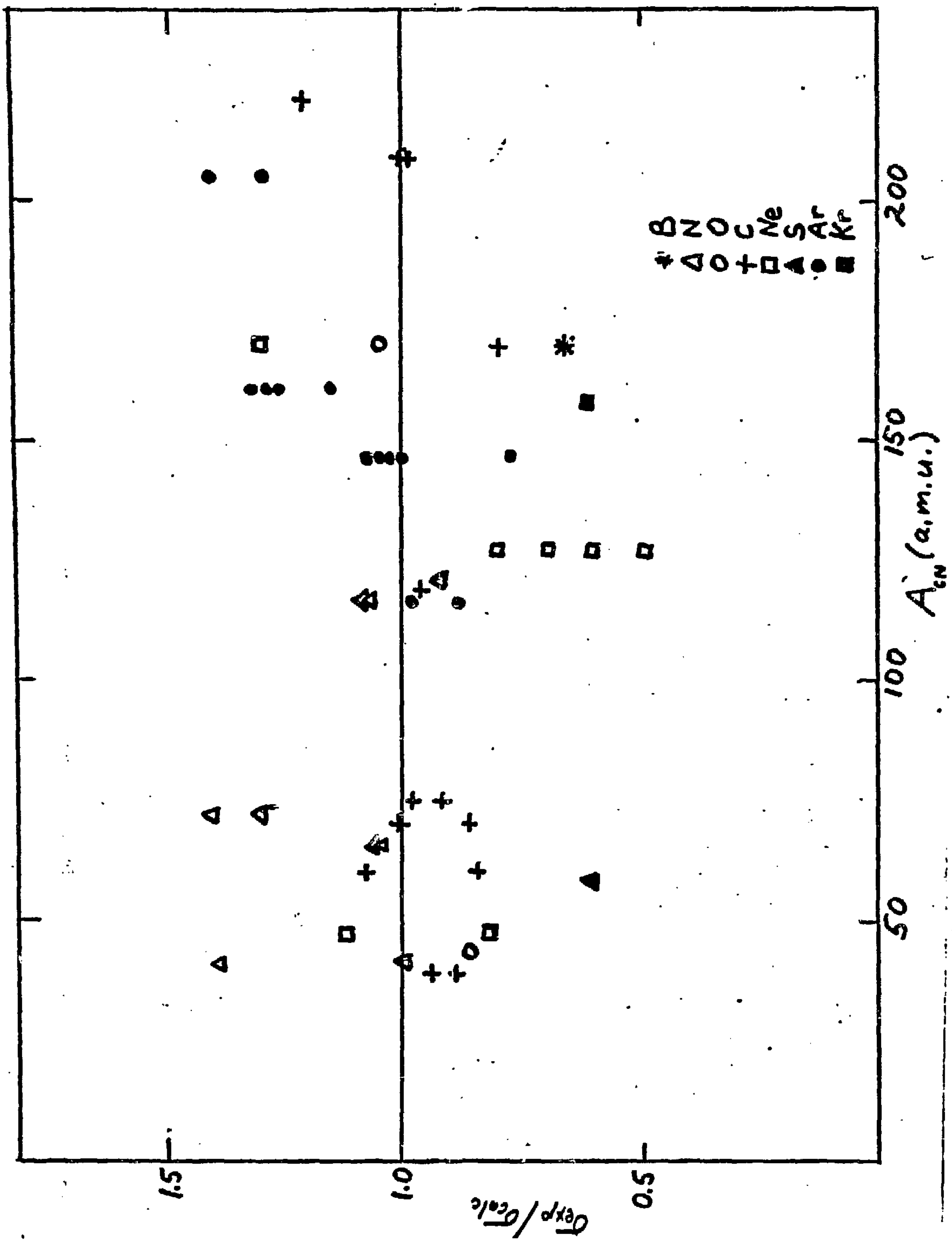

Fig.3. Ratio of experimental to calculated cross sections for heavy ion fusion as a function of the compound nucleus mass. Various bombarding ions are indicated.