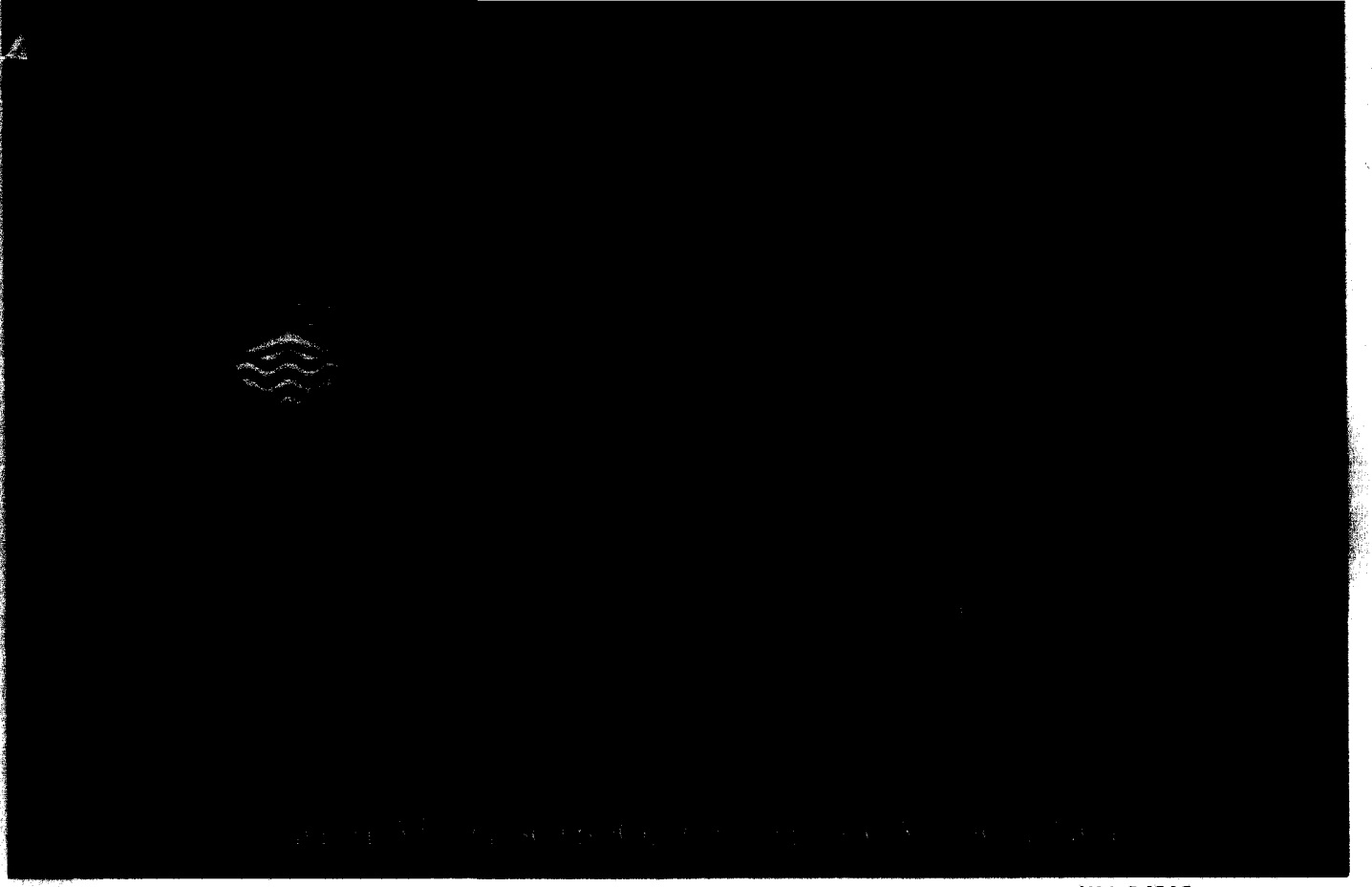

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SYSTEMATICS OF COULOMB-NUCLEAR INTERFERENCE: IMPLICATIONS FOR RELIABLE MEASUREMENT OF THE REORIENTATION EFFECT

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Abstract - Data are presented which show an inverse correlation between Coulomb excitation probability and the nuclear separation corresponding to onset of Coulomb-nuclear interference. They demonstrate that the safe energy for reorientation effect measurements should always be determined experimentally.

Static electric quadrupole moments of nuclear excited states are frequently determined from experiments which use the reorientation effect in Coulomb excitation [1]. A necessary condition for the validity of such determinations is that the data analysed should be obtained at bombarding energies sufficiently low to ensure that interference from nuclear interactions is negligible. However, because the Coulomb excitation probability increases rapidly with increasing energy, it is desirable to work at the highest possible bombarding energy consistent with negligible nuclear interference. The use of "unsafe" bombarding energies in the past has often resulted in erroneous determinations of quadrupole moments; examples have been discussed by Thomson et al. [2], Lesser et al. [3], and Fewell et al. [4]. A striking instance occurred in the recent controversy concerning the quadrupole moment of the first 3^- state in ^{208}Pb [5,6].

It has become customary (see, for example, refs. [1] and [7]) to specify the "maximum safe energy" E_s in terms of a minimum distance of closest approach, S_{min} fm, between the surfaces of two nuclei in a head-on collision:

$$E_s = 1.44\ Z_1 Z_2 \left(1 + \frac{A_1}{A_2}\right)\left[r_o\left(A_1^{1/3} + A_2^{1/3}\right) + S_{min}\right]^{-1} \qquad (1)$$

where (Z_1,A_1) and (Z_2,A_2) are the atomic and mass numbers of the projectile and target, respectively, the nuclear radius is equal to $r_o A^{1/3}$, and E_s is the laboratory kinetic energy in MeV. For $r_o = 1.25$ fm values of S_{min} recommended as "safe" have ranged from 3 fm [8], through 5.1 fm [1], to 6.0 fm [3]. Recently Cline has argued [9] that for projectile excitation of the first excited state of ^{18}O a separation distance exceeding 7.5 fm is required to ensure that Coulomb-nuclear interference is negligible. The use of formulae such as (1) may however be unduly simplistic, since it implies that the safe energy is determined completely

by the masses and charges of the interacting nuclei, and is independent of such factors as scattering angle, nuclear deformation, the relative probabilities for Coulomb and nuclear excitation, or, for that matter, the accuracy of the data. We demonstrate herein that, in the absence of reliable calculations of Coulomb-nuclear interference effects, it is essential to measure directly the magnitude of the interference contribution for each experimental configuration used.

In fig. 1 we show excitation functions for the inelastic scattering of oxygen ions from nuclei with A ≈ 200; these data were obtained at the ANU during a program of quadrupole moment measurements. The double ratio R_{exp}/R_{comp} is plotted as a function of the distance of closest approach, S, between the nuclear surfaces in a head-on collision (assuming a nuclear radius parameter r_o = 1.25 fm); R_{exp} is the measured excitation probability for the first 2^+ state of one of the interacting nuclei, and R_{comp} is the excitation probability computed assuming a pure Coulomb interaction. The quantity R_{exp} was determined from spectra of scattered particles observed at back angles (171° to 175°) with an annular counter; experimental details are given in refs. [6], [10] and [11]. The results shown in fig. 1 are for excitation of the first 2^+ states in ^{198}Hg (E_x = 0.412 MeV) and ^{204}Pb (E_x = 0.899 MeV) by ^{16}O projectiles, and for projectile excitation of the first 2^+ state in ^{18}O (E_x = 1.982 MeV) by a ^{208}Pb target. The ^{198}Hg data have been previously published by Esat et al. [12], and part of the ^{18}O data by Fewell et al. [4]. It is clear from fig. 1 that, no matter what criteria are adopted for determining safe energies from the data, the corresponding values of S_{min} vary substantially. Thus the use of a simple expression such as equation (1) to choose safe energies, with its assumption of a constant value for S_{min}, is clearly unreliable.

For the data considered here it is found that larger values for S_{min} (and deeper interference minima) correspond to smaller values of the Coulomb excitation probability; for ^{198}Hg, ^{204}Pb and ^{18}O these excitation probabilities are approximately 10^{-1}, 10^{-2} and 10^{-3}, respectively. This correlation may be qualitatively understood as follows. For a given pair of interacting nuclei, the energy at which the excitation probability deviates by more than some specified percentage from that due to pure Coulomb excitation depends upon the detailed variation of the Coulomb and nuclear reaction amplitudes as a function of bombarding energy. If, for the cases shown in fig. 1, the differences in Coulomb amplitudes are greater than the differences in the nuclear amplitudes, then for smaller Coulomb excitation probabilities the effect of nuclear excitation will become apparent at larger distances of separation. If the three cases are ranked in order of decreasing Coulomb excitation probability, then this is also the order of increasing excitation energy and decreasing B(E2). Variations in B(E2) are expected to affect nuclear and Coulomb excitation probabilities similarly, while the relatively long interaction time of the Coulomb excitation process results in a more rapid decrease of excitation probability with increasing excitation energy than is found in nuclear excitation. Therefore the dependence on excitation energy is likely to be more important than decreasing B(E2) in determining the behaviour observed in fig. 1. However, it should be recognised that other parameters, e.g. nuclear deformation, could be significant.

Feng et al [5] concluded from DWBA calculations of Coulomb-nuclear interference that the minimum safe distance increases strongly with increasing multipolarity of excitation. In fig. 2 we display previously unpublished data for 2^+ and 3^- excitations in ^{204}Pb and ^{206}Pb, in each case induced by ^{16}O projectiles. The excitation energies of the 2^+ states are 0.899 and 0.803 MeV for ^{204}Pb and ^{206}Pb, respectively, and for the 3^- states they are 2.634 and 2.648 MeV. It is clear that the safe

distance for the E3 excitation in these nuclei is indeed considerably greater than that for the E2 excitation. However, it is possible that this is not due solely to the different multipolarities but reflects the different excitation probabilities involved. It is interesting to note that the E3 excitations in the Pb isotopes and the E2 excitation in ^{18}O (fig. 1), which all have very small excitation probabilities, show very similar interference behaviour for R_{exp}/R_{comp}. In each case the interference minimum is remarkably deep, corresponding to almost complete destructive interference. It would be of great interest if DWBA calculations similar to those of Feng et al. were to be performed for the specific cases considered here.

The results presented in this letter demonstrate that the use of a simple "safe-energy" formula involving only the masses and charges of the interacting nuclei is unreliable, and that for all reorientation experiments the maximum safe energy should be determined by direct measurement for the particular experimental configuration involved.

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Figure Captions

Fig. 1 Plots of the double ratio R_{exp}/R_{comp} as a function of distance of closest approach S for excitation of the first 2^+ states in ^{198}Hg and ^{204}Pb by ^{16}O projectiles, and for excitation of the first 2^+ state in ^{18}O projectiles by a ^{208}Pb target. Error bars are shown for representative points; in many cases they are smaller than the data points. The quadrupole moments used in calculating R_{comp} were obtained from refs. [12], [10] and [4] for ^{198}Hg, ^{204}Pb and ^{18}O, respectively.

Fig. 2 Plots of the double ratio R_{exp}/R_{comp} as a function of distance of closest approach S for excitation of the first 2^+ and 3^- states in ^{204}Pb and ^{206}Pb. Error bars are shown for representative points; in many cases they are smaller than the data points. The quadrupole moments used in calculating R_{comp} for the 2^+ states were as given in ref. [10]. The quadrupole moments of the 3^- states are not known; it was assumed that they are zero.

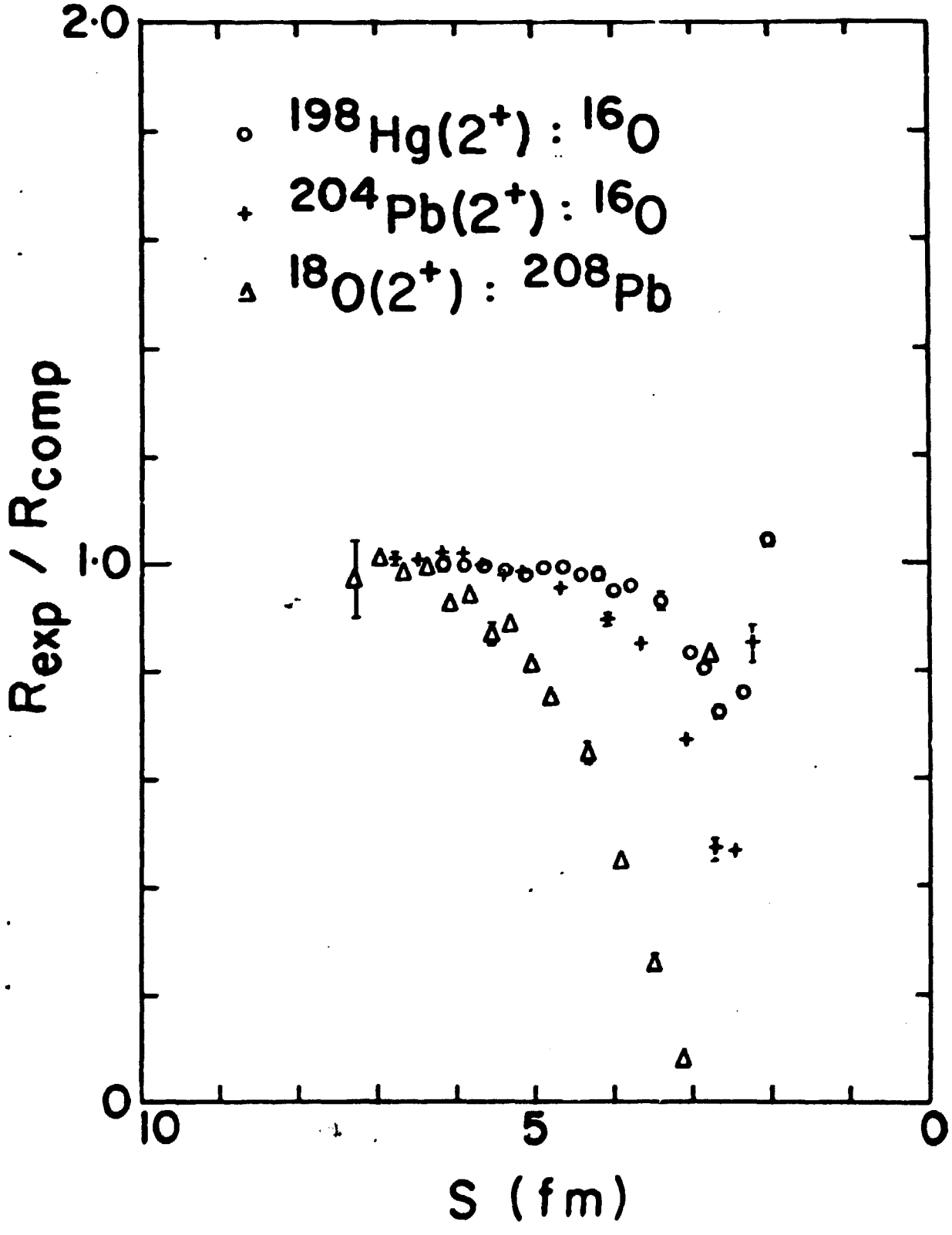

Fig. 1

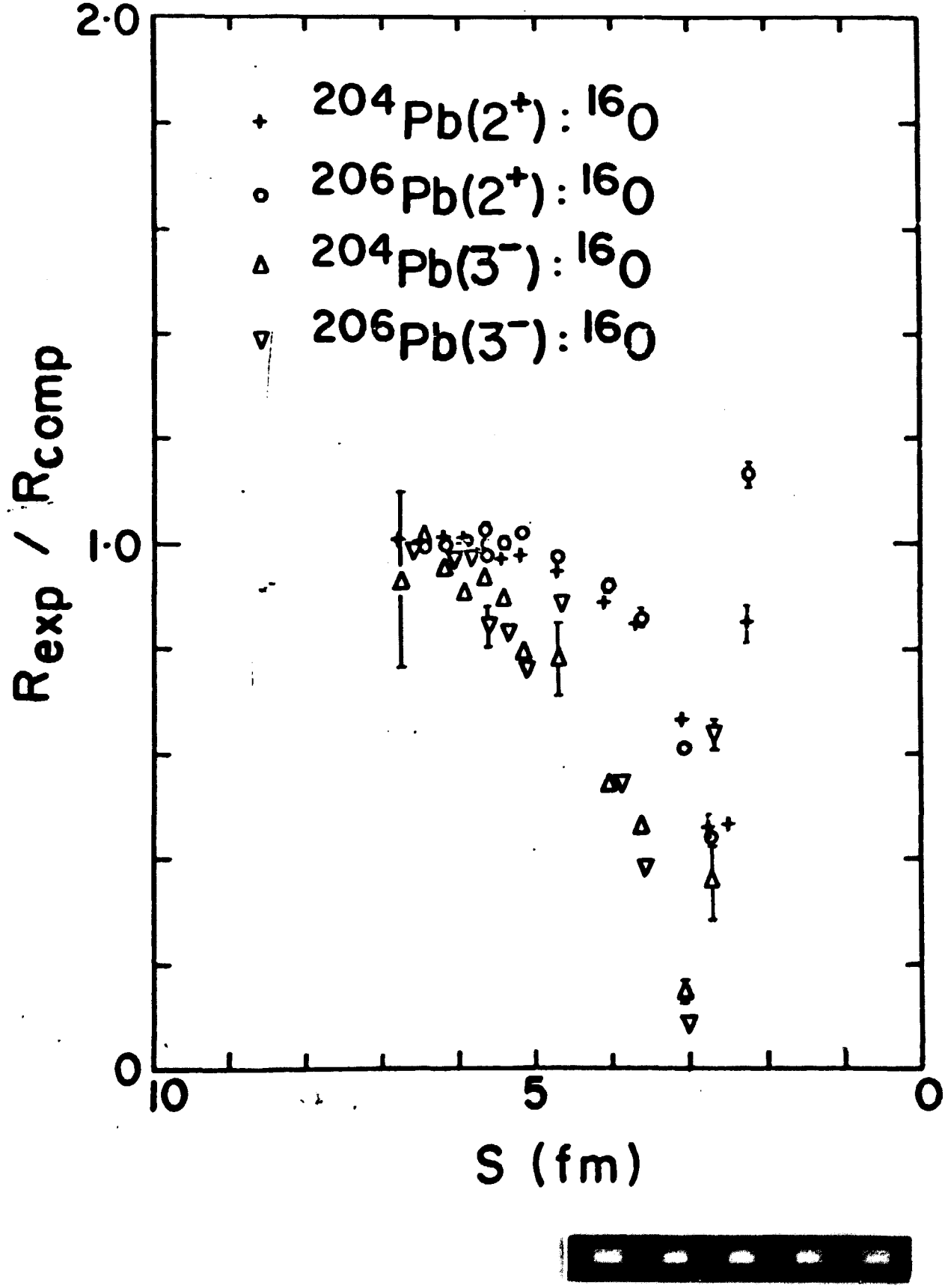
2·0
1·0
0
R_{exp} / R_{comp}
$^{204}Pb(2^+) : ^{16}O$
$^{206}Pb(2^+) : ^{16}O$
$^{204}Pb(3^-) : ^{16}O$
$^{206}Pb(3^-) : ^{16}O$
10
5
0
S (fm)

Fig. 2