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A COMPLETE RIDGE-LINE POTENTIAL FOR COMPLEX FRAGMENT EMISSION

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Abstract

Cross sections were measured for fragments (4<Z<27) from the 5.0, 6.2, 6.9, 8.0, 10.2 and 12.7 MeV/N ^{63}Cu + ^{12}C reactions. Excitation functions were constructed for each Z value, and a nearly complete set of mass-asymmetric barriers has been obtained for ^{75}Br. There is excellent agreement between the experimentally determined barriers and the finite-range model calculations, while there is strong disagreement with the liquid-drop model calculations.

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Fission saddle point shapes for nuclei with a small fissility parameter ($x < .7$) are strongly constricted at the neck, so that the nascent fission fragments are already well defined in mass. Therefore a physical significance can be assigned to the mass asymmetry parameter $A_1/(A_1+A_2)$ in the neighborhood of the saddle. It is then possible to cut the potential energy surface of the nucleus with a line passing through the fission saddle point along the mass asymmetry coordinate in such a way that each of its points is a saddle point if one freezes the mass asymmetry coordinate. The locus of all these conditional saddle points, or conditional barriers is called the ridge line[1]. This line controls the emission of complex fragments and can be determined from complex fragment excitation functions.

Theoretical conditional barriers have been calculated, both with the liquid-drop model and the finite-range model[2]. The results of these calculations differ by as much as 15 MeV for medium mass nuclei. Thus, the measurements of conditional barriers over the entire range of mass asymmetries in a single nucleus is of great importance for testing the liquid-drop model and its finite-range and surface-diffuseness refinements[3,4,5].

The major objective of the present work is to provide, for the first time, a complete set of experimental asymmetric fission barriers for a single nucleus, against which macroscopic models can be tested. Earlier limited experimental work[6] for ^{111}In has shown good agreement between the experimentally determined barriers and the finite-range model predictions over a small range of mass asymmetries. In this paper we present a nearly complete experimental ridge line of conditional barriers at zero angular momentum for ^{75}Br.

The reaction ^{63}Cu + ^{12}C was chosen because Han et al[7] had identified for all Z-values of emitted fragments an isotropic equilibrium component of the cross section at 12.7 MeV/N which was attributed to compound nucleus decay following complete fusion.

The major difficulty associated with the present undertaking is the measurement of the very low cross sections for complex fragment emission at excitation energies near the barrier. This problem was minimized by taking advantage of the reverse kinematics focusing, which allows one to detect a large fraction of the total complex fragments emitted, without detector threshold problems in a low background environment. With the availability of heavier beams, such a technique can be extended easily throughout the periodic table.

Complex fragment excitation functions were measured for the reaction $^{63}Cu + ^{12}C$ at six bombarding energies. The experiment was performed at the 88-inch Cyclotron of Lawrence Berkeley Laboratory. The ^{63}Cu ions impinged on a ^{12}C target of 0.5 mg/cm^2 thickness. Fragments were detected in two position sensitive ΔE-E quad telescopes placed on either side of the beam. Each quad unit consisted of four separate gas-silicon (ΔE-E) telescopes which covered 25° degrees in plane and 5° degrees out of plane. The active area of each telescope subtended 5° degrees. With these telescopes, the energy, the atomic number, the in-plane and out-of-plane angles could be determined for each fragment that traversed the ΔE(gas) and stopped in the E(silicon) detector. Continuous angular distributions over 25° lab intervals were obtained by overlapping the two quad units so that the dead areas between telescopes were covered. In this way, complete and continuous angular distributions were obtained. The atomic number of the fragments was determined from the measured ΔE and E values. Examples of ΔE-E spectra illustrating the Z resolution achieved have been shown in Ref. 7.

The cross sections were extracted by integrating over the isotropic component of the angular distributions $d\sigma/d\theta$, which was dominant for most of the fragments. This isotropic component arises from compound nucleus decay. When the angular distributions were anisotropic (e.g. compound nucleus component + deep inelastic), a constant equal to the minimum value of $d\sigma/d\theta$ was taken as an upper limit for the compound nucleus cross sections[7]. The deep inelastic component appeared mostly for Z values less than 9 and was backward peaked in the center of mass.

The complex fragments were measured in a region of atomic charges between 5 and 26, which covers the range of asymmetries between Z/Z_{cn} =0.14 - 0.74 where Z/Z_{cn} =0.50 corresponds to symmetric splitting, and Z_{cn} is the compound nucleus atomic number. Decay products lighter than Z=5 and heavier than Z=26 were not analyzed because of the difficulty of identifying atomic numbers at the extreme ends of this large dynamic range. As can be seen from Figure 1, cross sections as low as a few microbarns were measured at excitation energies as low as 50 MeV or 10-15 MeV above the typical barrier.

The excitation functions obtained from the $^{63}Cu + ^{12}C$ measurements are shown in Figure 1 with their respective fits for a series of decay products. The experimental excitation function data have been fit with functions obtained from a transition-state formalism, analogous to that used to fit fission excitation functions[1]. At the highest excitation energies, second chance emission is not negligible with respect to first chance emission. Therefore both first and second chance emission were included in the calculations. The excitation functions were analyzed by a means of a two parameter fit. One of these parameters was the conditional fission barrier and the other the ratio of the level density parameters at the saddle point (a_z) and at equilibrium (a_n). A Fermi gas level density expression was used in these calculations. Because of the rather small values of the angular momentum especially at the lower energies, a simple angular momentum dependence was included by the addition of the rotational energies appropriate to the ground and saddle point deformations to the zero angular momentum barriers. The maximum angular momentum for fusion was calculated at each energy from the Bass model[8]. For the highest energies, the Bass values were slightly lowered (by $1\hbar$ or $2\hbar$) in order to improve agreement. The value of the level density parameter a_n at the ground state was choosen to be a_n=A/9. The fits are shown in Figure 1 by the solid lines. Excellent agreement is obtained for all Z values. The extracted barriers (Figure 2) and ratio of level density parameters (Figure 3) are subject to several uncertainties because of the assumptions made in this analysis. The sensitivity of the fit was examined with respect to changes in other parameters. A variation of the level density parameter within reasonable limits (between A/8 and A/10) introduces an uncertainty in the extracted barriers and values of a_z/a_n of at most $\pm 2\%$ for all values of Z without changing significantly the χ^2 of each fit. In addition, all the cross sections have been increased and decreased systematically by 50% from the values shown in Figure 1 in order to allow for possible unexpected systematic errors. The results indicate that such a large systematic error introduces a rather small uncertainty of at most $\pm 2\%$ in the extracted barriers and values of a_z/a_n. The affect of charge loss by the fragments due to sequential evaporation has been determined from the Z_1-Z_2 coincidences. The average total charge loss at the higher energy is about 2 units and it decreases rapidly to less than half a unit with decreasing energy. Thus, no correction in the abscissae of Fig. 2 and 3 has been applied.

A check that our results are internally consistent can be made by comparing the barriers for complementary atomic numbers (atomic numbers whose sum is equal to the atomic number of the compound nucleus). By examining Table 1 one can see that most of the barriers for complementary charges (e.g. B_z for Z=15 and B_z for Z=20) have almost the same value, within 1 Mev. Lighter fragments tend to have slightly smaller barriers. This difference is probably due to the difficulties in identifying the heavier fragment atomic numbers.

The extracted barriers increase as a function of mass asymmetry, peak at symmetry and then fall off. This is the trend expected for a system with A=75 whose fissility parameter x=0.28 lies well below the Businaro-Gallone point[5,9]. Figure 2 shows barriers calculated with both the liquid-drop model and the finite-range model. As can be seen agreement between the experimental barriers and those calculated with the finite range model[10] is remarkably good while the liquid drop barriers are significantly higher. The values of a_z/a_n extracted from the fits span the range of values from 0.910 to 0.990 and most values are centered around 0.930. The ratio a_z/a_n decreases as a function of mass asymmetry with a minimum around symmetric splitting and then increases again. This behavior is not well understood and is currently under investigation.

To summarize, we have determined the nearly complete ridge line of the potential energy surface for ^{75}Br and have demonstrated that its dependence with mass asymmetry agrees with that predicted by theory for systems below the Businaro-Gallone point. Also the small uncertainties of the extracted conditional barriers ($\pm$ 3%) allow us to verify the importance of the finite-range correction to the liquid-drop model. As can be seen from figure 2 the remarkable agreement between the experimentally determined conditional barriers and those predicted by theory justify the incorporation of finite-range effects in the liquid-drop model.

Acknowledgement

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Table Caption

Table 1. Tabulated values of the finite range, liquid drop and experimental barriers (in MeV) and the ratio of the level density parameters as determined from the fitting procedure. The errors are those arising from the χ^2 of the fitting procedure. To these values an overall systematic error of the order of ± 3% MeV can be assigned as discussed in the text.

Z	F.R.	L.D.	Exper. barrier	$R=a_z/a_n$
5	25.7	42.0	27.3 ± .1	.990 ± .002
6	27.8	44.0	26.8 ± .1	.971 ± .003
7	29.9	45.4	29.8 ± .1	.959 ± .003
8	31.8	46.4	30.0 ± .1	.941 ± .003
9	33.0	47.9	32.8 ± .1	.928 ± .003
10	34.1	48.5	33.4 ± .1	.933 ± .003
11	35.0	48.9	34.3 ± .1	.922 ± .003
12	35.9	49.6	36.0 ± .1	.944 ± .003
13	36.4	49.9	35.6 ± .2	.914 ± .004
14	36.8	50.1	35.7 ± .2	.915 ± .004
15	37.0	50.3	36.9 ± .2	.922 ± .003
16	37.1	50.4	36.5 ± .2	.908 ± .004
17	37.2	50.5	37.3 ± .2	.918 ± .004
18	37.2	50.5	36.8 ± .2	.912 ± .004
19	37.1	50.4	37.2 ± .2	.919 ± .004
20	37.0	50.3	37.0 ± .2	.924 ± .004
21	36.8	50.1	36.8 ± .2	.930 ± .004
22	36.4	49.9	36.5 ± .2	.937 ± .004
23	35.9	49.6	36.4 ± .2	.952 ± .004
24	35.0	48.9	34.8 ± .2	.953 ± .004
25	34.1	48.5	35.2 ± .2	.990 ± .004
26	33.0	47.9	32.8 ± .2	.984 ± .004

Figure Captions

Fig.1 : Dependence of the total integrated cross sections for emission of complex fragments on the center-of-mass energy, $E_{c.m.}$ in the reaction $^{63}Cu + {}^{12}C$. The points and error bars correspond to the experimental cross sections with statistical errors. The curves are fits with the parameters shown in Figs.2 & 3. The numbers to the right indicate the factor by which each curve and set of experimental points was multiplied by in order to separate it from its neighboring curves for visual display purposes.

Fig.2 : The emission barriers, B_z, extracted in fitting the excitation functions as a function of the fragment charge or asymmetry, Z/Z_{cn}. ($Z/Z_{cn} = 0.5$ corresponds to symmetric splitting.) The points are the extracted barriers and the error bars shown are those arising from the χ^2 of the fitting procedure. Where none are shown, the errors are smaller than the size of tbe points. The predicted values from the finite range model and the liquid drop model are shown by the solid and dashed lines respectively. The large error bar represents the estimated systematic error arising from the variation of a_n and from the maximum uncertainties in the cross section as discussed in the text.

Fig.3 : The ratio of the level density parameters, extracted in fitting the excitation functions as a function of asymmetry, Z/Z_{cn} . The error bars shown are those arising from the χ^2 of the fitting procedure and where none are shown, the errors are smaller than the size of tbe points. The large error bar represents the estimated systematic error arising from the variation of a_n and from the maximum uncertainties in the cross section as discussed in the text.

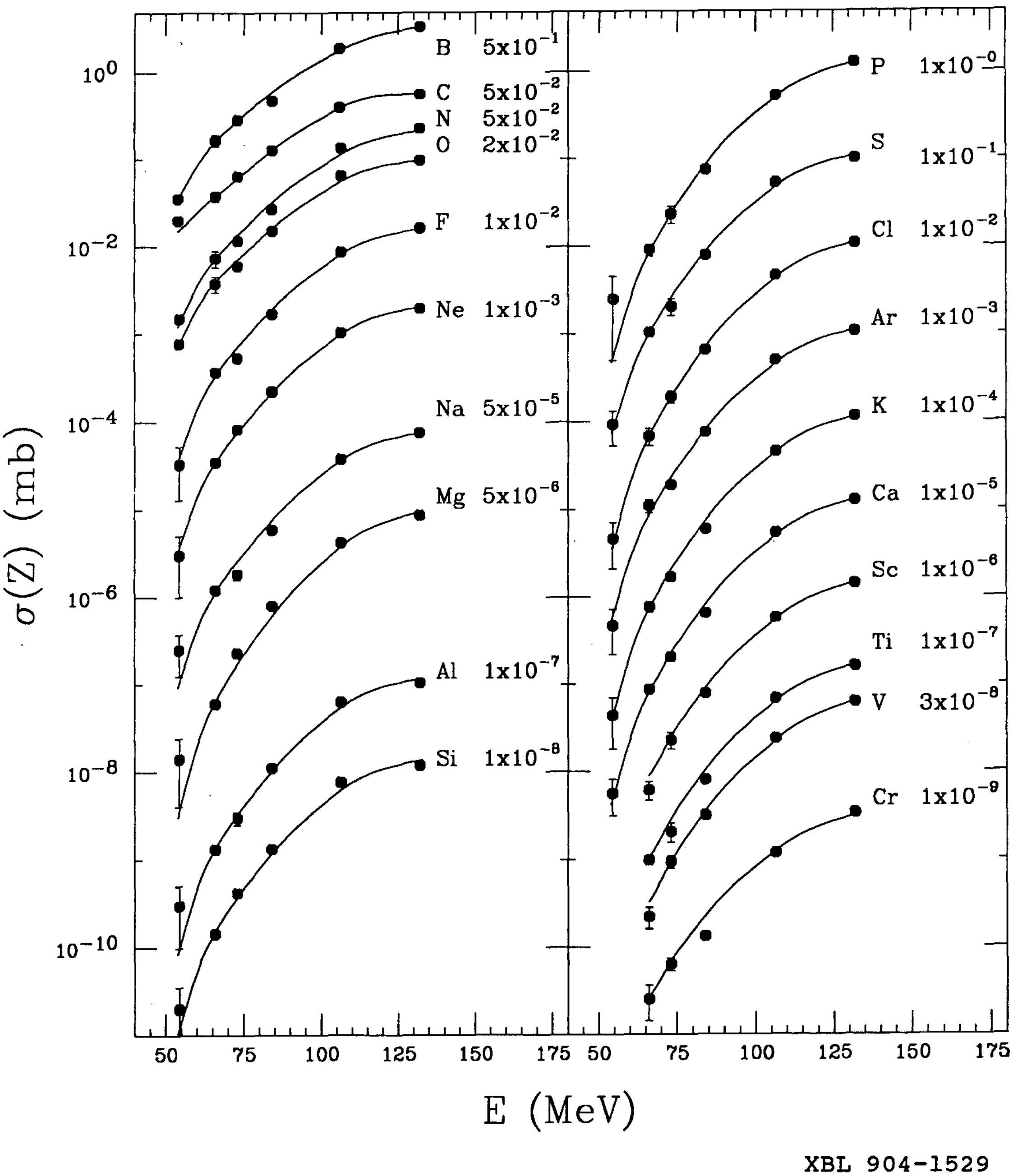

σ(Z) (mb)
E (MeV)
B 5x10^-1
C 5x10^-2
N 5x10^-2
O 2x10^-2
F 1x10^-2
Ne 1x10^-3
Na 5x10^-5
Mg 5x10^-6
Al 1x10^-7
Si 1x10^-8
P 1x10^-0
S 1x10^-1
Cl 1x10^-2
Ar 1x10^-3
K 1x10^-4
Ca 1x10^-5
Sc 1x10^-6
Ti 1x10^-7
V 3x10^-8
Cr 1x10^-9
XBL 904-1529

Figure 1

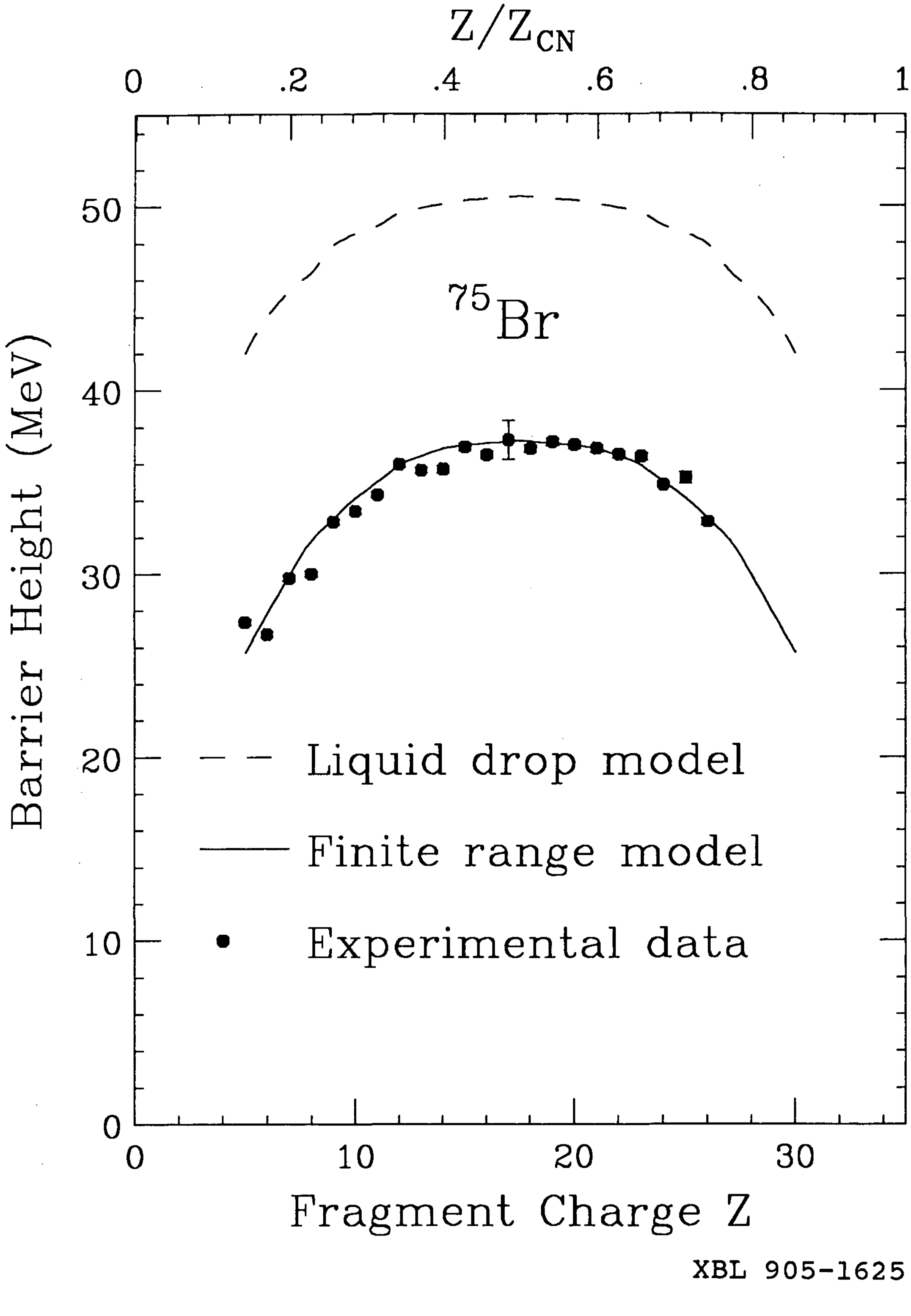
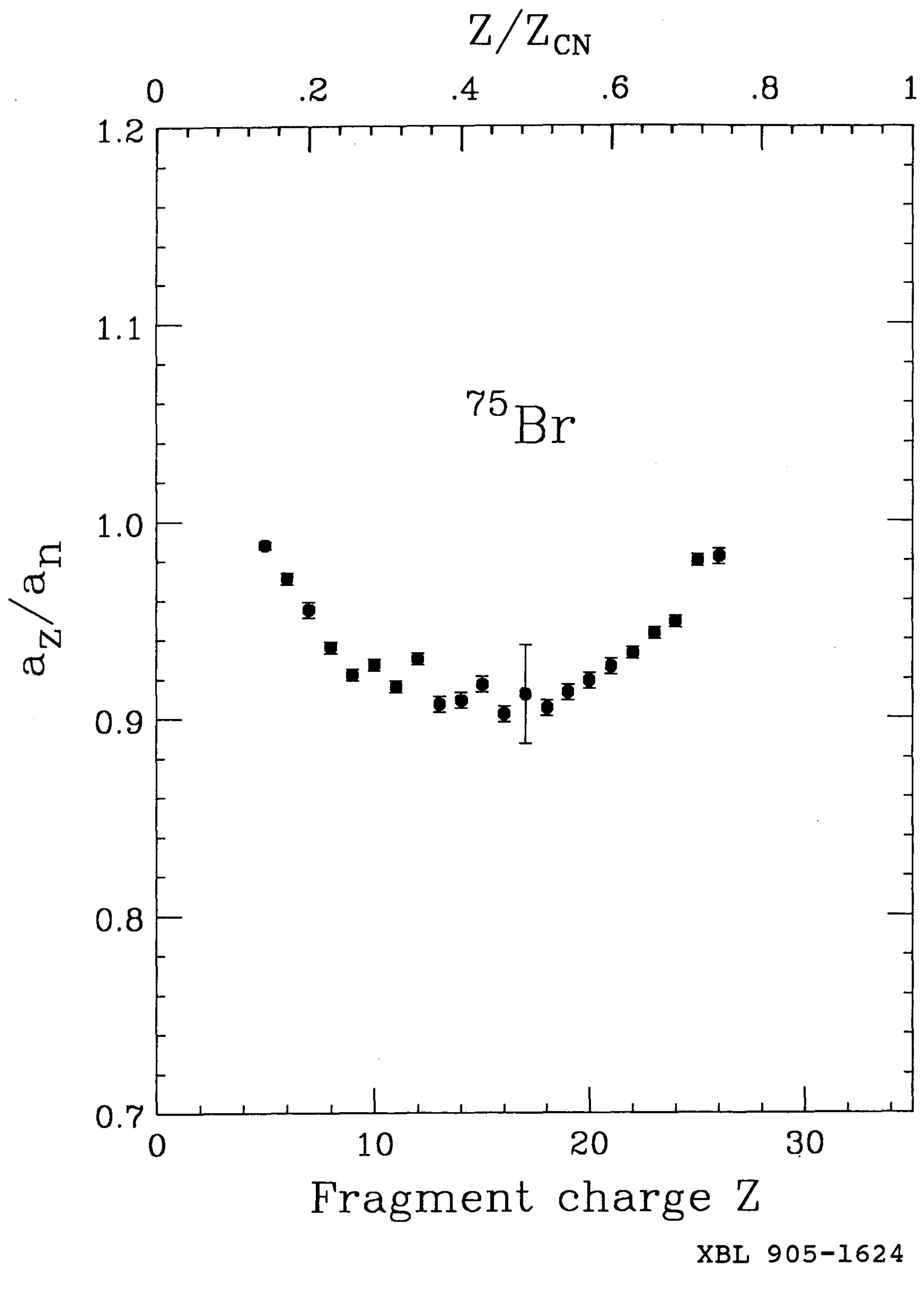

Z/Z_CN
0
.2
.4
.6
.8
1
50
40
30
20
10
0
75Br
Barrier Height (MeV)
Liquid drop model
Finite range model
Experimental data
0
10
20
30
Fragment Charge Z
XBL 905-1625

Figure 2



Z/Z_CN
0
.2
.4
.6
.8
1
1.2
1.1
1.0
0.9
0.8
0.7
^{75}Br
a_Z/a_n
0
10
20
30
Fragment charge Z
XBL 905-1624

Figure 3