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TRENDS OF ISOTOPE YIELDS OBSERVED IN REACTIONS INDUCED BY ^{16}O IONS OF 140, 315 AND 33600 MeV*

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Abstract:

Isotope yields from reactions induced by ^{16}O ions of 140 and 315 MeV on ^{94}Zr, ^{197}Au, ^{208}Pb and ^{232}Th targets are measured and compared with published data at 33.6 GeV. The previously reported similarity of cross sections at 315 MeV and 33.6 GeV is augmented by the fact that the relative isotope yields are essentially target independent at 315 MeV (as has been established at 33.6 GeV). Significant differences are observed between cross sections at 140 and 315 MeV.

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The recently observed [1] similarity of cross sections for reactions induced by ^{16}O on ^{208}Pb at incident energies of 33.6 GeV and 315 MeV suggests two immediate experimental extensions: 1) At what lower energy do the particle yields begin to differ significantly from the high energy results and how do they differ? 2) Are the relative cross sections at the lower energies target independent as has been observed [2] and explained [3-5] at 33.6 GeV? In this letter we report results on these two questions.

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The experiments were performed at the 88-Inch Cyclotron of the Lawrence Berkeley Laboratory. Cross sections for the reactions induced by ^{16}O ions of 140 MeV and 315 MeV were obtained for ^{94}Zr, ^{197}Au, ^{208}Pb and ^{232}Th targets of 0.5, 1.8, 0.7 and 10 mg/cm^2 thickness, respectively. Isotope separation was obtained by means of triple ΔE-ΔE-E solid state detector telescopes using detectors of 17, 26, 3000 μm and 40, 80, 3000 μm thickness at the energies of 140 and 315 MeV, respectively. For all particles, broad, bell-shaped energy spectra are observed which are similar to those reported in ref. [6]. At 140 MeV, the angular distributions show a maximum at the grazing angle for reaction products close to the projectile, whereas they decrease monotonically with increasing scattering angle for particles which differ by more than four nucleons from the projectile. The angular distributions at 315 MeV exhibit a nearly exponential fall-off towards large angles for all particles observed. Details of the energy and angular distributions will be presented and discussed in a forthcoming paper. Here we consider the target and energy dependence of the relative isotope yields.

In order to reduce the effect of different angular distributions for different reaction products, the cross sections were integrated over the angular intervals of 15°-30° for the ^{94}Zr target and 20°-45° for the ^{197}Au and ^{208}Pb targets at 140 MeV. At 315 MeV the cross sections were integrated between 10° and 20° for the ^{197}Au and ^{232}Th targets; for the ^{94}Zr target at 315 MeV, the differential cross section at 10° was used for the comparison of particle yields. Total particle yields for ^{16}O + ^{208}Pb at 315 MeV were taken from ref. [1]. The cross sections at 33.6 GeV were taken from ref. [2].

The energy dependence of the relative particle yields is displayed in fig. 1. Here the ratios of the element and isotope yields measured for $^{16}O + ^{208}Pb$ at 140 and 315 MeV (fig. 1a) and at 315 MeV and 33.6 GeV (fig.1b, taken from ref. [1]) are shown. The relative particle yields vary significantly between 140 and 315 MeV and remain nearly constant between 315 MeV and 33.6 GeV. In particular, there is a definite trend towards smaller cross sections for lighter fragments at 140 MeV as compared to 315 MeV and 33.6 GeV. This observation corroborates the suggestion [1] that relative particle cross sections vary significantly for relative particle velocities smaller than the mean nucleon velocity inside nuclei (Fermi velocity) and tend to be constant for larger velocities.

As has already been reported in ref. [2], the relative particle yields are target independent at 33.6 GeV incident energy, i.e. the cross sections can be written in the form

$$\sigma(a + b \rightarrow x) = \Gamma(a,x)\ c(a,b)\ . \qquad (1)$$

Here, a and b denote the projectile and target nuclei, respectively, and x is the observed particle. If eq. (1) holds, the ratios of particle yields $\sigma(a + b \rightarrow x)/\sigma(a + b' \rightarrow x)$ should be independent of x for different targets b and b'. We shall, loosely, refer to eq. (1) as factorisation. At relativistic energies the factor c(a,b) was shown to depend only on the nuclear radii [2]. It has already been pointed out in ref. [3] that factorisation is, e.g., a simple consequence of the statistical model of nuclear decay [1,5]. More generally, however, it may also be expected to hold, at least approximately, if only gross properties of the colliding nuclei are important and nuclear structure effects are negligible.

In order to investigate the validity of eq. (1) over a wide range of incident energies, we have displayed in figs. 2-4 the ratios $\sigma(^{16}O + b \rightarrow x)/\sigma(^{16}O + ^{208}Pb \rightarrow x)$ for different targets b and the three energies considered here. Several features in these data should be noted: 1) The cross sections factor with good accuracy both at 33.6 GeV [2] (see fig. 2) and at 315 MeV (see fig. 3). This corroborates the presumed similarity of the reaction mechanism for collisions in the energy range between 20 MeV/A and 2 GeV/A. However, it is not possible to determine the functional form of c(a,b) at 315 MeV since the cross sections have been determined over only a limited angular range. This procedure establishes the relative particle yields within the shown accuracy but does not determine the total yields. 2) At 140 MeV incident energy, factorisation does not apply. There is still a remarkable similarity between the cross sections on the ^{197}Au and ^{208}Pb targets (fig. 4a). For the ^{94}Zr target, however, there is a systematic trend towards increasing yields for the lighter elements (fig. 4b). This could be due to the fact that the energy above the Coulomb barrier increases from 3.5 MeV/A for $^{16}O + ^{208}Pb$ to 5.4 MeV/A for $^{16}O + ^{94}Zr$. Note, that an increase of light particle yields is also observed by increasing the beam energy from 140 MeV to 315 MeV (see fig. 1a).

The similarity of particle yields for $^{16}O + ^{197}Au$ and $^{16}O + ^{208}Pb$ at 140 MeV is rather surprising and cannot be anticipated from the systematics [6] which predicts the isotope production cross sections to be given by [6-8]

$$\sigma(A,Z) \sim \exp([\Delta V_c + Q_{gg}]/T) \quad (2)$$

Here A and Z are the mass and charge of the observed nucleus, ΔV_c is the difference between the entrance and exit channel Coulomb barriers, Q_{gg} is the ground state Q-value of the corresponding transfer reaction and T is an effective temperature. Since T should not change significantly [7,8] between $^{16}O + {}^{197}Au$ and $^{16}O + {}^{208}Pb$, constant relative yields are expected only if the difference

$$\Delta = \Delta V_c\ ({}^{197}Au) + Q_{gg}\ ({}^{197}Au) - \Delta V_c\ ({}^{208}Pb) - Q_{gg}\ ({}^{208}Pb) \approx \text{constant}$$

for each exit channel. However, Δ changes by more than 10 MeV over the range of particles considered here; in particular it varies by about 7 MeV for the carbon isotopes. Using typical experimental temperatures of $T \approx 2\text{-}3$ MeV [6], one expects a variation of relative particle yields by at least one order of magnitude, in disagreement with the experimental observations.

We have found, however, that the Q_{gg} - systematics also apply if Q_{gg} is calculated by using the liquid drop masses for nuclei close to the target nucleus. This is reasonable, since the residual nuclei are expected to be highly excited [6,7] and the level densities might become independent of pairing and shell corrections [9]. Such a modified Q_{gg}-systematics changes very smoothly with the target mass and charge and could explain the observed similarity of cross sections for $^{16}O + {}^{197}Au$ and $^{16}O + {}^{208}Pb$ at 140 MeV. Note, however, that the validity of the Q_{gg}-systematics becomes increasingly worse at the higher energies [1].

It should be noted that the fundamental assumption underlying the derivations of eq. (2) is the two-body nature of the final state. This has, however, not been proven experimentally. In fact, it has been proposed that the reaction products might be highly excited and decay in flight leading to isotope distributions which would also agree with experimental observations [10]. Such an assumption would lead to a simple understanding of the similarities of relative isotope yields for different target nuclei already observed at 140 MeV. The decay in flight (or fragmentation) of the excited projectile has been assumed to be very important at relativistic energies [3,5,11] and, consequently, it is highly interesting to apply this approach over the entire energy range between non-relativistic and relativistic energies, in order to predict the energy dependence of peripheral interactions between heavy ions.

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Figure Captions

Fig. 1. Comparison of isotope yields for reactions induced by ^{16}O on ^{208}Pb at incident energies of (a) 140 and 315 MeV and (b) 315 MeV and 33.6 GeV. The data at 315 MeV were taken from ref. [1] and at 33.6 GeV from ref. [2]. The vertical scale of part (a) is in arbitrary units.

Fig. 2. Comparison of isotope yields observed in the bombardment of ^{16}O ions on Cu, Ag and Pb targets at 33.6 GeV laboratory energy. Data have been taken from ref. [2].

Fig. 3. Comparison of isotope yields observed in the bombardment of ^{232}Th, ^{208}Pb, ^{197}Au and ^{94}Zr targets by ^{16}O ions at 315 MeV laboratory energy. Data for the ^{208}Pb target have been taken from ref. [1]. The vertical scale is in arbitrary units.

Fig. 4. Comparison of isotope yields observed in the bombardment of ^{208}Pb, ^{197}Au and ^{94}Zr targets by ^{16}O ions at 140 MeV laboratory energy. The vertical scale is in arbitrary units.

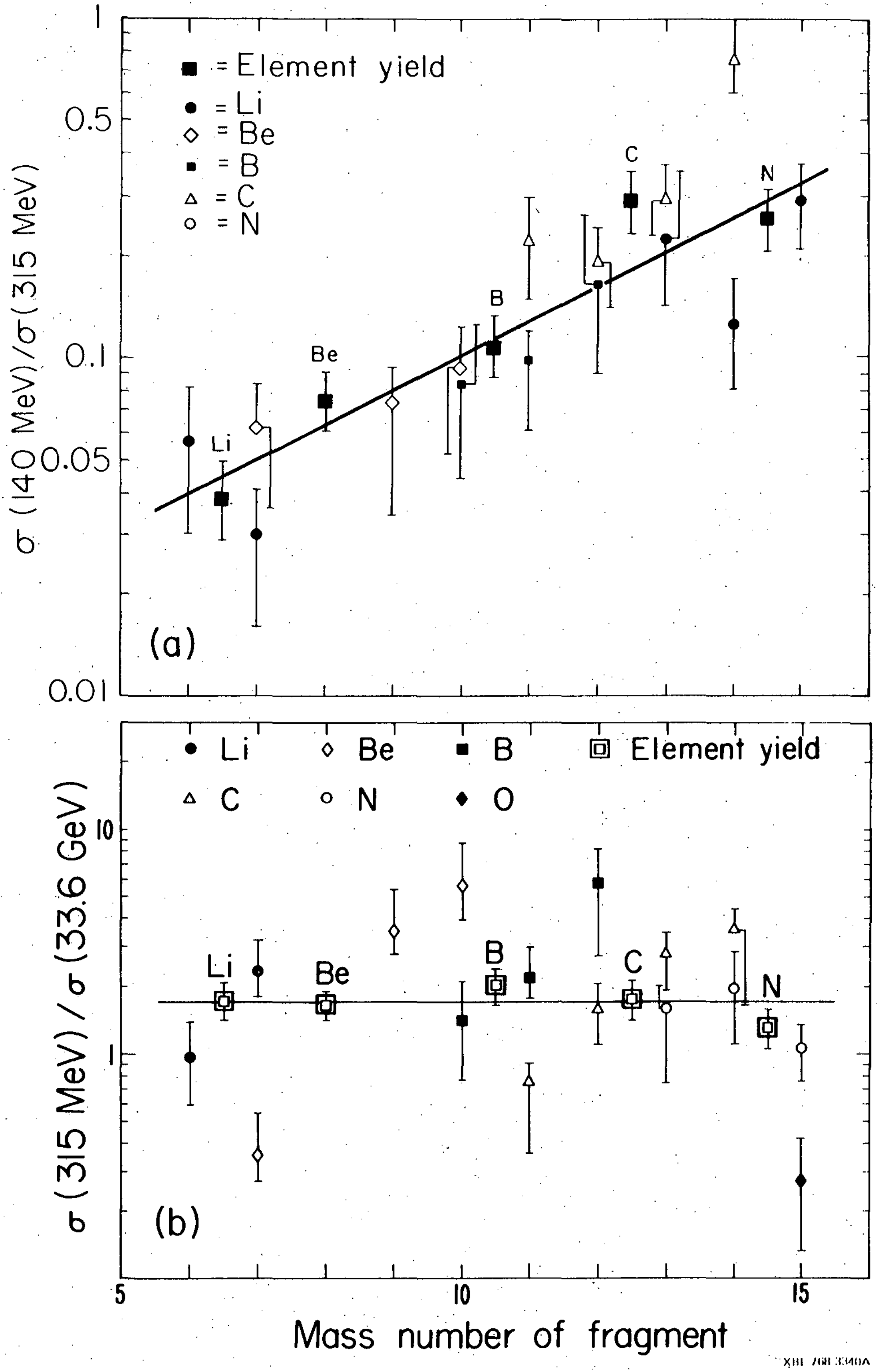
■ = Element yield
● = Li
◇ = Be
▪ = B
△ = C
○ = N
Li
Be
B
C
N
(a)
σ (140 MeV)/σ(315 MeV)
1
0.5
0.1
0.05
0.01
● Li
◇ Be
▪ B
▣ Element yield
△ C
○ N
◆ O
Li
Be
B
C
N
(b)
σ (315 MeV) / σ (33.6 GeV)
10
1
5
10
15
Mass number of fragment
XBL 768-3340A

Fig. 1

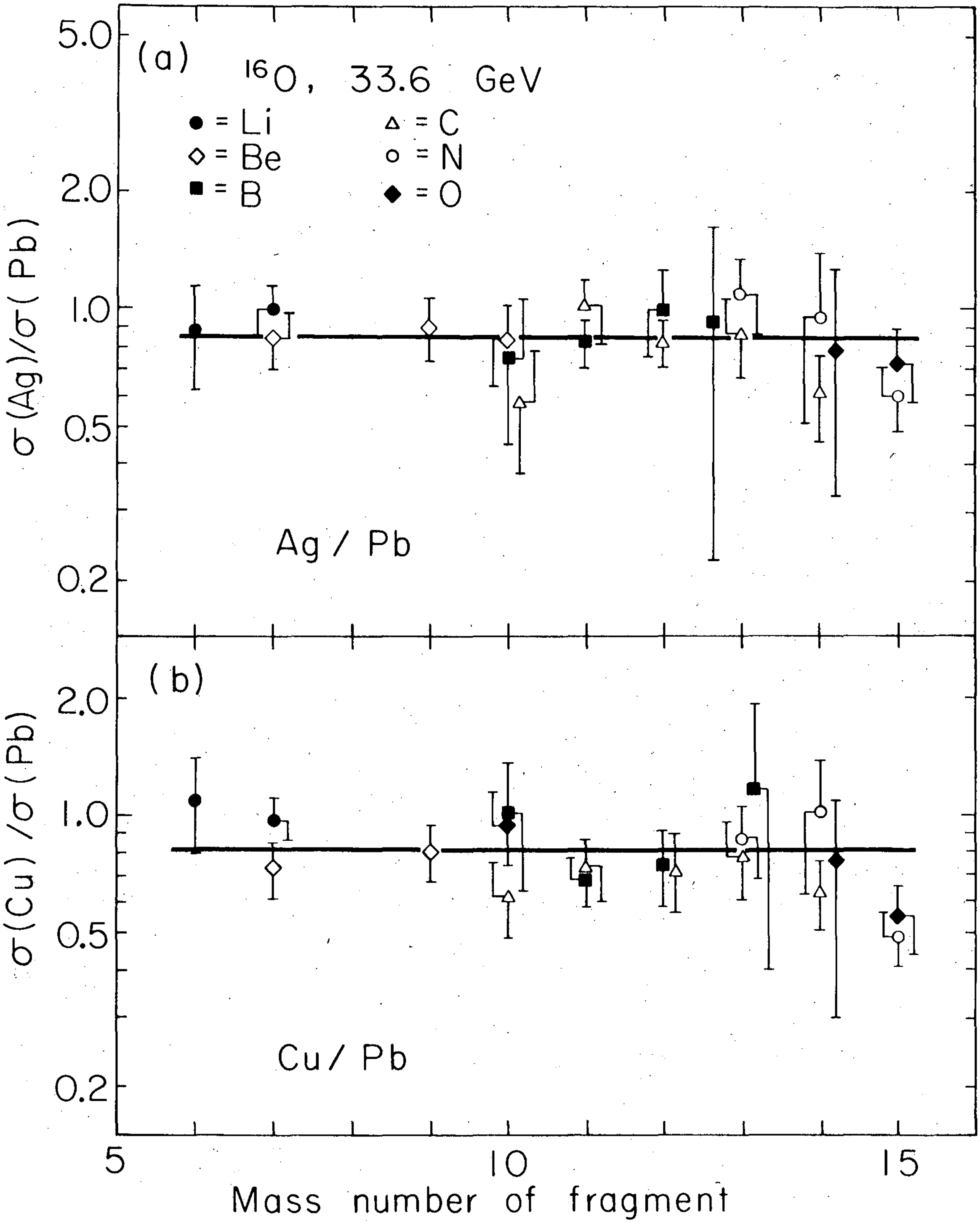

Fig. 2

XBL769-3953

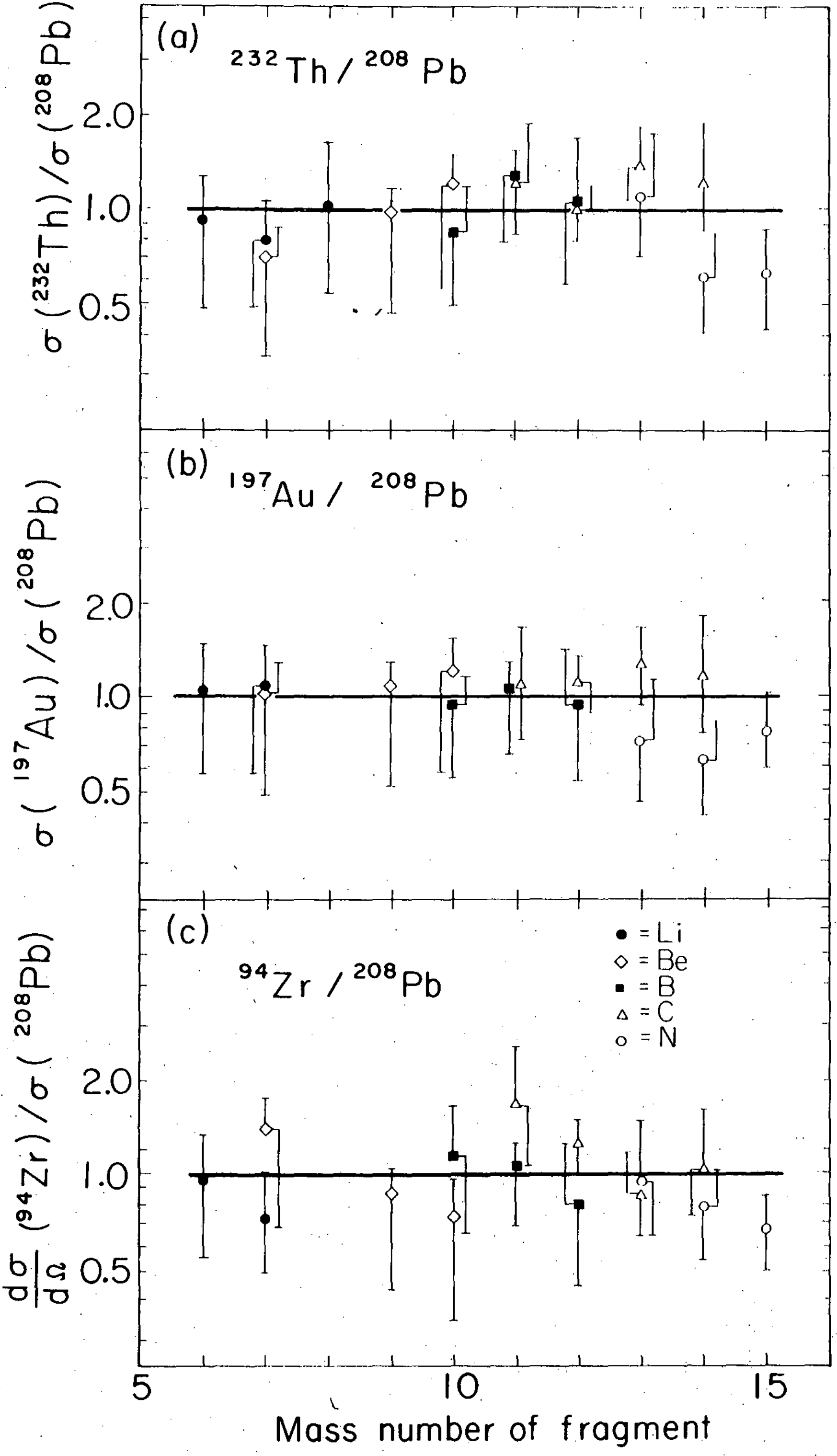

Fig. 3

XBL 769 - 3954

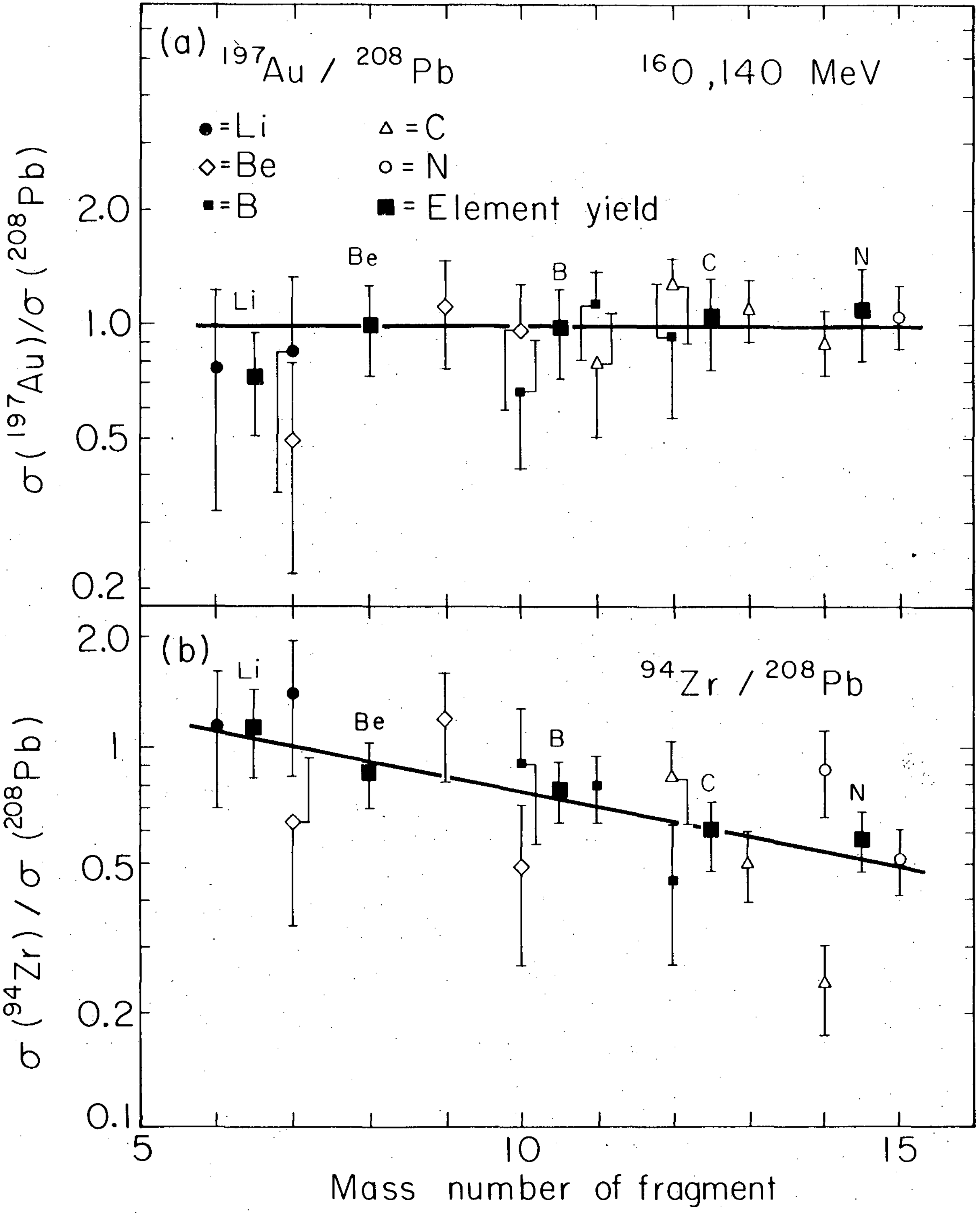

Fig. 4

XBL769-3949

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