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November 1984

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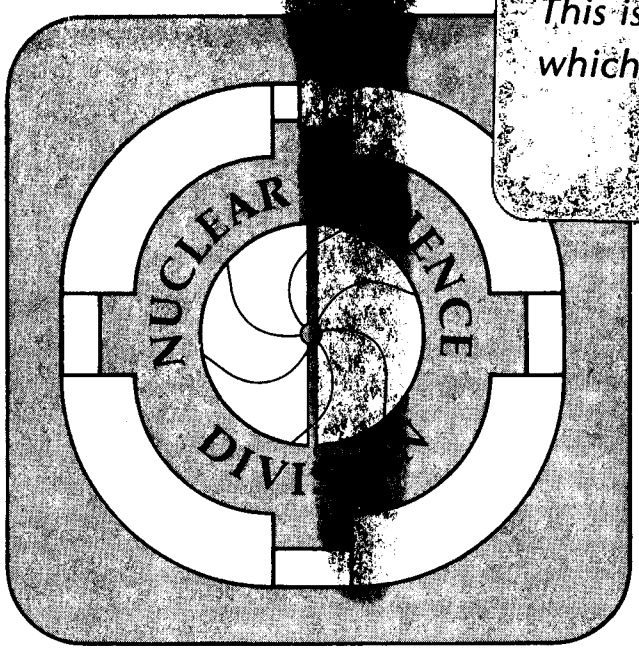

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Unusual Behavior of Projectile Fragments Formed in the Bombardment of Copper with Relativistic Ar Ions

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Unusual Behavior of Projectile Fragments Formed in the Bombardment of Copper with Relativistic Ar Ions

Abstract

The interaction properties of projectile fragments from the fragmentation of 0.9 A GeV and 1.8 A GeV ^{40}Ar with Cu have been studied using radioactivation techniques. Projectile fragments formed in the interaction of the primary Ar beam with a thick Cu disk (the "target" disk) interacted with a second "detector" Cu disk. The relative reaction product yields in the two disks were measured as a function of the separation between the disks. A large increase in the yield of "deep spallation" products (^{24}Na, ^{28}Mg) in the detector disk was observed as the projectile energy increased from 0.9 A GeV to 1.8 A GeV. At 1.8 A GeV (but not at 0.9 A GeV) the yields of the deep spallation products decreased as the separation between the disks increased indicating either a dramatic broadening of the relevant projectile fragment angular distribution between 0.9 A GeV and 1.8 A GeV or a decay in flight of some of the projectile fragments at 1.8 A GeV (but not at 0.9 A GeV). Calculations will be discussed that cast doubt on the first possibility.

Introduction

The formation of projectile fragments with anomalously short mean free paths in relativistic heavy ion collisions has attracted considerable interest in recent years.[1] The existence of these so-called anomalons has not been definitively established.[2-10] Thus, it is important that as many different techniques as possible be used to study the problem. We report here the first results of experiments in which the formation, interaction, and possible decay of projectile fragments has been investigated using activation techniques. (The word "decay"in this context should be taken to mean some drastic change as a function of time in the interaction cross section of the projectile fragments.)

The principle of the experiment is shown in Figure 1. An Ar ion beam is used to irradiate two Cu disks. The primary Ar beam along with any secondary fragments from Ar-Cu interactions can induce target fragmentation reactions in the Cu blocks producing the usual observable radioactive products. The ratio, R, of the radionuclide activities found in the downstream disk (Cu 2 or Cu 4) to those in the upstream disk (Cu 1 or Cu 3) is measured for three separations of the disks, d= 0.0 cm (contact), 10 cm, and 20 cm.

For radionuclides resulting from the interaction of the primary Ar beam or strongly forward-peaked projectile fragments with the disks, we would expect R to be independent of the distance between the disks (provided the beam or projectile fragments are not diverging). If R decreases with increasing distance between the disks, then the species inducing the target fragmentation reactions in the second disk either have a broad angular distribution causing them to "miss" the second disk as it is moved further from the first disk or decay in flight occurs between the disks. To evaluate the former possibility, large annular guard rings are installed around the second disk. If broad projectile fragment angular distributions are the cause of R decreasing with distance, this should result in significant activities being induced in the guard rings when the disks are far apart. In the absence of broad projectile fragment angular distributions, a decrease of R with distance may be a measure of the lifetime of any decaying projectile fragment species.

We also note that for radionuclides resulting from interactions of the primary beam with the disks, we expect the value of R to be less than 1 due to attenuation of the primary beam in the upstream disk (see trajectories Ar-1 and Ar-2, Figure 1c). Due to target fragmentation reactions in the downstream or "detector" disk induced by projectile fragments from interactions in the first or "target" disk, (trajectory Ar-3) however, the value of R may be (and almost always is) greater than 1. If R was especially large, this might be evidence for unusually large interaction cross sections for the projectile fragments (or some subset thereof) similar to that possibly attributed to "anomalons". In the absence of a detailed knowledge of the multiplicity, composition, angular distributions and momentum spectra of <u>all</u> fast projectile fragments, however, a definitive interpretation of large R values in terms of the existence of anomalons is not possible at the present time.

In our experiments, the circular Cu disks were 1 cm thick and 8 cm in diameter. The 1 cm thick guard rings had inside diameters of 8 cm and outside diameters of 14 cm. Thus the rings subtended angles of approximately 83-86 degrees with respect to the center of the first disk when the disks were in contact and angles of 11-20 degrees when the disks were separated by 20 cm. The Cu disks were irradiated with 0.9 A GeV and 1.8 A GeV ^{40}Ar using the irradiation station of the LBL Bevalac. Autoradiographs of each irradiated disk showed the beam spot size to be less than 1 cm in diameter (see Figure 1b) and to be the same for all disks. Each disk configuration was irradiated with about 10^{12} ions over a period of 2-4 hours. Irradiations with 0.9 A GeV and 1.8 A GeV were done on two separate occasions.

The radionuclides present in the irradiated Cu disks and guard rings were assayed by off-line gamma ray spectroscopy.[11] Counting was begun within a few hours after the end of irradiation (at LBL) and was continued for several months (at Marburg). Independent determinations of most of the radionuclides present in each disk were made at LBL, Purdue, and Marburg. All the results agreed within experimental uncertainties and the results from the different laboratories were averaged to give the final results.

Results and Discussion

In Figure 2, we show the dependence of the ratios R_d on product mass number for two different separations, d, of the disks in irradiations using 0.9 A GeV and 1.8 A GeV ^{40}Ar. The dependence of R_d upon A is a reflection of the energy spectrum and angular distribution of the projectile fragments causing the secondary target fragmentation reactions that make $R > 1$ in each disk configuration. Focussing our attention on the irradiation with 0.9 A GeV ^{40}Ar (Figure 2b), we note that when the two disks are in contact (R_0), the projectile fragments most likely to strike the detector disk lead to the formation (by target fragmentation) of products with A = 55 and substantial yields are seen for all products with $A > 40$. The products with $A < 40$ (^{7}Be, ^{24}Na, ^{28}Mg) are

believed to be formed only in high energy deposition target fragmentation events ($E_{threshold}$ > 1 GeV) and thus their production in secondary target fragmentation events is suppressed (R_0 = 1.1 - 1.2).

When the disks are moved to 20 cm apart, then the "detector" disk is sampling a different subset of the projectile fragments created in the "target" disk, i.e., the more strongly forward-focussed and thus higher energy fragments. As a result, the projectile fragments most likely to reach the second disk now lead to the formation of products with A = 45 and there is a decrease (relative to the contact configuration) of the yields of fragments with A = 50-60. The fragments with A < 40 are produced with the same yields regardless of disk separation because they are only produced (in either case) by highly forward-focussed , energetic projectile fragments.

The radioactivities found in the guard rings support this interpretation. When the disks are in contact, no activity (< (1 %) of the disk activity for ^{24}Na) corresponding to A < 40 products is found in the guard ring. The activities found in the guard rings when the disks are separated by 20 cm are given in Table 1. Again very small activity levels are seen for A < 40 products in the guard ring.

Let us consider the irradiation with 1.8 GeV ^{40}Ar.(Figure 2a) The dependence of R_0 upon A for A > 40 is similar to that observed with 0.9 A GeV ^{40}Ar except for the shift of the most probable secondary product mass number to a slightly lower value (A = 50). The data for R_{20} is also similar (for A > 40) to that observed at 0.9 A GeV with the possible exception of a slight downward shift of the most probable fragment A value. But the results for fragments with A < 40 are significantly different from those measured with 0.9 A GeV ^{40}Ar. The values of R_0 range from 1.3 to 1.6, substantially higher than observed at 0.9 A GeV. Furthermore, the ratios decrease with separation between the disks with the values of R_{20} being 1.1 - 1.2. The variation of R with distance for both bombarding energies is shown in Figure 3 for both ^{24}Na and ^{28}Mg.

To better illustrate the differences between the light (A < 40) residue results at 0.9 A GeV and 1.8 A GeV, let us consider the quantity

$$X_d(\%) = 100\ (R_d^* - 1)$$

where R_d^* is defined analogously to R_d but with the activity in the guard rings added to that of the "detector" disks. For ^{24}Na we obtain

$$X_0 = 17\pm2 \quad X_{20} = 14\pm3 \quad X_{20} - X_0 = -(3\pm3)\ \%\ \text{at 0.9 A GeV}$$

and

$$X_0 = 50\pm2 \quad X_{20} = 34\pm2 \quad X_{20} - X_0 = -(16\pm3)\ \%\ \text{at 1.8 A GeV}$$

Thus, at 0.9 A GeV, by adding the ^{24}Na activity in the guard ring to that of the "detector" disk, we are able to account for any apparent loss of activity with increasing disk separation due to the finite width of the secondary fragment angular distribution. At 1.8 A GeV, however, the same procedure would indicate (16±3) % of the activty is "missing". Qualitatively similar results (with larger uncertainties) are obtained for ^{28}Mg.

At first glance the observations appear to be consistent with at least two different explanations. The first of these explanations asserts that in going from 0.9 to 1.8 A GeV, more energetic projectile fragments emerging at large angles (with respect to the beam direction) were made. The increased yields of these fragments would account for the increase in R_0 while the broad angular distribution would cause them to miss the second disk as the disks were moved apart.

The second explanation involves the formation of a new unusual type of energetic projectile fragment as the beam energy increases from 0.9 A GeV to 1.8 A GeV. Such a species would be short-lived (approximately 10^{-10} sec), " decaying" in flight between the

disks and have a large interaction cross section with matter, accounting for the increase in R_0 at 1.8 A GeV.

Certain observations and calculations cast doubt on the first possibility. The A<40 activities observed in the guard ring at 1.8 A GeV are a small fraction of the A<40 activities present in the disks (Table 1). This observation and the known energy spectra and angular distributions of normal projectile fragments[12], mid-rapidity protons[13], and pions[14] are inconsistent with the suggestion that they are responsible for the increase in R_0 at 1.8 A GeV and the decrease of R with distance provided one takes into account the known (high) threshold for A<40 production from Cu and the low mean transverse momenta of all secondaries.

To illustrate this point, we have performed a Monte Carlo calculation of the expected relative ^{24}Na activities in the disks and guard rings (as well as "missed" activity) for a disk separation of d=20cm. In this calculation, we evaluated the ^{24}Na production in the second disk and its guard ring due to three different types of secondaries produced in the first disk: (a) protons evaporated from projectile fragments moving with beam velocity (b) "mid-rapidity" protons "evaporated" from a fireball moving with the p-p center of mass velocity and T = 120 MeV[13] and (c) pions which are treated as "evaporating" from the p-p center of mass with T = 80 MeV.[14] (It is easy to show that for a relativistic nucleus evaporating secondary particles of mass m with temperature T, the root mean square angle of emission of the secondary particle in the laboratory frame is given by

$$\theta_{rms} \simeq \frac{\sqrt{2T/m}}{\sqrt{\gamma^2-1}}$$

where γ is the Lorentz factor for the emitting system. At any given temperature, the lightest evaporation product has the broadest angular distribution. Thus it is sufficient for our purpose to consider only the case of the lightest secondaries.) We have further assumed that 80% of the protons evaporated from the projectile fragments had T = 10 MeV

and 20% had T = 40 MeV[12] and the three types of secondaries (a,b,c) are produced in equal abundance.

In the computation, each evaporated particle is assigned momentum components p_x^*, p_y^*, and p_z^* drawn randomly from a Gaussian distribution of zero mean and a dispersion $\sigma = (mT)^{1/2}$ (where p_i^* refers to the relevant moving frame). The quantities p_z^* and the total energy E^* of the emitted particle are Lorentz-transformed into the laboratory frame quantities $p_{\parallel}$ and E_L. Since the transverse momentum p_T is invariant under Lorentz transformation, each emitted particle emerges at lab angle θ where

$$\theta = \tan^{-1} (p_T / p_{\parallel})$$

The value of θ for each particle emerging from the first disk will determine whether that particle will strike the second disk, its guard ring or miss both. If a secondary particle is calculated to be emitted at an angle such that it strikes the disk or guard ring, its probability of inducing a Cu$\rightarrow{}^{24}$Na reaction is calculated using the known excitation function for the Cu(p,X)^{24}Na reaction.[15] One keeps track of the number of ^{24}Na nuclei made in the disk, guard ring, and the number of particles which "missed" both the disk and guard ring, but could have induced the Cu $\rightarrow$ Na reaction.

The results of this calculation are shown in Table 2. The relative number of ^{24}Na product nuclei expected to be found in the guard ring is 5% at 0.9 A GeV and decreases to <1% at 1.8 A GeV. The contributions from "mid-rapidity" protons to the ^{24}Na activities (columns 2 and 5) are so low as to also exclude the possibility that even the most energetic protons (T = 40 MeV) evaporated from the target nucleus could play any significant role in this problem. Thus, on the basis of conventional nuclear physics, one would not expect any secondary fragments to be produced at 1.8 A GeV that have broader angular distributions than those observed at 0.9 A GeV. Hence, the explanation advanced earlier that the decrease of R with separation of the disks at 1.8 A GeV (but not at 0.9 A GeV) was due to a broadening of the secondary fragment angular distribution with

increasing projectile energy is not consistent with the calculations presented herein or the "ring data."

We conclude that in the interaction of 1.8 A GeV ^{40}Ar with Cu either we have observed a new unusual type of projectile fragmentation with an anomalously broad angular distribution and unusually large transverse momenta or we have observed an unusual, unstable projectile fragment species that has a large interaction cross section with matter.

The authors are grateful to the operations staff of the LBL Bevalac and Dr. Fred Lothrop for supplying us with excellent Ar beams. One of us (NTP) acknowledges the receipt of a Senior U.S. Scientist Award from the A. v. Humboldt Foundation and the hospitality of the Kernchemie, Marburg University. One of us (EMF) acknowledges the hospitality of his colleagues at Marburg University. The nuclear chemists from Marburg gratefully acknowledge the generous hospitality of Professor G.T. Seaborg during their stay in Berkeley. We want to thank Professor R. Weiner (Marburg) for many stimulating discussions.

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Table 1

Effect of large angle secondary fragments on the observed values of R_{20}, i.e., the comparison of C_{ring} with C_{disk} at d = 20 cm. (C is the activity of a specific nuclide in either the ring or the disk while Ω is the solid angle of the ring or second disk relative to the center of the first disk.

Nuclide	$\frac{C_{ring}}{\Omega_{ring}} \Big/ \frac{C_{disk}}{\Omega_{disk}}$ (at 1.8 AGeV)	$\frac{C_{ring}}{\Omega_{ring}} \Big/ \frac{C_{disk}}{\Omega_{disk}}$ (at 0.9 AGeV)
^{7}Be	0.038 ± 0.007	0.025 ± 0.018
^{22}Na	≤ 0.038	≤ 0.034
^{24}Na	0.038 ± 0.005	0.021 ± 0.004
^{28}Mg	0.027 ± 0.006	0.026 ± 0.004
^{44}Sc	0.071 ± 0.005	0.066 ± 0.004
^{46}Sc	0.084 ± 0.004	0.074 ± 0.005
^{54}Mn	0.093 ± 0.004	0.089 ± 0.004
^{56}Co	0.090 ± 0.004	0.088 ± 0.005
^{58}Co	0.089 ± 0.004	0.086 ± 0.004

The relative number of ^{24}Na nuclei calculated to be formed in the downstream Cu disk and guard ring and the number of particles of sufficient energy to induce the Cu$\rightarrow{}^{24}Na$ reaction calculated to "miss" both the disk and guard ring. The sources of the induced activity are discussed in the text.

E_{proj} = 0.9 A GeV

	Source of Induced Activity		
	P.F. Protons	Mid-rapidity Protons	Pions
Disk	100.0	0.2	0.1
Ring	5.5	0.3	0.1
"Lost"	0.3	1.0	0.1

E_{proj} = 1.8 A GeV

	Source of Induced Activity		
	P.F. Protons	Mid-rapidity Protons	Pions
Disk	100.0	0.3	0.1
Ring	0.5	0.4	0.2
"Lost"	0.003	0.7	0.3

Figure Captions

Figure 1: a) Schematic diagram of the target arrangement. The two copper disks (dia = 8 cm, thickness = 1 cm) are separated by a distance d (d = 0,10, or 20 cm). The downstream disk is surrounded by a 1 cm thick Cu ring in the contact and d = 20 cm configurations. b) Autoradiographic picture of the activity distribution in a Cu disk. There was no significant difference between the pictures for Cu disks 1-4. c) Schematic representation of 3 different types of interaction in the two Cu disks.

Figure 2: Product mass number dependence of the ratio R of the activity in the downstream to upstream Cu disks for nuclides produced in the interaction of copper with 0.9 A GeV ^{40}Ar ions (bottom) and 1.8 A GeV ^{40}Ar ions (top)

Figure 3: The ratio R_d for ^{24}Na and ^{28}Mg as a function of the separation distance d between the Cu disks for 0.9 and 1.8 A GeV ^{40}Ar irradiations.

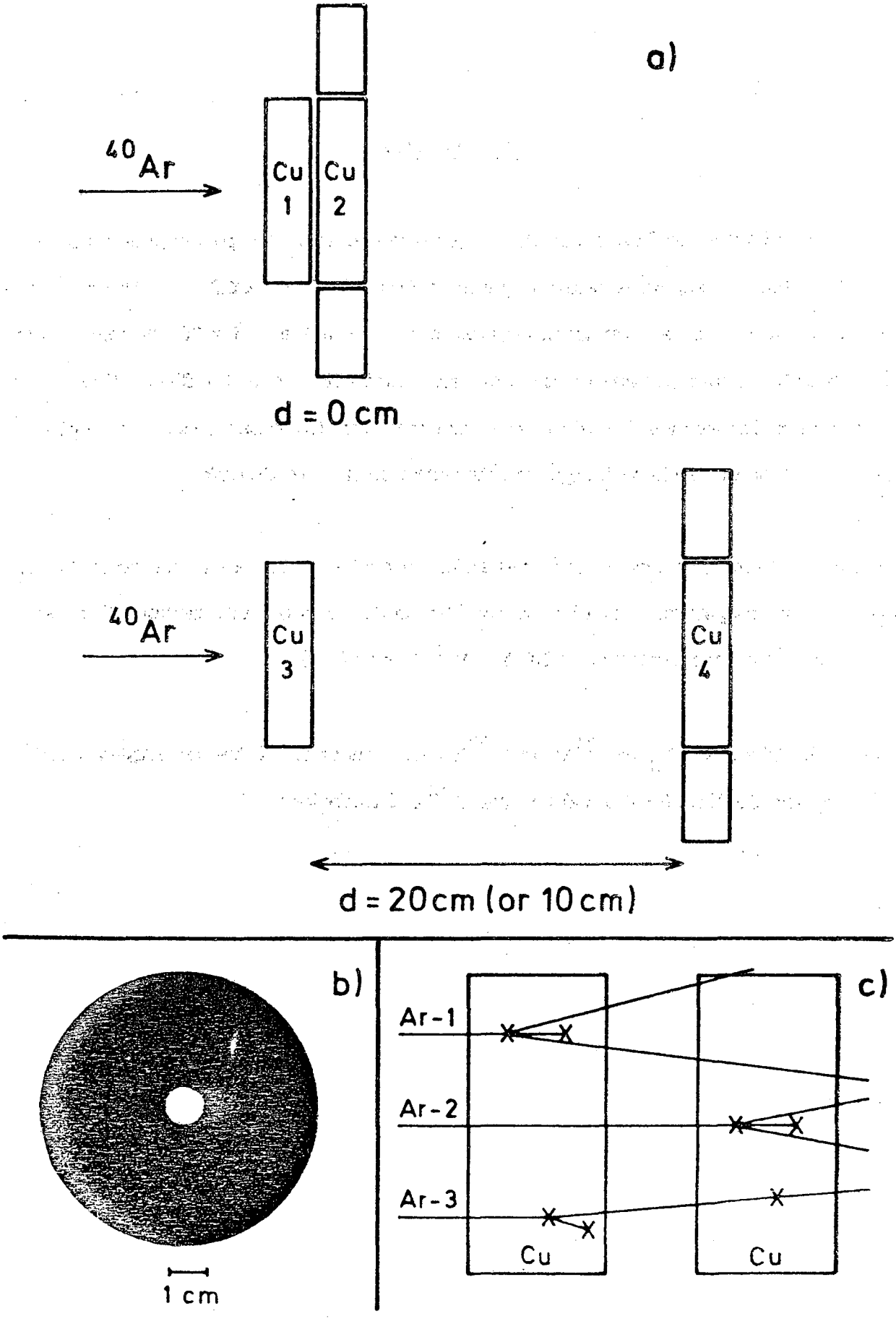
a)
^{40}Ar
Cu 1
Cu 2
d = 0 cm
^{40}Ar
Cu 3
Cu 4
d = 20 cm (or 10 cm)
b)
1 cm
c)
Ar-1
Ar-2
Ar-3
Cu
Cu

Figure 1

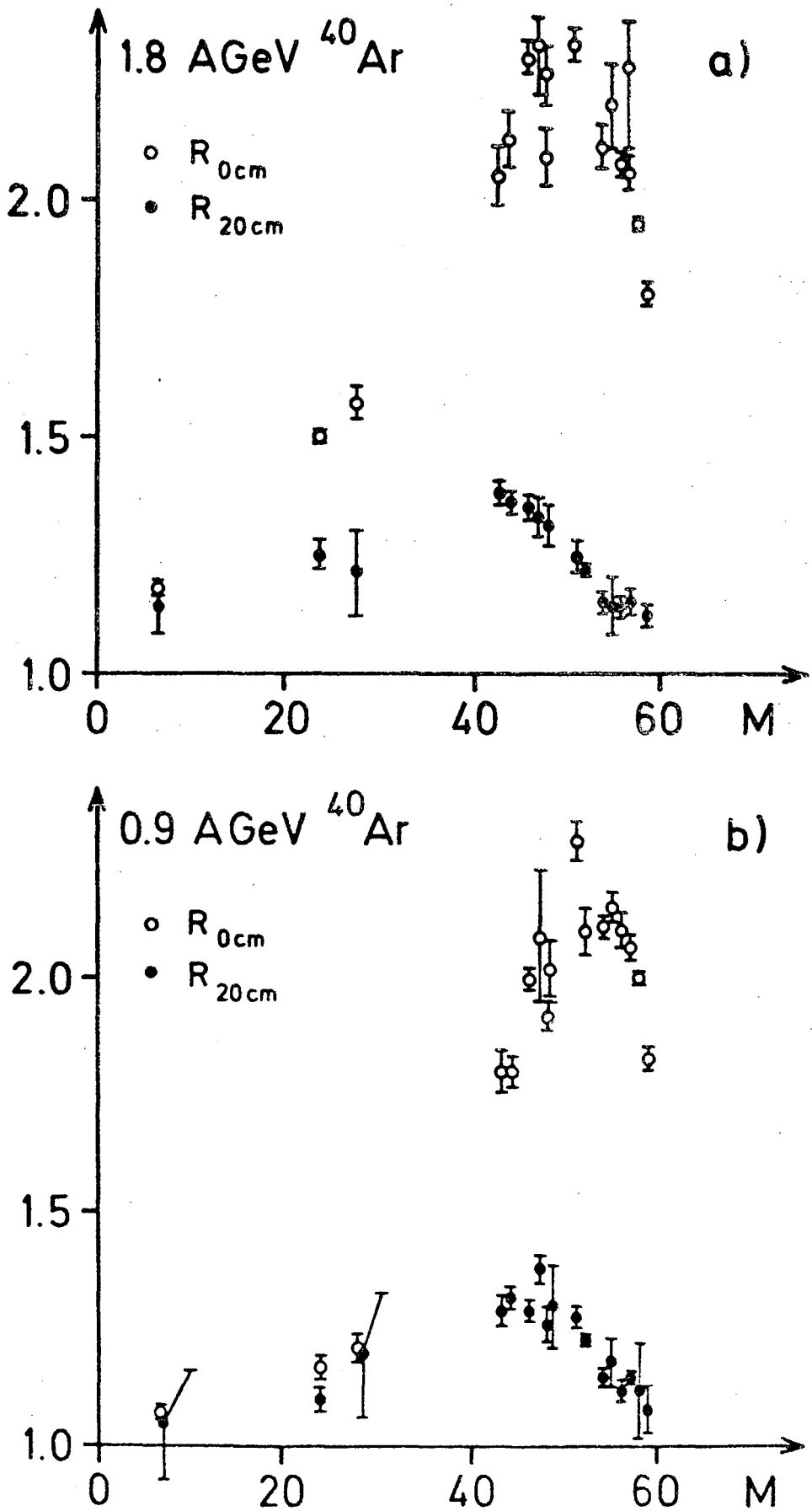
1.8 AGeV ^{40}Ar
a)
R_{0cm}
R_{20cm}
2.0
1.5
1.0
0
20
40
60
M
0.9 AGeV ^{40}Ar
b)
R_{0cm}
R_{20cm}
2.0
1.5
1.0
0
20
40
60
M

Figure 2

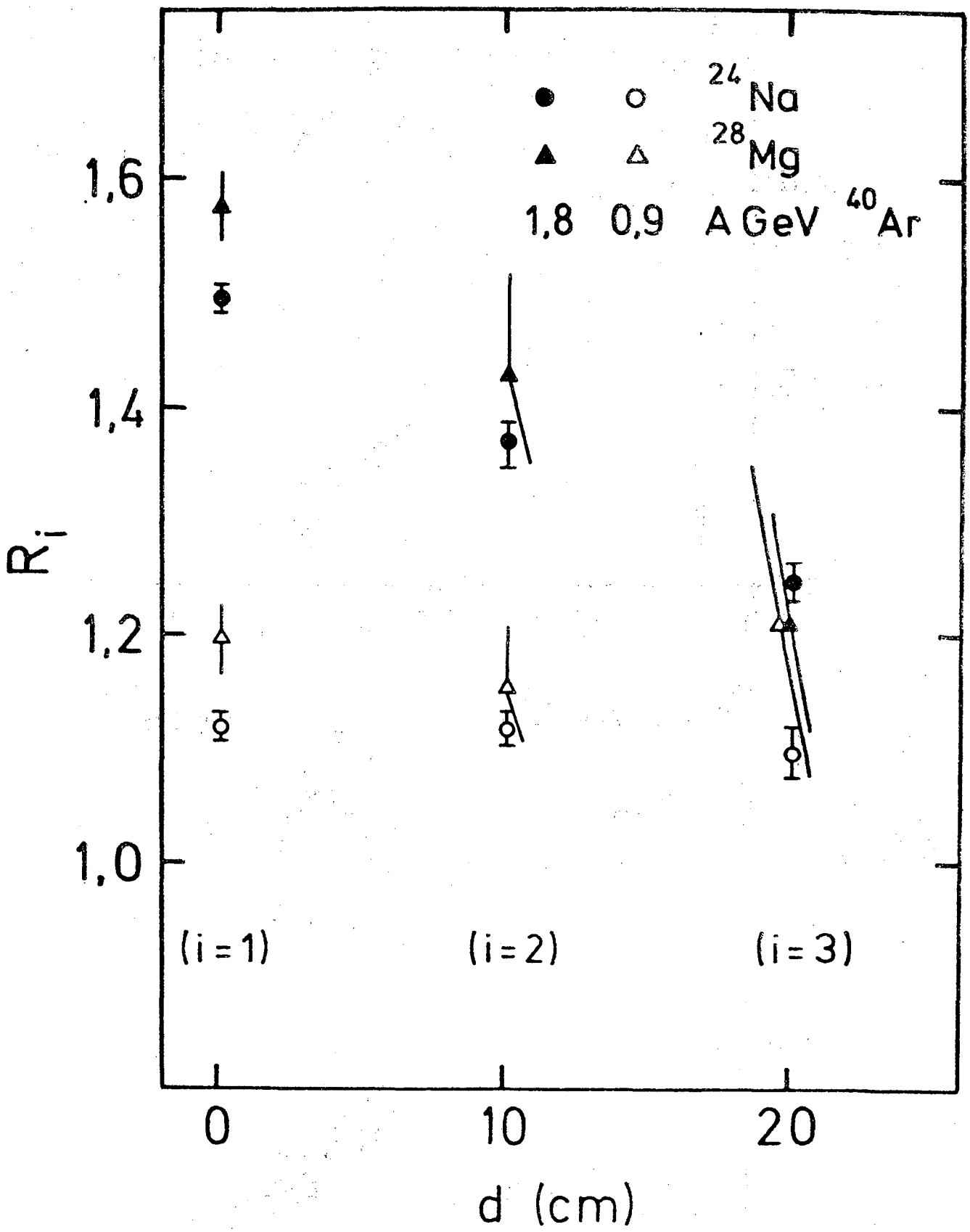

Figure 3

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