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COMMENTS OF A PAPER ON "ELASTICALLY SCATTERED RECOIL NUCLEI IN SOLID-STATE DETECTORS"+

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+Work supported by NASA contract 9-8165 and by McDonnell-Douglas Corporation Contract Z80058T.

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I. INTRODUCTION

In ~~a recent letter, Horn and Von Oertzen[1] suggested using~~ elastically scattered recoil nuclei to measure the registration characteristics of solid state track detectors. To support this suggestion they showed pictures of tracks, in mica, that they attributed to elastically scattered K and Fe nuclei produced by an irradiation with 32 MeV O^{16} ions.

Although this is an interesting observation, we believe that their interpretation is incorrect. In what follows below we first show that the measured characteristics of the tracks do not match the theoretically predicted features for elastic processes. We next show that the experimental features are consistent with those predicted for inelastic (mostly compound nucleus) reactions. However, we cannot rule out the possibility that they are produced by contaminant ions present in the incident beam.

II. GEOMETRICAL CHARACTERISTICS OF THE TRACKS

We have measured the geometrical characteristics of the tracks studied by Horn and Von Oertzen*. The following features were observed:

1. The tracks are strongly peaked in the forward direction, all the laboratory angles being less than 20° from the beam direction.

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*We want to emphasize the generous cooperation of Dr. Horn and Dr. Von Oertzen, who sent us a piece of their irradiated muscovite, for study.

2. Their length distribution around the mean value (~3 microns) is approximately gaussian with no evidence of an appreciable yield of tracks with much shorter lengths (Figure 1a).
3. In particular, there is no tendency for the tracks to shorten as the angle with respect to the beam increases.
4. No new tracks have appeared on fresh surfaces obtained by removing and etching thin successive layers (~3 microns) from the surface exposed to the ions.

III. ELASTIC PROCESSES

Following these observations we calculated what should be expected for elastic scattering processes*. All the calculations were performed using the classical Rutherford formula, for coulomb scattering. This formula is not strictly valid for elastic scattering at these energies, particularly for near head-on collisions where the departures from experiment become increasingly large. However, these deviations are in such a sense as to <u>increase</u> the disagreement with experiment noted below. Use of a more complicated, but more correct, formulation would therefore only reinforce the conclusions of this paper.

In agreement with the most recent experimental work,[3] we also assumed that mica would register the following ions: 3 MeV Ne^{20}, 14 MeV Si^{28} and 9 MeV Ar^{40} with respective experimental track

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*These calculations will be described in detail in another publication.[2]

lengths of ~1 micron, ~3 microns, and ~3 microns.* With the above model we predict the following experimental features for tracks produced by elastic scattering processes:

1. The track length distribution should be similar to that shown in Figure 1b; this distribution reflects the basic properties of Rutherford collisions: there are many more recoils produced at large angles than at small angles. Such large angle events have low energy. Hence there should be many more short tracks than long ones.
2. The track lengths should also become increasingly shorter at large angles as the recoil energy approaches threshold.
3. Notwithstanding the above, tracks of ~3 microns in length should be seen at all inclination angles between 0° and 90°. These tracks would be produced, for example, by silicon recoils emitted at 45° to the beam direction, as shown in Figure 2.
4. Contrary to the statement by Horn and Von Oertzen, Si and Al recoils are probably much more important than K and Fe recoils.

It can be seen that the experimental data are completely inconsistent with the predicted features. Although our calculations may have to be modified somewhat in the light of future data on

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*It should be pointed out, however, that we have noted[4] that, in our view, the registration characteristics of mica for low energy, low mass ions needs to be verified before being completely accepted.

the registration characteristics of mica, we see no way to modify the essential qualitative aspect of our comparison. Elastic recoils should not be peaked in the forward direction; the observed tracks are. For this reason, we believe that the interpretation of Horn and Von Oertzen is incorrect.

IV. INELASTIC PROCESSES

It remains to find a satisfactory explanation for the observed tracks. Inelastic nuclear processes provide a possible solution to the problem. In fact, a much earlier observation of tracks produced by incident oxygen ions of higher energy was explained on this basis by Price and Walker.[5] This possibility was rejected by Horn and Von Oertzen in their work by the following phrase: "compound nucleus formation above the Coulomb barrier will give no observable tracks because the lifetimes of the compound nuclei are too short." But if the lifetimes of compound nuclei are indeed too short, those of the products of reactions such as ${}_{8}O^{16}({}_{8}O^{16}, \alpha){}_{14}Si^{28}$ are most certainly not!

The kinetic energy of the bombarding ions is high enough to allow their interaction with all the major constituents of mica (Table I, column 2). The following inelastic processes can play a role in producing tracks: (1) for small and intermediate impact parameters the two nuclei may form either a complete fusion compound nuclei (CFCN) or a partial fusion compound nuclei (PFCN); (2) for large impact parameters several "barrier" processes occur, in particular transfer reactions.

For 32 MeV oxygen ions we can exclude the transfer and the PFCN reactions for several reasons that are discussed in more detail elsewhere[2]. But the CFCN reactions, on the other hand, seem to give all the required characteristics. Consider for example the possible reaction ${}_8O^{16}({}_8O^{16},\alpha){}_{14}Si^{28}$:

1. The average kinetic energy of the product nucleus is ~14 MeV and the corresponding track length is ~3 microns[5];
2. The maximum angle of emission of the recoil is ~26°;
3. By referring to Table II (column 4) we see that at a depth of 3 to 4 microns, the values of the cross sections are very small and therefore the track density should drop sharply with increasing depth.

The above characteristics are completely compatible with the experimental observations; thus compound nucleus processes provide a likely explanation of the observed tracks.

However, it must be noted that there are some difficulties with this interpretation. For one thing, it is not clear that the observed track density is compatible with the cross-sections calculated by Thomas[10]. Unfortunately, the experiment of Horn and Von Oertzen was not done in a way that makes it possible to compare theoretical and experimental track densities. Since most reaction nuclei are projected in the forward direction, it is necessary to produce the reaction nuclei in a thin converter film placed <u>upstream</u> in the beam and then observe them in a detector placed in a <u>downstream</u> position. This point is discussed in detail in a paper by Crozaz *et al.*[6] Suffice it to say here that with an assumed effective interaction length of 3μ, the predicted track density calculated from the cross-sections given in Table II is 100 times the observed density of ~5 x 10^6 t/cm^2.

This lower density could be easily explained by the fact that most of the interaction tracks are produced in the interior of the sample and then projected forward. They cannot therefore be revealed by etching the external surface as was done by Horn and Von Oertzen. However, if this were the correct explanation then we would expect to see an increase in the track density as small amounts of the surface were removed and then re-attacked. No such increase was observed by us when we performed this experiment on the Horn and Von Oertzen sample. It must be admitted, however, that this is a difficult experiment since the amounts of mica removed are very small. It is also difficult to interpret because the cross-sections drop rapidly with increasing depth due to the energy loss of the incident particles.

We also consider it possible that the actual flux value was lower than that quoted by Horn and Von Oertzen (~10^{14} ions/cm^2). In mica samples irradiated either with the same flux of 11 MeV α-particles[6] or in a flux fifty times smaller of low energy oxygen ions[5], we observe interaction track densities in excess of 10^7/cm^2 as opposed to the value of 5 x 10^6/cm^2 observed here. The differences are difficult to interpret, however, because of the different experimental conditions.

V. CONTAMINATION OF THE INCIDENT BEAM

The above difficulties make it impossible for us to conclude that the tracks seen by Horn and Von Oertzen are "certainly" the result of compound nucleus reactions. Another explanation is that the accelerator beam could be contaminated with unidentified heavy ions having the same magnetic rigidity but a higher rate of primary ionization than the nominal ions.

The track density and the quoted flux value would imply a degree of contamination of $\sim 10^{-8}$. Such a value is very small compared to the one ($\sim 10^{-4}$) observed during similar irradiation with the HILAC Berkeley accelerator[7] and therefore is not, a priori, improbable. Furthermore such "contamination" tracks should be essentially observed on the surface exposed to the ion beam (see reference 6, p. 4) and the spatial distribution of the tracks should be narrowly peaked in the forward direction because the beam divergence is usually very small. Therefore it is difficult to rule out the possibility that the tracks observed by Horn and Von Oertzen have been produced by contaminant ions by the incident beam*.

It might be argued that the angular spread of the beam is too narrow to be compatible with the observed rather broad distribution of tracks. To counter this remark we have plotted on Figure 3 the azimuthal distributions of tracks of ~3 microns in length produced by arsenic ions of 16 MeV accelerated for another purpose[9] in the same accelerator. It is clear that the spatial distribution of the arsenic ion tracks is much broader than 1° and quite comparable to the one corresponding to the tracks

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*Such a contamination could be also responsible for the tracks observed later by Horn and Von Oertzen in olivine crystals irradiated with 32 MeV sulfur ions and attributed by them to elastically scattered iron nuclei[8].

observed by Horn and Von Oertzen.

As discussed in detail by Crozaz et al.[6], it is not a completely trivial matter to prove that any observed tracks are due to interaction nuclei and not to beam contaminants, an essential set of experiments must be performed using different thicknesses of "converter" materials placed upstream from the detector.

VI. CONCLUSIONS

The tracks observed by Horn and Von Oertzen are certainly not due to elastically scattered recoil nuclei. They could be produced either by compound nucleus reactions or by contaminant ions present in the incident beam.

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TABLE I

Targets	Coulomb barrier (in MeV)	σ_{cn} (in mb)	w_c[†] (in microns)
$_8O^{16}$	13.0	470**	3 - 4.5
$_{13}Al^{27}$	19.3	303*	0.8 - 2.7
$_{14}Si^{28}$	20.7	210**	0.15 - 2.7
$_{19}K^{40}$	26.4	45*	0 - 2
$_{26}Fe^{56}$	33.2	< 1**	0

*Values calculated for 32 MeV oxygen ions by Thomas[10].

**Values obtained by applying the method of extrapolation proposed by Thomas[10].

[†] w_c is a critical depth below which the values of σ_{cn} are reduced at least by a factor of 100. The first value has been deduced directly from the classical expression for σ_{cn}, and the second one has been obtained from the data of Thomas[10].

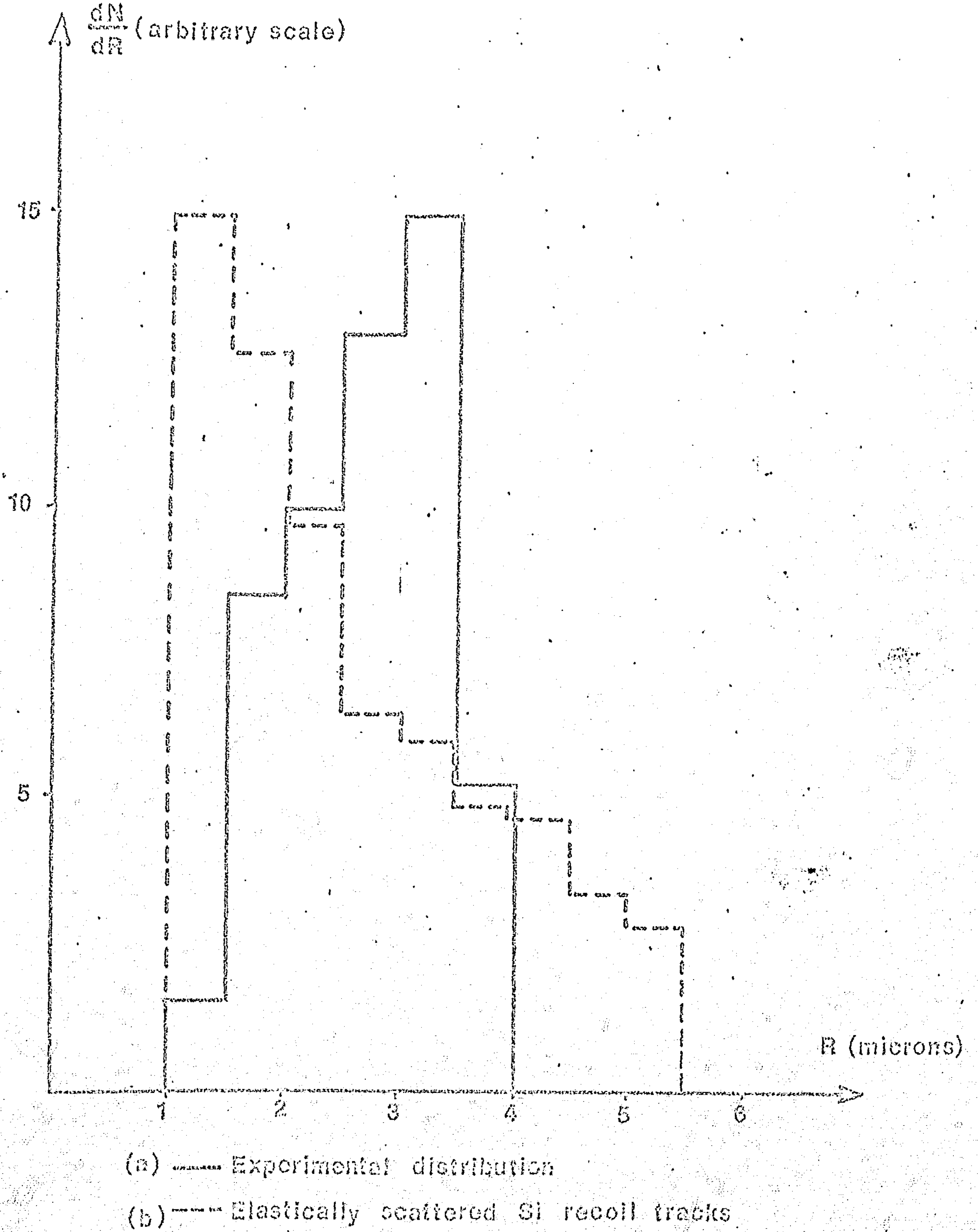

FIGURE 1: TRACK LENGTH DISTRIBUTIONS

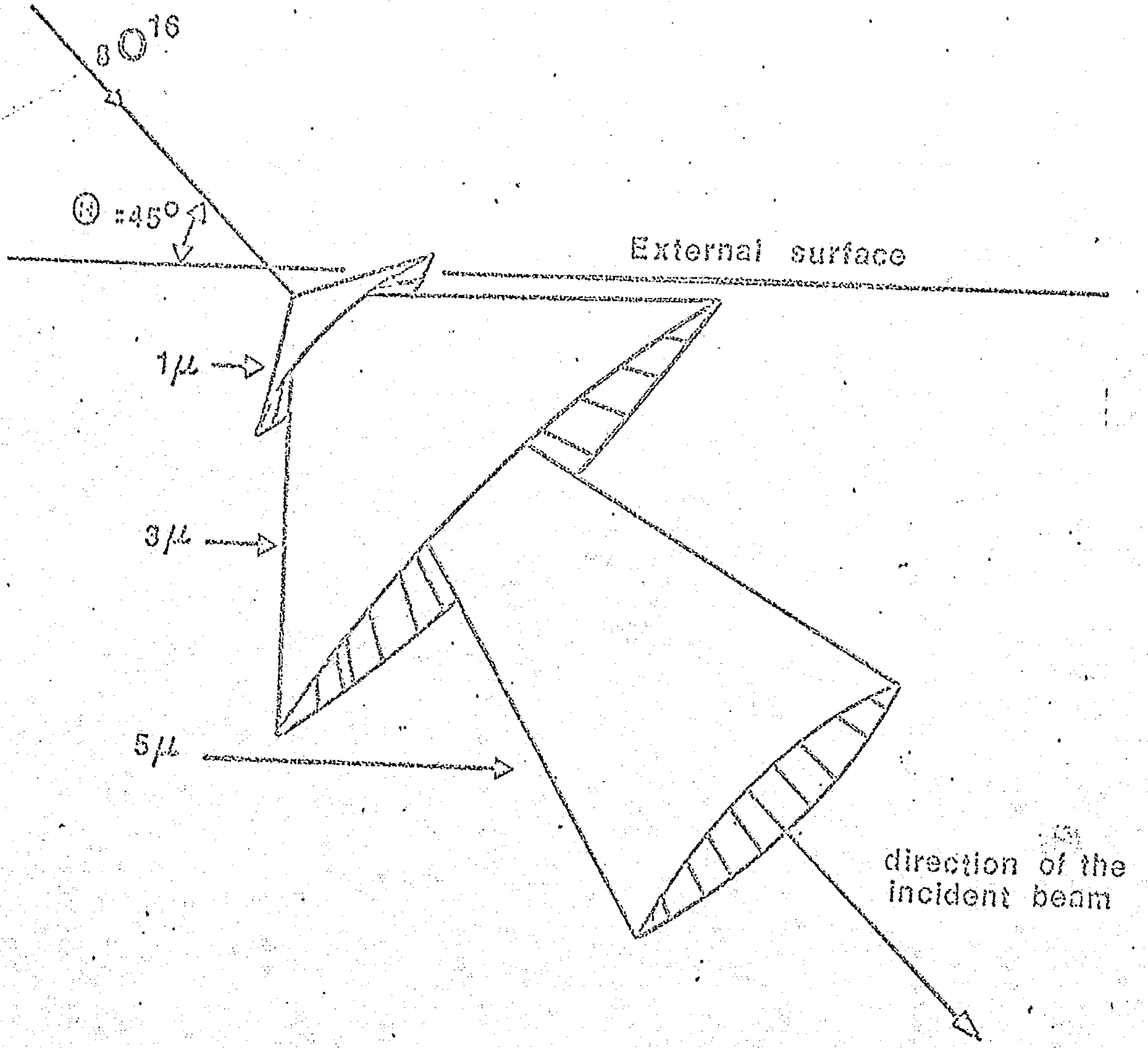

FIGURE 2:

SPATIAL DISTRIBUTION OF ELASTICALLY SCATTERED SILICON RECOIL TRACKS IN MUSCOVITE

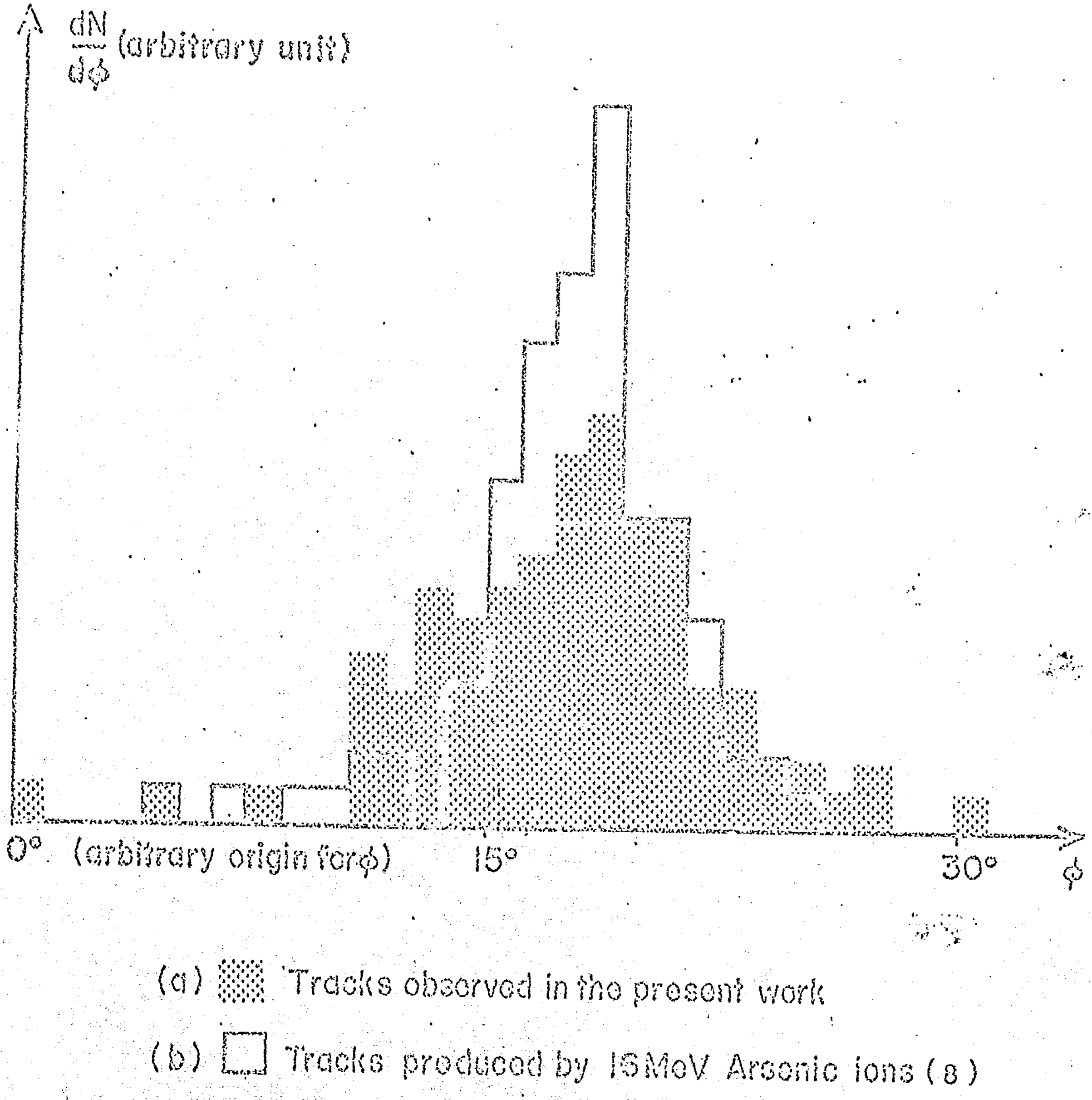

FIGURE 3: AZIMUTHAL ANGLE DISTRIBUTIONS