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# Fragmentation of Accelerated 2.1 GeV/nucleon $^{12}C$, $^{14}N$ and $^{16}O$ Ions in Nuclear Emulsion (*).

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**Summary.** — The inelastic-interaction mean free path and fragmentation parameters in nuclear emulsion of accelerated 2.1 GeV/nucleon $^{12}C$, $^{14}N$ and $^{16}O$ have been determined. The discrimination of the targets has been achieved with a new method. The global results obtained for the three ions have been compared with the *M*-group of the cosmic radiation.

## 1. – Introduction.

To extrapolate the cosmic-ray spectra obtained at the top of the atmosphere to the sources, it is necessary to know the fragmentation parameters both in air and hydrogen. So far nuclear emulsions exposed to cosmic radiation have been used in determining their fragmentation parameters. The facilities offered by the Berkeley L.B.L. have allowed us to make an analogous determination

(*) This work has been partially supported by Junta de Energía Nuclear and Comisión Nacional de Investigación del Espacio (Spain).

of the interaction mean free path and fragmentation parameters in nuclear emulsion, with the advantage over cosmic ray of having known charge and well-defined energy.

This work deals with the fragmentation of 2.1 GeV/nucleon $^{12}C$, $^{14}N$ and $^{16}O$ ions. As the contribution of fluorine to the $M$-group $(6 \leqslant Z \leqslant 9)$ of the cosmic radiation is negligible $(\leqslant 4\%$ (1)), a comparison can be made with the previous data obtained in that group.

Several stacks of Ilford nuclear emulsion were exposed at the Berkeley Bevatron (Table I). The intensities of the beam were measured by scintillation counters. The beams penetrate at zero degree with respect to the larger area of the plate and normal to its smaller side. The emulsion plates were developed by the two-temperature method.

TABLE I. – *Data of the exposure performed.*

| | Emulsion type | Plate size (cm³) | Number of plates used | Beam intensity (particles/cm²) | Exposure date |
|---|---|---|---|---|---|
| $^{12}C$ | Ilford G5 | $3.5 \times 19.5 \times 0.06$ | 3 | $10^4$ | I -1972 |
| | Ilford K5 | $3.5 \times 10.5 \times 0.06$ | 7 | $10^4$ | VI-1972 |
| $^{14}N$ | Ilford G5 | $5 \times 5 \times 0.06$ | 1 | $5 \cdot 10^4$ | X -1971 |
| $^{16}O$ | Ilford K5 | $3.5 \times 10.5 \times 0.06$ | 6 | $10^4$ | VI-1972 |

## 2. – Identification of the target nuclei.

The different kind of nuclei contained in the emulsion can be classified into two categories: light nuclei (C, N and O) and heavy nuclei (I, S, Ag and Br). We shall call « blacks » those tracks which show a ionization $I \geqslant 10 I_0$, $I_0$ being the ionization of a proton at minimum, « grey » those with $10 I_0 > I > 1.4 I_0$ and « relativistic » those with $I \leqslant 1.4 I_0$. In terms of energy the conditions mentioned correspond to the ionization of a proton of $E \leqslant 30$ MeV, $30 \text{ MeV} < E < 360$ MeV and $E \geqslant 360$ MeV respectively.

In the type of interactions studied the heavy component $N_h$ (black + grey tracks) is formed not only by fragments from the target but also by fragments from the projectile. In certain types of interactions such as those with a jet of relativistic particles of different charges, the jet can be taken as produced by the fragmentation of the projectile, but in general this possibility depends on the impact parameter in each interaction, which conditions the

(1) V. L. GINZBURG and S. I. SYROVATSKII: *The Origin of Cosmic Rays* (Oxford, 1964).

number of nucleons of the projectile and the target which interact in a first stage, in the extreme cases (central or quasi-central collision) the fragmentation products of the projectile and target are mixed in such a way that it is difficult to discriminate which belong to which. In this situation a criterion for discrimination based exclusively on the value of $N_h$ would not have much significance.

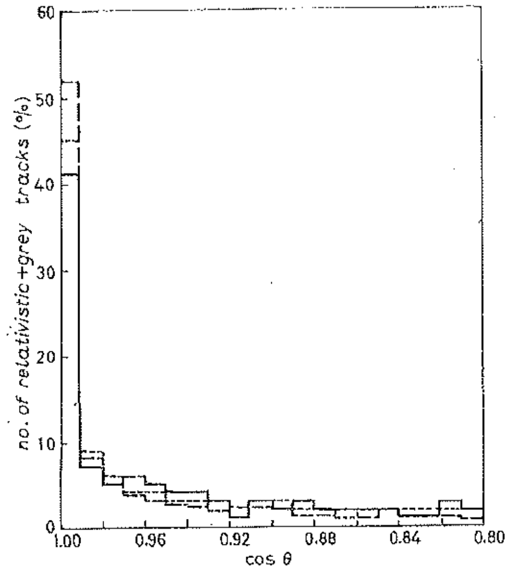


Fig. 1. – Angular distributions of relativistic + grey tracks emitted in the interactions produced with $^{12}C$, $^{14}N$ and $^{16}O$ of 2.1 GeV/nucleon: ——— $^{12}C$, — — — $^{14}N$, - - - $^{16}O$.

In this work we have used several discrimination criteria. The heavy component from the target $N_{h(t)} = N_h - N_{h(p)}$, where $N_{h(p)}$ is the contribution of the projectile to the value of $N_h$, deduced from the energetic fragments of the jet. Figure 1 shows the angular distributions of relativistic tracks plus grey tracks for the ions in the interval $0.80 \leqslant \cos\theta \leqslant 1.00$ for all the interactions studied. These distributions show a pronounced peak from which we conclude that almost all the interactions have a cone angle of the order of 8°($\cos 8° \simeq 0.99$). The value taken as representative of $N_{h(p)}$ is, consequently, the number of energetic fragments emitted with $\theta \leqslant 8°$. The black and grey tracks emitted in this angular interval are considered as coming from the projectile because of their energy. The contributions of black and grey tracks from the target have been determined by measuring their residual range.

Other criteria used were:

*a*) The interaction was with a light target if $N_{h(t)} \leqslant 8$ for interactions of a jet of fragmentation. In the case of dispersed fragments (no jet) the value taken was $N_{h(t)} \leqslant 12$.

*b*) Among the $N_{h(t)} \leqslant 8$ there should not appear any recoil nucleus (residual range $\leqslant 10$ μm), otherwise the interaction is taken to occur with an heavy nucleus.

*c*) In the case $N_{h(t)} \leqslant 8$ the presence of tracks with residual range between 10 and 50 μm is additional evidence of interaction with light nuclei, due to the fact that in any case these tracks are produced by alpha-particles whose emission is favoured by the lower potential barrier of the light nucleus.

The application of these criteria to the interactions studied gives us the classification shown in Table II.

TABLE II. – *Classification of the interactions on the basis of the target size.*

| | Number of interactions | Light target | Heavy target |
|---|---|---|---|
| $^{12}$C | 105 | 41% | 59% |
| $^{14}$N | 102 | 65% | 35% |
| $^{16}$O | 109 | 28% | 72% |

## 3. – Results.

3.1. *Interaction mean free paths.* – In order to obtain the interaction mean free path for the three ions studied, we have followed the tracks found at the entrance of the beam in the plates until they interact or leave them. We have considered as interaction any process resulting in a star with a minimum of one heavily ionizing particle ejected, *i.e.* the mean free paths obtained are the inelastic ones. In Table III we give the scanning results as well as the interaction mean free paths.

TABLE III. – *Scanning and λ results.*

| | Number of tracks followed | Number of interactions found | Total length followed (m) | $\lambda$ (g/cm$^2$) |
|---|---|---|---|---|
| $^{12}$C | 458 | 203 | 30.0 | $56.7 \pm 3.8$ |
| $^{14}$N | 508 | 123 | 16.8 | $55.1 \pm 2.3$ |
| $^{16}$O | 913 | 424 | 59.4 | $53.6 \pm 2.7$ |

The result for $^{14}$N was obtained by measuring the attenuation of the flux at different distances from the entrance in the plate (Fig. 2). This method was preferred due to the good collimation of the incident beam. For $^{12}$C and $^{16}O$ we have used the method of the total length divided by the number of interactions found, because of the bad definition of the beams. With the three values obtained we have calculated the corresponding value of the

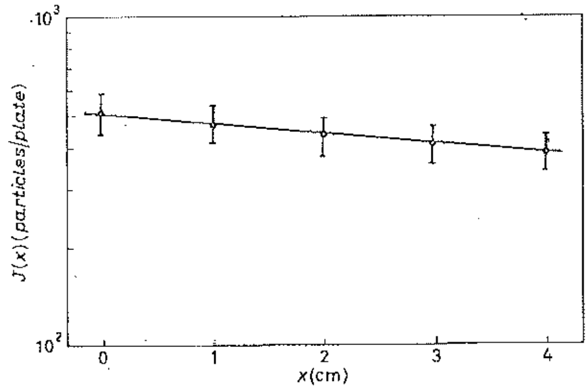


Fig. 2. – Least-squares fit to calculate $\lambda$ in $^{14}N$ of 2.1 GeV/nucleon.

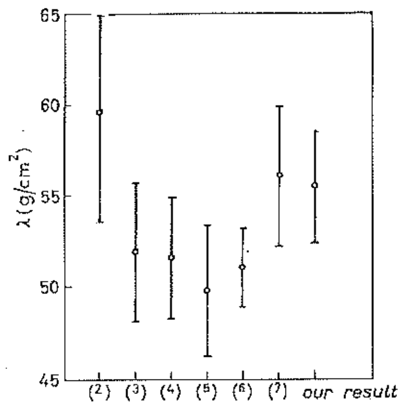


Fig. 3. – Interaction mean free paths of $M$-group ions. The numbers in parentheses are references.

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(7) M. W. Friedlander, K. A. Neelakantan, S. Tokunaga, G. R. Stevenson and C. J. Waddington: *Phil. Mag.*, **8**, 1691 (1963).

$M$-group using the expression

$$\langle\lambda_M\rangle = \left(\sum_{i=1}^{3}\lambda_i N_i\right)\Big/\left(\sum_{i=1}^{3} N_i\right),$$

where $\lambda_i$ is the interaction mean free path of the ion considered and $N_i$ the relative abundancies of the three ions in the $M$-group of cosmic radiation (44:21:31 [1]). The mean value ($\langle\lambda_M\rangle$) is showm in Fig. 3, together with the results obtained by other authors using cosmic rays. It can be noticed that our result is slightly higher than the results previously obtained and is in good agreement with that found by FRIEDLANDER *et al.* [7].

3'2. *Fragmentation parameters.* – To obtain the fragmentation parameters, scanning of interactions over the volume was performed. The interactions were measured and their geometry reconstructed. The results presented here were derived from 105 interactions of $^{12}C$, 102 of $^{14}N$ and 109 of $^{16}O$. In addition to the geometric measurements we have performed measurements of ionization by blob counting. In the energetic fragments ejected at $\theta \leqslant 8°$ with respect to the direction of the incident ion ($\Omega \simeq 6\cdot 10^{-2}$ sr), opacity measurements were made [8]. To make those measurements comparable amongst the three ions we have used as photometric parameter the relative opacity (opacity of the ejected ion divided by the opacity of the incident ion). As the energies per nucleon of both ions are the same [9], this parameter is only dependent on the charge of the ejected ion, which allow us to determine its charge. Furthermore, if we use that ratio, the possible effects due to uneven development, background, etc. are conveniently compensated in the global study of the three ions.

TABLE IV. – *Fragmentation parameters of* $^{12}C$, $^{14}N$, $^{16}O$ *and M-group at* 2.1 GeV/nucleon.

| Emergent | Alpha | | | $L$ | | |
|---|---|---|---|---|---|---|
| Incident | Target | | | | | |
| | Light | Heavy | All | Light | Heavy | All |
| $^{12}C$ | 0.88 ± 0.22 | 0.72 ± 0.18 | 0.80 ± 0.14 | 0.38 ± 0.14 | 0.14 ± 0.08 | 0.25 ± 0.08 |
| $^{14}N$ | 1.04 ± 0.16 | 1.03 ± 0.20 | 1.03 ± 0.13 | 0.34 ± 0.09 | 0.25 ± 0.10 | 0.30 ± 0.07 |
| $^{16}O$ | 0.96 ± 0.19 | 0.66 ± 0.12 | 0.73 ± 0.10 | 0.38 ± 0.12 | 0.34 ± 0.08 | 0.35 ± 0.07 |
| $M$ | 0.97 ± 0.11 | 0.79 ± 0.09 | 0.87 ± 0.07 | 0.36 ± 0.07 | 0.27 ± 0.05 | 0.31 ± 0.04 |

(8) J. SEQUEIROS, F. FERNÁNDEZ, R. KAISER and V. GANDÍA: *Nucl. Instr. Meth.*, **104**, 469 (1972).
(9) H. H. HECKMAN, D. E. GREINER, P. J. LINDSTRON and F. S. BIESER: *Phys. Rev. Lett.*, **28**, 926 (1972).

Table IV shows the results obtained for the fragmentation parameters of the three ions and that of the $M$-group (obtained as a global result of the three) in ions of the $L$-group and alpha-particles, for light, heavy and all target types. It can be noted that the values are very similar for the different groups of targets; this might indicate that the fragmentation is independent of the target (9). The same can be obtained from Fig. 4, where we have represented the values given in the literature and our results for the $M$-group. On the other hand the produc-

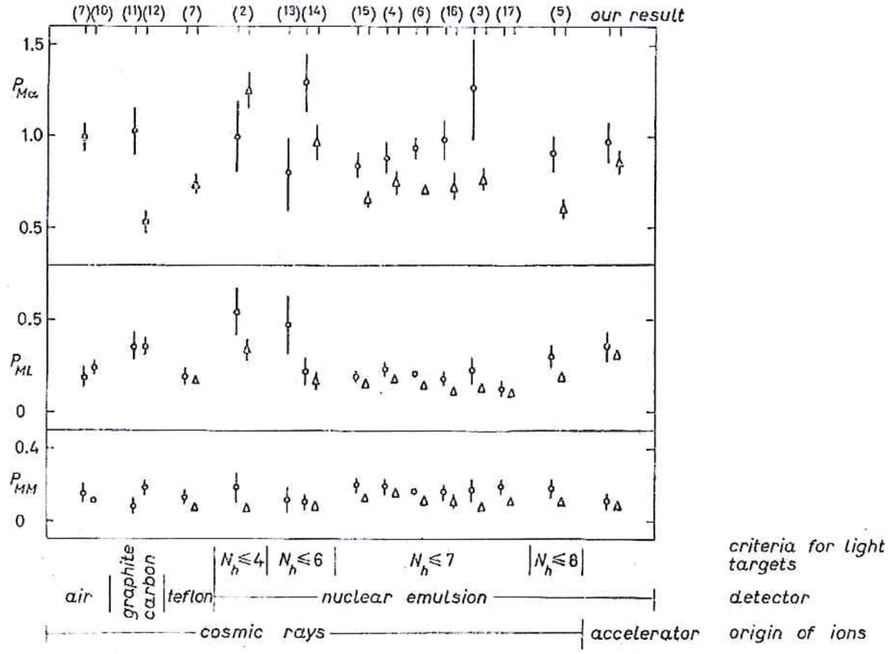


Fig. 4. – Fragmentation parameters of $M$-group ions. The numbers in parentheses are references. o light target, ▵ heavy target.

tion of alpha-particles and $M$-group ions is in good agreement with that obtained from cosmic rays, but nevertheless we have found a greater production of $L$-group ions than there.

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● RIASSUNTO (*)

Si sono determinati il cammino libero medio ed i parametri d'interazione delle interazioni anelastiche in emulsioni nucleari di $^{12}C$, $^{14}N$ e $^{16}O$ accelerati a 2.1 GeV/nucleone. Si è ottenuta la discriminazione dei bersagli facendo uso di un nuovo metodo. Si sono confrontati i risultati globali ottenuti per i tre ioni con il gruppo $M$ della radiazione cosmica.

(*) *Traduzione a cura della Redazione.*

**Фрагментация ускоренных ионов $^{12}C$, $^{14}N$ и $^{16}O$ до энергии 2.1 ГэВ/нуклон в ядерных эмульсиях.**

**Резюме (*).** — Определяются средняя длина свободного пробега относительно неупругого взаимодействия и параметы фрагментации в ядерной эмульсии ускоренных ионов $^{12}C$, $^{14}N$ и $^{16}O$ с энергией 2.1 ГэВ/нуклон. Распознавание мишеней производится с помощью нового метода. Было проведено сравнение глобального результата, полученного для трех ионов, с $M$ группой космического излучения.

(*) *Переведено редакцией.*

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