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Antiproton Annihilation on Ag/Br Nuclei.

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Abstract. – The charged-prong multiplicity distribution of ($\bar{p}$, Ag/Br) annihilation events has been measured in photographic emulsion at incoming $\bar{p}$ momenta of 500, 400, 300 MeV/c and at rest. In the light of INC model predictions, the results show that the low-multiplicity events are produced mainly by nuclear surface annihilations and the higher multiplicity events can be interpreted as annihilations occurred in deep nuclear matter.

Antiproton annihilation in photographic emulsion has been studied at rest and in flight at energies below 250 MeV by EKSPONG *et al.* [1] and recently at 1.4 GeV/c by BREIVIK *et al.* [2]. In these experiments the $\bar{p}$ beam was noticeably pion contaminated. The aim of the measurements was the study of the mechanisms of $\bar{p}$ annihilation in nuclear matter. In particular, theoretical studies [3-6] stress the interest of the investigation of nuclear matter under extreme temperature and pressure. By using antiprotons, it is possible to induce nuclear multifragmentation and spallation reactions such as those produced in medium-energy collisions of heavy ions [7], but with a probe which deposits a fixed amount of energy in the nucleus.

In this paper we present the preliminary results we obtained by measuring the charged-prong multiplicity distributions of the stars produced by $\bar{p}$ annihilation in photographic emulsion nuclei. The emulsion chamber consisted of 50 plates of NIKFI-BR, each of dimensions $(20 \times 10 \times 0.06)\ cm^3$. The chamber was exposed to the 609 MeV/c ($\Delta p/p = 10^{-3}$) $\bar{p}$ beam of the LEAR facility at CERN.

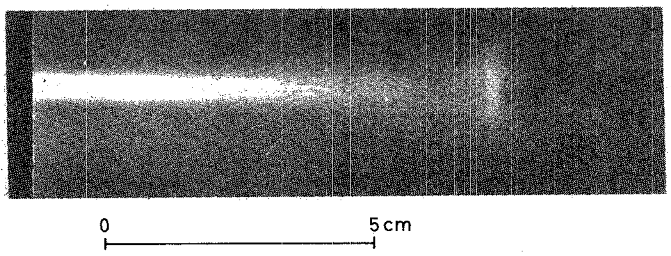

Fig. 1. – Antiproton beam stopping in the central layer of the emulsion chamber.

In fig. 1 the beam stopping in the central layer of the stack is shown. The range of the antiprotons, measured from the edge of the emulsion chamber, turned out to be (8.59 ± 0.13) cm, corresponding to (180 ± 2) MeV incoming beam kinetic energy, a value in fairly good agreement with the LEAR beam control data. The exposure time was about 2 s, yielding approximately $2 \cdot 10^5$ stopped antiprotons. Each plate of the emulsion chamber was marked [8] by a 1 mm^2 grid and developed. Scanning and measurements were carried out by means of microscopes (magnification 1350 ×) with the «area method». The data involve a total number of 1280 events of antiprotons at rest; 347 events at (300 ± 11) MeV/c; 430 events at (400 ± 5) MeV/c and 561 events at (500 ± 4) MeV/c measured up to now.

The measured multiplicities include all the charged particles (pions protons, nuclear fragments, etc.) with the exclusion of very slow particles which have tracks shorter than $(1 \div 3)$ μm, for instance, protons with energy less than $(0.07 \div 0.2)$ MeV and alpha-particles with energy less than $(0.28 \div 0.85)$ MeV (see table I). The antiproton interactions in flight were measured at different distances from the centre of the stopping regions, in 2 mm depth zones, crossing the beam path shown in fig. 1. The vertices of different events are well distinguished permitting a good measurement of the charged-prong multiplicity for each individual star, as in the cases presented in ref. [1].

TABLE I. – *Range energy values in nuclear emulsion for minimum detectable lengths* ($(1 \div 3)$ μm).

Particles or nuclear fragments	$L = 1$ μm (MeV)	$L = 3$ μm (MeV)
p	0.071	0.215
d	0.094	0.283
t	0.104	0.312
α	0.285	0.857
^{12}C	0.833	3.428
^{16}O	1.400	4.833
^{20}Ne	2.000	6.250

In fig. 2 the charged multiplicity distributions at the four above energies are shown. It is evident that the percentage of high-multiplicity events increases with the $\bar{p}$ energy.

At rest, the average value $\langle M \rangle$ of the total multiplicity is (4.9 ± 0.1), which is close to the values obtained in ^{12}C ($\langle M \rangle = 4.0$ at rest and $\langle M \rangle = 4.7$ in flight) by AGNEW *et al.* [9] and in ^{4}He ($\langle M \rangle = 4.1$ in flight) by our collaboration [10]. The highest charged-prong multiplicity found at rest turns out to be 18, but $(95 \pm 1)\%$ of the events have $M < 10$, which is also the highest value found for ^{4}He and ^{12}C.

For 300, 400 and 500 MeV/c antiproton momenta, the number of events with $M \geqslant 10$ increases (up to about 20%) and, consequently, so does the average multiplicity, reaching the values (7.4 ± 0.4), (7.6 ± 0.4) and (7.6 ± 0.3) at the three momenta, respectively. These values are in agreement with the mean value 7.66 reported in ref. [1] for antiprotons with energies spread in the range from $(10 \div 250)$ MeV.

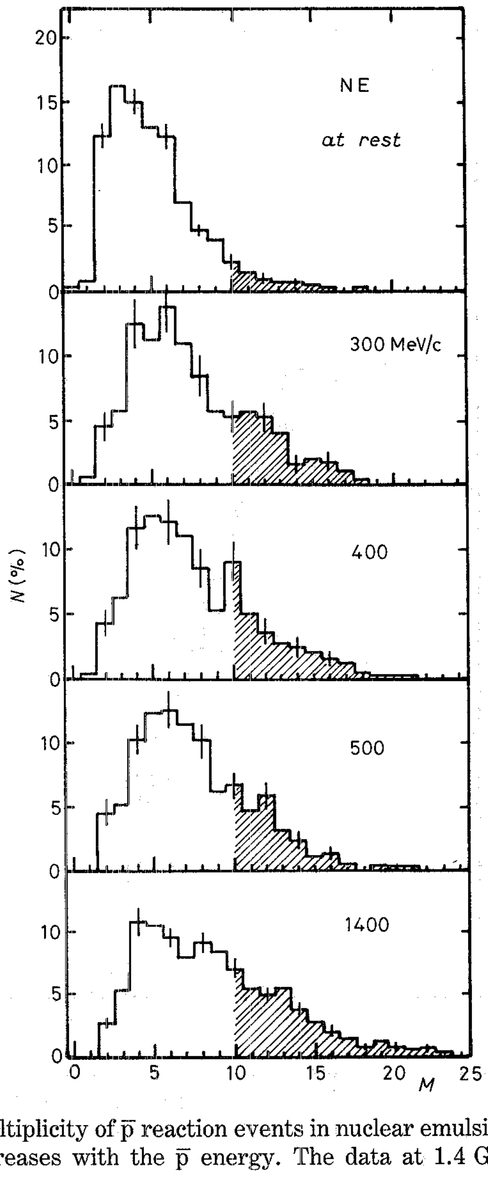

Fig. 2. – Charged-prong multiplicity of $\bar{p}$ reaction events in nuclear emulsion. The high-multiplicity tail ($M > 10$, hatched area) increases with the $\bar{p}$ energy. The data at 1.4 GeV/c are from ref. [2].

A photographic emulsion contains about 77% in weight of Ag ($\bar{A} = 108$) and Br ($\bar{A} = 80$) and about 23% of ${}^{12}_{6}$C, ${}^{14}_{7}$N, ${}^{16}_{8}$O. Since the $\bar{\text{p}}$-nucleus reaction cross-sections ($\sigma_{\text{R}} = \sigma_{\text{tot}} - \sigma_{\text{el}}$) show a very good agreement with a $A^{\frac{2}{3}}$ power law (see ref. [10-13]), it is to estimate the σ_{R} values for all the nuclei present in a photographic emulsion. It turns out that the $\bar{\text{p}}$ interactions on the light nuclei (C, N, O) of the emulsion are about $(28 \pm 2)\%$ of the total number of events. Moreover, taking into account the charged-prong multiplicity measured in ^{12}C [9], and in ^{4}He and Ne by our collaboration [10, 11], it also turns out that most of these events are concentrated in the $M < 10$ region. Therefore, we can assume with good approximation that all the events with $M \geq 10$ are ($\bar{\text{p}}$, Ag/Br) interactions.

Finally, since the analysis of the reaction channels in $\bar{\text{p}}$-nucleus interactions has shown that inelastic processes have small cross-sections in comparison with annihilation [9-12], all the nonelastic events can be considered, within this approximation, as $\bar{\text{p}}$ annihilations.

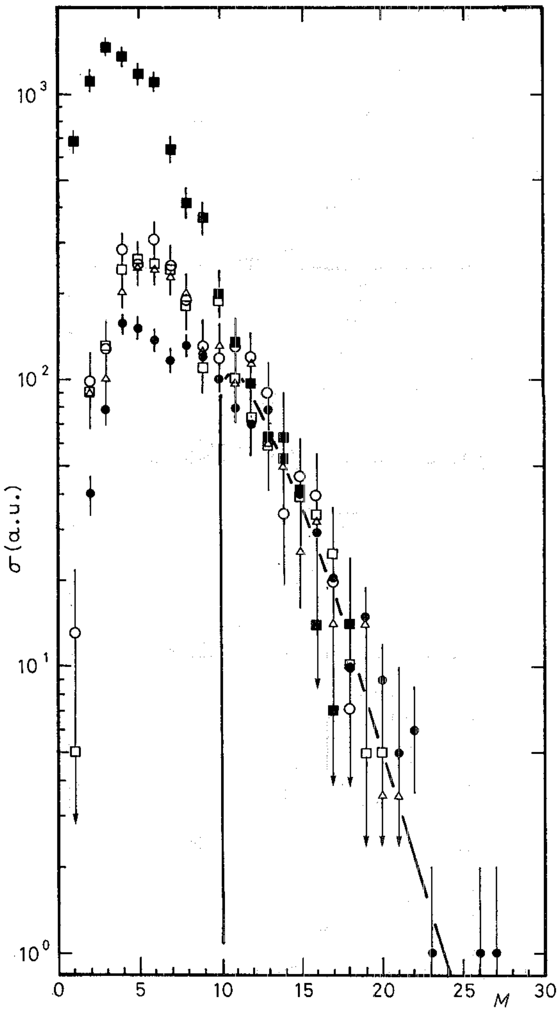

Fig. 3. – Multiplicity cross-sections for $\bar{\text{p}}$ interaction in nuclear emulsion. The data at 1400 MeV/c are from ref. [2]; all the other data are from the present experiment: ■ at rest, ○ 300 MeV/c, □ 400 MeV/c, △ 500 MeV/c, ● 1400 MeV/c. The full line represents a fit performed with the Maxwell distribution (1) of the ($\bar{\text{p}}$, Ag/Br) interaction events.

The energy dependence of the $\bar{p}$-nucleus cross-section being known [10-13], we normalized the histograms at 300, 400 and 500 MeV/c in fig. 2 to areas proportional to the corresponding reaction cross-section values. We treated in the same way the data at 1400 MeV/c obtained by BREIVIK *et al.* [2]. The new multiplicity distributions are reported on a semi-logarithmic scale in fig. 3. We observe that while the 300, 400 and 500 MeV/c histograms are close in shape and magnitude to each other, the 1400 MeV/c multiplicity distribution is very different for $M < 10$. Instead all histograms overlap within the errors, for $M \geq 10$. For this reason, the at-rest data reported on the same figure were normalized to the same multiplicity values in the region $M \geq 10$. The roughly linear slope for high-M values suggests an exponential behaviour, *i.e.* a static mechanism in the charged-prong production. Tentatively, the exponential part of the multiplicity distributions has been fitted with a Maxwell distribution:

$$\sigma(M)\,\mathrm{d}M \propto \sqrt{M - M_0}\,\exp\left[-(M - M_0)/T\right]\mathrm{d}M\,, \tag{1}$$

where $M_0 = 10$ and T represents the temperature (measured in M units) of the statistical production of events with high charged-prong multiplicity. Formula (1) fits well all the experimental distributions, with T values within 10% of the mean value. Such a statistical mechanism could be justified by taking into account the relatively large number of particles involved. In each event, some of the 2 GeV energy released in the annihilation is shared among final particles.

To obtain the total number of interaction events on Ag/Br, we subtracted the number of events C, O and N previously deduced. Having taken into account this correction, the relative percentages of events with $M < 10$ and $M \geq 10$ at the four considered energies are listed in table II, together with the values from ref. [2]. In table III the average charged-prong multiplicities of annihilation events in Ag/Br nuclei for $M < 10$ and $M \geq 10$, together with the values from ref. [2], are given.

TABLE II. – *Relative percentage of* $\bar{p}$ *annihilation events occurring on* Ag/Br *nuclei according to the charged-prong multiplicity* M.

$\bar{p}$ momentum (MeV/c)	($M < 10$) (%)	($M \geq 10$) (%)
at rest	93 ± 1	7 ± 1
300	71 ± 5	29 ± 5
400	74 ± 4	26 ± 4
500	72 ± 4	28 ± 4
1400 [2]	63 ± 3	37 ± 3

TABLE III. – *Average charged-prong multiplicities* $\langle M \rangle$ *of annihilation events in* Ag/Br *nuclei. The data are from this experiment and from* ref. [2]

$\bar{p}$ momentum (MeV/c)	($M < 10$)	($M \geq 10$)
at rest	4.5 ± 0.1	12.8 ± 1.6
300	5.9 ± 0.4	12.9 ± 1.5
400	6.1 ± 0.3	13.5 ± 1.5
500	6.1 ± 0.3	13.1 ± 1.2
1400 [2]	6.3 ± 0.2	13.9 ± 0.7

Now we discuss our results in the light of some theoretical predictions coming mainly from the so-called Monte Carlo intranuclear cascade (INC) models [4, 14-17].

Very schematically, annihilations are expected to occur both on the surface of the nucleus and deep inside the nucleus. In the first case the cross-section is expected to follow the energy behaviour of the $\bar{p}$-nucleon reaction cross-section, which increases as the energy decreases. A quite different behaviour *vs.* energy is expected for the annihilations inside the nucleus, due to Pauli blocking, Fermi motion and the attraction produced by the Coulomb and nuclear potentials [15]. Thus, for example, a strong attractive real potential increases the $\bar{p}p$ and $\bar{p}n$ relative momentum, so that the effective free cross-section inside the nucleus should be smaller than that on the surface. In ref. [15] it is also shown that the penetration of antiprotons into the nucleus changes little with energy, although the cross-section increases rapidly at low energy.

The models predict significant correlations between the depth of the annihilation point, the number of interacting pions, the energy transferred to the nucleons and the number of excited nucleons. In the presence of deep annihilations, one should observe a high number of charged particles in the final state (nuclear fragments and pions). Moreover, this effect should be rather invariant with energy.

Thus, we stress the following points:

a) At rest, most of the events have a multiplicity $M < 10$, with a mean multiplicity of 4.5, which is very close to the value obtained in ^{4}He by our collaboration between 19.7 and 179.7 MeV [10]. Moreover, since the mean number of charged pions observed in annihilations on light nuclei is about 3 [1, 10, 17], the number of charged heavy particles involved in the interaction at rest is only 1-2, on the average. This indicates that there exists no significant interaction between the residual nucleus and the pions and other particles produced in the annihilation, just as expected in the case of annihilations on the nuclear surface [4].

b) For annihilations in flight the mean number of charged prongs with $M < 10$ is not very different from the corresponding value for events at rest, indicating that also events in flight with $M < 10$ occur mainly on the nuclear surface.

c) In an annihilation process up to 8-9 pions are created with a mean number of 5, of which 3 are charged. Therefore, events with a high multiplicity ($M = 10 \div 20$) must contain a relatively large number of heavy particles. INC model predictions indicate that a great part of the energy is transferred to the nucleus by the pions and a high number of nucleons are excited, if the annihilation occurs deep inside the nucleus. It is reasonable to expect that also a high number of heavy particles is ejected from the nucleus.

d) The cross-section for annihilation on the surface (very schematically, with $M < 10$) increases as the energy decreases, while the cross-section for $M \geqslant 10$ is independent of the energy within the experimental errors. As a consequence, the percentage of high-multiplicity events increases with energy (see fig. 2).

Following INC model predictions, the low-multiplicity events again display features of annihilations on the surface and the high-multiplicity events display features of deep annihilations.

e) As a last qualitative remark, we recall that CLOVER *et al.* [14] calculated the absorption probability (P_{abs}) in ^{12}C and ^{238}U as a function of the nuclear radius for 590 MeV/c antiprotons; they used two values, 0 and 250 MeV, for the real $\bar{p}$-nucleus potential. The P_{abs} maximum value occurs at about the nuclear matter half-density radius and the shape of the absorption probability distribution changes slightly as the nuclear radius increases [18]. For this reason, we assume that the absorption probability calculated for ^{238}U is valid for Ag and Br nuclei too. It is drawn in fig. 4 together with the Woods-Saxon distribution of the nuclear matter density $\rho(r)/\rho(0)$ for Ag and Br nuclei and a Gaussian absorption probability distribution for $\bar{p}$ annihilating at rest on ^{208}Pb given by ILJINOV *et al.* [4]. The figure shows that, at 590 MeV/c, the $\bar{p}$ annihilation probability in the region $\rho(r) > 0.75\rho(0)$ amounts to $(14 \div 27)\%$. This figure is in very good agreement with the percentage of annihilation events with $M \geqslant 10$ reported in table II.

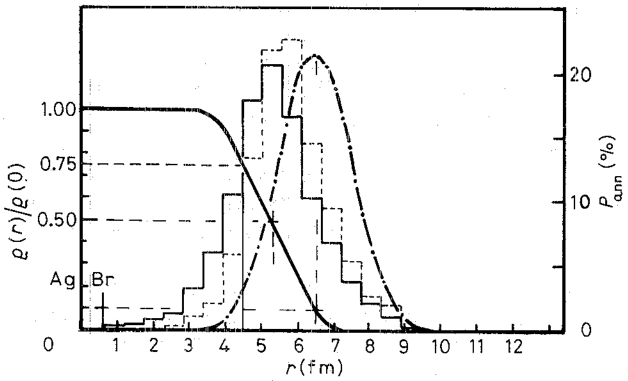

Fig. 4. – Probability of $\bar{p}$ annihilation in Ag and Br nuclei *vs.* the nuclear radius. The histogram is a calculation by CLOVER *et al.* [14] for 590 MeV/c $\bar{p}$ on ^{238}U (the solid curve corresponds to a $\bar{p}$-nucleus potential $V = 250$ MeV, the dashed curve corresponds to $V = 0$). The dot-dashed line is a calculation by ILJINOV *et al.* [4] for $\bar{p}$ at rest on ^{208}Pb. The origin of the radius scale corresponds to the centre of an Ag nucleus, while the centre of the Br nucleus is indicated [18].

In the case of $\bar{p}$ at rest, the P_{abs} maximum is in the $0.1\rho(0)$ region, while the $\bar{p}$ annihilation probability in the $\rho(r) > 0.75\rho(0)$ region is about 5%, again in very good agreement with the value quoted in table II.

Bearing clearly in mind that the multiplicity value $M = 10$ is not to be considered as a sharp separation between deep and surface annihilation events, it seems possible to conclude very schematically, that two mechanisms can be distinguished in $\bar{p}$ annihilation in medium and heavy nuclei:

a) Annihilation on the nuclear surface, with production of events the number of which increases at low antiproton energies. The σ_R value increasing at lower energies, as in the case of ($\bar{p}$, N) interaction, indicates that the main mechanism of surface annihilation is annihilation on a quasi-free nucleon, which is the dominant absorption mechanism at rest (93%), in agreement with the $A^{\frac{2}{3}}$ power law behaviour found for the reaction cross-sections on many nuclei at the same $\bar{p}$ energies [10-13].

b) Annihilation in the deep nuclear matter, in the more dense region of the nucleus. These events are produced by a mechanism different from annihilation on a quasi-free nucleon, since their reaction cross-section is nearly independent of energy.

The study (in progress) of angular and range distributions of secondary particles will lead to a better understanding of the intriguing problems of nuclear multifragmentation, in parallel to the studies performed through medium- and high-energy collisions of heavy ions.

* * *

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REFERENCES

[1] A. G. EKSPONG *et al.*: *Nucl. Phys.*, 22, 353 (1961) and literature quoted therein.
[2] F. O. BREIVIK, T. JACOBSEN and S. O. SORENSEN: *Phys. Scr.*, 28, 362 (1983).
[3] J. RAFELSKY: *Phys. Lett. B*, **91**, 281 (1983).
[4] A. S. ILJINOV, V. I. NAZARUK and S. E. CHIGRINOV: *Nucl. Phys. A*, **382**, 378 (1982).
[5] M. CAHAY, J. CUGNON and J. VANDERMEULEN: *Phys. Lett. B*, **115**, 7 (1982); *Nucl. Phys. A*, **393**, 237 (1983).
[6] S. C. PHATAK and N. SARMA: *Phys. Rev.*, in press.
[7] X. CAMPI and J. DESBOIS: IPNO/TH85-5 (1985).
[8] V. M. SIDOROV and M. I. TRUKIN: *Prib. Teckhn. Eksp.*, **6**, 109 (1957).
[9] L. E. AGNEW, T. ELIOFF, W. B. FOWLER, R. L. LANDER, W. M. POWELL, E. SEGRÈ, H. M. STEINER, H. S. WHITE, C. WIEGAN and T. YPSILANTIS: *Phys. Rev.*, **118**, 1371 (1960).
[10] F. BALESTRA, S. BOSSOLASCO, M. P. BUSSA, L. FERRERO, D. PANZIERI, G. PIRAGINO, F. TOSELLO, C. GUARALDO, A. MAGGIORA, YU. A. BATUSOV, I. V. FALOMKIN, G. B. PONTECORVO, M. G. SAPOZHNIKOV, G. BENDISCIOLI, V. FILIPPINI, G. FUMAGALLI, C. MARCIANO, A. ROTONDI, A. ZENONI, E. LODI RIZZINI, M. VASCON and G. ZANELLA: *Phys. Rev. B*, **149**, 69 (1984); *Phys. Lett. B*, **165**, 265 (1985).
[11] F. BALESTRA, S. BOSSOLASCO, M. P. BUSSA, L. BUSSO, L. FERRERO, A. GRASSO, D. PANZIERI, G. PIRAGINO, F. TOSELLO, G. BENDISCIOLI, V. FILIPPINI, G. FUMAGALLI, C. MARCIANO, A. ROTONDI, A. ZENONI, C. GUARALDO, A. MAGGIORA, YU. A. BATUSOV, I. V. FALOMKIN, G. B. PONTECORVO, M. VASCON, G. ZANELLA and E. LODI RIZZINI: *Nucl. Phys. A*, **452**, 573 (1986).
[12] D. GARRETA, P. BIRIEN, G. BRUGE, A. CHAUMEAUX, D. M. DRAKE, S. JANOUIN, D. LEGRAND, M. C. LEMAIRE, B. MAYER, J. PAIN, J. C. PENG, M. BERRADA, J. P. BOCQUET, E. MONNAND, J. MOUGEY, P. PERRIN, E. ASLANIDES, O. BING, L. LICHTENSTAND and A. I. YAVIN: *Phys. Lett. B*, **135**, 266 (1984); **149**, 64 (1984); **150**, 95 (1985).
[13] K. NAKAMURA, J. CHIBA, T. FUJII, H. IWASAKI, T. KAGEYAMA, S. KURIBAYASHI, T. SUMIYOSHI, T. TAKEDA, H. IKEDA and Y. TAKADA: *Phys. Rev. Lett.*, 52, 731 (1984); R. J. ABRAMS, R. L. COOL, G. GIACOMELLI, T. F. KYCIA, B. A. LEONTIC, K. K. LI, A. LUNDBY, D. N. MICHAEL and J. TEIGER: **4**, 3235 (1971); S. P. DENISOV, S. V. DONSKOV, YU. P. GORIN, R. N. KRASNOKOTSKY, A. I. PETRUKHIN, YU. D. PROKOSHKIN and D. A. STOYANORA: *Nucl. Phys. B*, **61**, 62 (1973); A. S. CARROLL, I.-H. CHIANG, T. F. KYCIA, K. K. LI, M. D. MARX, D. C. RAHM, W. F. BAKER, D. P. EARTY, G. GIACOMELLI, A. M. JONCKHEERE, P. F. KOEHLER, P. O. MAZUR, R. RUBINSTEIN and O. FACKLER: *Phys. Lett. B*, 80, 319 (1979); T. KAMAE, H. AIHARA, J. CHIBA, H. FUJII, T. FUJII, H. IAWASAKI, K. NAKAMURA, T. SUMIYOSHI, Y. TAKADA, T. TAKEDA, M. YAMAUCHI, H. FUKUMA and T. TAKESHITA: *Phys. Rev.*, 44, 1438 (1980).
[14] M. R. CLOVER, R. M. DE VRIES, N. J. DI GIACOMO and Y. YARIV: *Phys. Rev. C*, **26**, 2138 (1982).
[15] N. J. DI GIACOMO and R. M. DE VRIES: Report LANL (Los Alamos, Cal., 1980).
[16] J. CUGNON and J. VANDERMEULEN: *Nucl. Phys. A*, **445**, 717 (1985).
[17] R. BIZZARRI, P. GUIDONI, F. MARCELJA, F. MARZANO, E. COSTELLI and M. SESSA: *Nuovo Cimento A*, **22**, 225 (1974).
[18] L. B. R. ELTON: *Nuclear Sizes* (Oxford University Press, Oxford, 1961).