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CONSULTATIVE ASSEMBLY

WORKING PARTY ON AEROSPACE PHYSIOLOGY AND MEDICINE

WORKING PARTY ON SPACE BIOPHYSICS

convened at the instance of the
COMMITTEE ON SCIENCE AND TECHNOLOGY

Extracts from the letter of Dr. BERRY, MD
Nasa Director for Life Sciences, Washington DC 020546
to

WALTER H. INGE, JR., Lt Colonel, USAF
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... We have reviewed with great interest your letter report of the meeting of the Working Party on Aerospace Physiology and Medicine of the Council of Europe. Before I attempt to provide answers to the several issues you have identified, I wish to thank you for clarifying for us the areas of confusion in the European scientific community regarding the space flight opportunities and methods for approaching NASA. Although many of us had felt that such a lack of current information prevailed, it has been difficult to get the members of the European scientific community to acknowledge this point and in turn allow us to provide the information they need.

Let me now address the specific issues raised in your report:

1. Availability of data and information on US space flight programmes and plans - The NASA normally maintains a European representative in the United States Embassy in Paris, France, who acts as the interface for NASA with national and multinational space programmes in Europe. It just happens that this position has been unfilled for the past several months. This may have led to the recent scarcity and lack of currency of information. However, NASA does intend to continue this office and a new European representative will be assigned in the future.

Other governments, institutions and individual scientists, however, can obtain information on NASA programmes through this office or through the Scientific Attache at any other local US Embassy. NASA attempts to keep their European representative and the Scientific Attaches in all embassies fairly current. On the other hand, if they do not have current or adequate information, they can quickly obtain it by direct query to us.

NASA scientists and engineers participate as a matter of course in international meetings that are frequently held in Europe, such as COSPAR, IAF and other more specialised space related meetings. These provide an excellent forum for providing information on NASA programmes. NASA participation is, of course, limited by the availability of travel funds and our busy schedule.

For the scientist who wishes to submit proposals directly to NASA, a set of policy guidelines for international scientific co-operative programmes is attached. Please note that foreign experiments normally require endorsement by the appropriate agency of the scientist's home government.

The biological community in Europe has been somewhat slow in getting organised or demonstrating an interest in space flight. The biologists have reported that they have been unable to identify areas of research which require flight in the unique environmental conditions found in space. Therefore, it has been quite difficult for our scientists to effectively relate to the European efforts and to anticipate their need for the data ahead of their meetings. The better we are able to understand their needs and plans, the better we will be able to meet their data needs. To resolve this problem, I would suggest that periodic discussions with us would prove useful in keeping us abreast of their efforts.

2. Flight reports - The results of all flights by the United States have been published in the open scientific literature. Although the NASA medical and biological team can use any scientific publication route, most have elected to publish the major portion of the flight data in a series of reports in the Journal of Aerospace Medicine, the official journal of the Aerospace Medical Association. This is a United States publication; however, it receives world-wide distribution and should be available in the larger scientific and technical libraries throughout Europe. There are also many European members of the ASMA who receive these journals for their own libraries and could be a source of data as well. In addition, there are numerous official NASA scientific and technical reports which are being published on a continuing basis on almost any subject. Included are two categories, Life Sciences and Biotechnology, which cover most Life Sciences reports. A listing and brief abstract of each report can be found in the NASA publication, Scientific and Technical Aerospace Reports (STAR). This is published by the Scientific and Technical Information Office, Headquarters, NASA, Washington, DC 20546. Copies of the STAR reports can be obtained through this office. Another source of abstract listing of NASA reports is the International Aerospace Abstracts published by the American Institute of Aeronautics and Astronautics, 750 Third Avenue, New York, NY 10017. Copies of the full articles listed in these publications, in abstract form, can be purchased through the National Technical Information Services, Springfield, VA 22151, for a nominal fee.

3. Post-Apollo Experiments - After Apollo, there are three flight programmes which will or may carry biological experiments:

(a) Skylab - Skylab is scheduled for flight beginning in the second quarter of 1973. This programme plans a series of three manned visits to the Skylab laboratory. A major element of the research programme includes the accomplishment of a significant number of medical and biological experiments. As we noted in our separate response on the query by Professor Rybak, there is literally no opportunity to get a

new experiment on this flight programme at this late date. The experiment payload for Skylab was presented and discussed at the ESRO sponsored Colloquium on the "Post-Apollo Participation by Biology", which was held in Paris in February 1971. The publication of the proceedings of this meeting is an excellent point of reference for the Skylab Life Sciences Programme.

(b) The joint US/USSR Apollo-Soyuz rendezvous and docking mission is scheduled for flight in 1975. For this mission there still remains a few months before final selection of experiments for this mission is completed. It should be noted that by the very nature of the vehicles, the weight limits available for experiments and the overriding need to insure accomplishment of successful docking during the mission will cause the number of experiments to be selected to be quite small; very low in weight; simple in nature; preferably passive in operation; and also there is a desire to have some element of each experiment that will permit the NASA and the Soviets to share in its scientific performance and/or reporting. In summary for the Apollo/Soyuz mission, the opportunities for outside scientists to participate will be quite limited.

(c) Shuttle missions - The programme to develop the shuttle vehicles began only during this last year. Here is the place where the European scientific community can expect to get its proposed experiments flown. Payloads for shuttle flight can be developed by any country or an appropriate consortium that is formed to sponsor and manage the development of payloads. The desires of the individual experimenter can be served best by proposing his experiment for consideration through such organisational structures. ESRO has acted as a consortium for organising and supporting European payloads in the past and it appears that this group will continue in this role in the future.

As you know, ESRO-EIDO are now examining the issue as to whether Europe, and they as the manager, wishes to undertake the development of a payload sortie module for all to use, including the United States. If Europe concludes that they do not want to do this, it appears that the United States will. Thus, a basic capability to carry payloads should be available from 1979 and beyond. The initial flights are proposed to be for 7 days' duration with extensions later to 30-day lengths.

Please note that I said that a capability will become available. Whether there will be any Life Sciences payloads or not or a sufficiently large demand to warrant a dedicated Life Sciences payload module or not will depend upon the identification of sufficient experiments to warrant undertaking such an effort.

Payloads for shuttle which are proposed from within the United States will be sponsored, selected, developed and flown by the scientific disciplinary office or agency that seeks to obtain the data. It now appears a similar philosophy will prevail in Europe.

ESRO and the United States each have a vigorous study effort now under way to identify the initial series of potential payloads and to begin sizing the traffic model requirements identified by each discipline in later shuttle periods. European life scientists would be well-advised to get their ideas for medical and biological experiments into the hands of these ESRO space biology and medical sciences study groups at an early date if they want early consideration for flight. NASA is attempting to do the same within the scientific community of the United States. In sponsoring payloads, NASA would intend to support the United States scientific community first and expect Europe to do the same for its scientific community.

The United States and ESRO study teams are attempting to fully co-ordinate their studies at the scientific disciplinary level. Professor Patricia Lindop, of the UK, attended the NASA Life Sciences Payloads Planning Meeting held here in Washington on 8-9 November. Continuing liaison is proposed to insure that any decisions regarding the Life Sciences' needs for shuttle flights will reflect the results of both study groups. I think this approach will allow for the development of a "European Plan" to which you referred and also circumvents any feeling that they must go to NASA for sponsorship. The effective co-ordination of all of the efforts for identifying Life Sciences payloads, on the other hand, should strengthen both the European and United States requirements for Life Sciences payloads when the two plans are taken to the respective agencies for approval.

4. For your own information, a new edition of the NASA Bioastronautics Data Book (NASA SP 3006) is now in publication and should be available in early 1973. This new edition will be greatly enlarged and much more complete. This may be something you may wish to order for your use in future meetings with European scientists.

I have forwarded this letter to you rather than to Dr. J. P. Massue, as you suggested, since you made the initial contact on this matter. You may feel free to pass on to him any or all of the information contained herein. However, if he seeks to effect a continuing dialogue on behalf of his group, I suggest that you recommend to him that he may want to contact our NASA European representative in the United States Embassy in Paris as a means of obtaining detailed data on future NASA programmes.

In closing, I want to thank you again for providing excellent insight into the nagging problem which has bothered us for some time. Hopefully, we will be able to be of greater help to the European biological community now that we understand the situation better.

Sincerely yours,

Charles A. Berry, MD
NASA Director for Life Sciences

ARBEITSGRUPPE
BIOPHYSIKALISCHE RAUMFORSCHUNG
AN DER UNIVERSITÄT FRANKFURT
Leiter: Priv. Doz. Dr. Horst Bückner

6 FRANKFURT/MAIN 70 , 2.3.1973
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Dr. Vinograd
Welcome in Frankfurt
Horst Bückner

Einladung

Anlässlich des Besuches von

Dr. Vinograd (Director Biomedical Research Division, NASA HQS)

und

Dr. Saunders (Chief Biology Program, NASA HQS)

findet ein Kolloquium und Experimentier-Treffen statt.

Thema: Biostack I und II

Zeit: Donnerstag, 8. 3. 1973, 10.00 Uhr

Ort: Arbeitsgruppe Biophysikalische Raumforschung
6000 Frankfurt / M. , Kennedy Allee 97

Ich erlaube mir, dazu einzuladen

Bückner

(Bückner P. I.)

Biostack Meeting 8. 3. 1973

Preliminary Program

10.00 Uhr	Introduction	P. I.
	Nuclear Emulsion	Strasbourg-Team
	AgCl-Crystals	IKF-Team
	Plastic-Detectors	Kiel-Team
	LIF-FLD	Paris-Team
	Animal Eggs	Toulouse-Team
	Animal Eggs	Marburg-Team
	Bacterial Spores	Frankfurt-Team
	Arabidopsis thaliana	Frankfurt-Team
	Vicia faba	Hannover-Team
	Preliminary Conclusion of the Experiments	P. I.
	Space Biophysics Group (Council of Europe)	President of this Group

L u n c h

15.00 Uhr Demonstration and Discussion
of the different Teams in Group in the laboratories

17.00 Uhr R e f r e s h m e n t s

Slides: "Preparation of the Experiments"

Preliminary Science Report

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Biostack II Experiment

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5) University of Strasbourg

6) University of Kiel

7) University of San Francisco

8) Atomic Energy Commission, France

9) Gesellschaft für Strahlen- und Umweltforschung, Frankfurt

10) University of Würzburg

11) US Representative for Biostack, University of Frankfurt

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Abstract

The objective of the Biostack II experiment is to establish the biological efficiency of individual cosmic heavy particles of high energy loss (HZE particles), penetrating different biological matter during space flight. For this purpose layers of several kinds of biological objects (*Bacillus subtilis* spores, *Colpoda cucullus* cysts, *Artemia salina* eggs, *Tribolium confusum* eggs, *Carausius morosus* eggs) were stacked alternately with different track detectors (nuclear emulsions, plastics, AgCl crystals). The results enable estimation of radiation hazards to the astronauts during long time space missions. This work complements the results of the first Biostack flown aboard Apollo 16. In this previous experiment already a variety of radiobiological endpoints differing in their sensitivity to the penetration of HZE particles have been found.

Animal eggs hit by a cosmic HZE particle, showed a high reduction in emergence and hatching and the induction of several development anomalies. The radiation detectors of Biostack II recorded a cosmic "background" radiation of 750 mrad. A fluence of 80-90 particles/cm² of estimated charge $Z \geq 6$ was measured, depending on the sensitivity of the detector. Absorption by the stack material itself reduced these values to about 70 %. These data are in agreement with the radiation results obtained from the first Biostack. The viability of the flown biological objects was not observed to be affected by the additional random space flight factors. From these observations a successful evaluation of the Biostack II experiment is supposed.

Figure captions

Fig. 1 Software of the Biostack composed of biological layers and sheets of radiation detectors.

Fig. 2 *Artemia salina* eggs embedded in a foil of polyvinyl alcohol (PVA), biological layer of the Biostack II flight unit.

Fig. 3 Track of a cosmic HZE particle penetrating a *Bacillus subtilis* subunit of the Biostack. (total length 1 900, μm)

Fig. 4 Nuclear emulsion K2 of the Biostack II flight unit showing the shadow of an egg of *Carausius morosus* and a track of a cosmic heavy particle that has hit the egg.

Fig. 5 K5 nuclear emulsion of Biostack II showing tracks of heavy ions and the coordinate grid.

Fig. 6 Etch cone and etch holes of cosmic heavy ions in Daicel cellulose nitrate sheets of Biostack II flight unit.

Fig. 7 Ellipses of etch cones in Daicel cellulose nitrate of Biostack II.

Fig. 8 Etch cone of a scattered heavy cosmic ray particle (about 750 μm long) in Daicel cellulose nitrate.

Fig. 9 Tracks recorded in AgCl crystals of Biostack II
L=light ($Z \leq 6$), M=medium ($Z = 6-9$), H=heavy ($Z = 9-15$),
V=very heavy ($Z = 14-26$), S =super heavy ($Z > 20$).

Fig. 10 Cell elongation after outgrowth of *Bacillus subtilis* spores of Biostack II flight control and ground control.

Fig. 11 Shadow of two *Artemia salina* eggs on K2 emulsion of Biostack II flight unit and a track of a cosmic heavy ion that hits one egg.

Fig. 12 Eggs of *Artemia salina* on a cellulose nitrate sheet of Biostack II flight unit and a track of a hitting cosmic ion.

Fig. 13 Egg of *Artemia salina* on a AgCl crystal of Biostack II flight unit hit by a heavy particle and marked by a numbered triangle; 3:1 magnification of the particle track besides.

Fig. 14 Abnormal nauplius with two abdomina of *Artemia salina* hatched from an egg that has been hit by a cosmic heavy particle.

Introduction

During space missions outside the magnetosphere of the Earth, the spacecraft encounters the full spectrum of galactic cosmic radiation. Outside the geomagnetic field there is no cut-off effect. Therefore the energy spectrum of cosmic ray nuclei includes particles of low energies. These heavy nuclei of extreme high values of linear energy transfer (LET) in the Bragg peak (HZE particles) may reach the astronauts despite a certain shielding by the spacecraft wall. These particles may stop in the biological matter. Therefore, the radiation hazards of man during long time space missions has to be well estimated, especially in regard to the HZE component of cosmic radiation which is not available on Earth. Likewise, all biological experiments in space should consider the possible influence of cosmic HZE particles.

The Biostack experiment provides a unique method to determine the biological efficiency of cosmic ray HZE particles during space flight. The last two Moon missions gave the last opportunity for several years to study this phenomenon outside the magnetosphere of the Earth. The Biostack II experiment aboard Apollo 17 complements the work of the first Biostack aboard Apollo 16 (1). The radiobiological endpoints studied in different biological objects are:

- 1) inhibition in germination
- 2) inhibition in cell growth
- 3) inhibition in organic development
- 4) development anomalies
- 5) mutation induction

The biological objects included in Biostack II, selected from scientific and technical points of view, were:

- 1) spores of the bacterium *Bacillus subtilis*
- 2) cysts of the protozoon *Colpoda cucullus*
- 3) seeds of the crucifer *Arabidopsis thaliana*
- 4) eggs of the shrimp *Artemia salina*
- 5) of the beetle *Tribolium confusum* and
- 6) of the grasshopper *Carausius morosus*

The biological area hit by a cosmic HZE particle was determined from adjacent physical track detectors as nuclear emulsions (Ilford K2 and K5), cellulose nitrate (CN) sheets, polycarbonate (Lexan) sheets and AgCl crystals. Thus, the Biostack II experiment is well applied to identify an individual cosmic ray HZE particle in correlation with the possible biological effects on its path. The results will deliver information on the biological mechanism of these HZE particles, not available on Earth, and thereby, on the radiation hazards of man in space.

In addition, the evaluation of the track detectors issues the spectra of cosmic ray ions in regard to their energy loss, charge and energy, that appear inside spacecrafts during missions outside the magnetosphere of the Earth. The modification of these spectra in relation to the absorption by the Biostack material will be measured. This gives practical information for establishing radiation protection requirements for manned space flights.

Interaction of cosmic HZE particles with biological matter

HZE particles are described to possess high biological efficiency. This statement is based on several balloon- and satellite-borne radiobiological studies, since Earth based equipments are incapable of producing accelerated particles of such features. Many effects due to cosmic heavy particles were observed, as mutation induction in *Escherichia coli* cells (2), in barley seeds (3) and in corn seeds (4), development disturbances in *Artemia salina* eggs (5,3), damage to hair follicles of black mice (6,7) and brain injuries in mice (8) and in monkeys (9). The light flashes experienced by the astronauts of the Apollo Moon missions incited systematic studies on this phenomenon on Earth (10) and in space (11). The results led to the suggestion, that the light flashes might be caused by ionization in the tissue of the retina due to galactic cosmic nuclei. Hazards associating this phenomenon could not be confirmed, up to now.

Surely the terms "dose" and "relative biological efficiency (RBE)" cannot be used to describe the biological effects of HZE particles, as one encounters in space. The terms "ion kill" (12) and "microbeam" (13) are used to describe the radiobiological significance of cosmic HZE particles. This indicates that a single traversal of a heavy nucleus with a sufficient high LET produces an energy dissipation in the biological microstructure comparable to a beam of narrow cross section. It is proposed to express the LET distribution in terms of integral track length, because

this gives a more complete picture of the energy dissipation pattern in tissue (14).

The understanding of these radiobiological problems would be improved by space experiments investigating the critical LET values of cosmic heavy particles for different types of biological damage. The Biostack experiment meet this requirement. The Biostack flown on board of Apollo 16 comprised a widespread spectrum of biological objects and radiobiological endpoints in relation to their degree of response to cosmic HZE particles (1). Some processes studied are not remarkably influenced by a penetrating cosmic ion. On the other hand, there were processes which were nearly completely disturbed or inhibited by the passage of a single ion, like emergence or hatching of *Artemia salina* eggs, partially resulting in malformations. Correlation of these effects with the charge and energy loss of the effective HZE particle results in determination of the critical LET thresholds for several radiobiological processes. Thus, this Biostack experiment and the Biostack II experiment are well suited to help understanding of the complex phenomenon of biological response to cosmic HZE particles penetration.

Apollo 17 flight unit

The Biostack II experiment has the same conception as the first Biostack flown aboard Apollo 16. A hermetically sealed cylindrical aluminum container of 10 cm in height and 12.5 cm in diameter contained a stack of 257 sheets (fig. 1). This stack was composed of monolayers of selected biological objects in resting state (fig. 2) sandwiched between several different visual detectors of cosmic ray particles. This arrangement makes it possible to trace the path of a heavy cosmic particle through the stack and to determine the heavy ion's trajectory in the biological layer (fig. 3). Individual evaluation of the hit biological objects in parallel with characterizing the respective hitting HZE particle will allow estimation of the biological efficiency of a HZE particle along its path.

The Biostack II storage area in the Apollo 17 command module was the same as used for the first Biostack on Apollo 16. In this area shielding to cosmic radiation was as minimal as possible.

After return to Frankfurt, the outward inspection of the 3 received Biostack II units (flight unit, back up and ground control unit) revealed no damages. The seals at the single screws and nuts were undamaged.

The Biostack II flight unit (S/N 7) and the back up unit (S/N 8), which is used as ground control unit, were

disassembled immediately after their arrival in Frankfurt. No changes or damages of the software could be noticed. The intended disassembly procedure went without complication. During disassembly, the pattern of the biological objects of those layers positioned directly over a nuclear emulsion K2 were transferred to the upper side of the corresponding emulsion by optical illumination (fig. 4), in a similar way as performed during the first Biostack disassembly (1). Further on each sheet of a nuclear emulsion a coordinate grid was placed on the bottom side by optical illumination. Subsequent to disassembly, the biological and physical component of the Biostack II flight unit and ground control unit were distributed to the different research laboratories for processing and evaluation.

Preliminary observations

a) Total dose of cosmic ionizing radiation

Total dose of cosmic ionizing radiation (background radiation) was measured by LiF thermoluminescence dosimetry (TLD). Three layers of LiF arranged in different depths of the stack showed the absorption of the cosmic ionizing radiation in the Biostack (table 1). For calibration a Cobalt 60 source was used, calibrated by "Bureau National de Métrologie".

^a Parallel measurement with two lithium isotopes, differing in the sensitivity to thermal neutrons, indicated that the thermal neutron dose was not detectable.

b) Particle detection

Three different kinds of visual track detectors were used in the Biostack for measurements of the heavy nuclear component of cosmic radiation: nuclear emulsions, plastics (cellulose nitrate and polycarbonate) and AgCl crystals.

The emulsions were developed without difficulties with the same methods as used for the first Biostack (1). All nuclear emulsions are well suited for the intended measurements (fig. 5). The influence of the fast particles of low charge ($Z=1$ or 2) is correlated with the number of stars produced by collisions of these particles with nuclei of the emulsion. The mean number of stars, obtained from evaluation of five K2 plates, was $12700/\text{cm}^3$. The fluence of the medium and heavy ions ($Z \geq 6$), counted in 40 cm^2 of K2 plates, positioned in the middle of the stack, was $40 \text{ particles}/\text{cm}^2$. Comparison of first data readout of several K2 plates, positioned in different depths of the stack, showed a slowing down from $50 \text{ particles}/\text{cm}^2$ to $30 \text{ particles}/\text{cm}^2$ from outside to inside. The total fluence of all heavy ions in the middle of the stack was $140 \text{ particles}/\text{cm}^2$. The photometric measurements of the charge of the cosmic ions are in progress.

All plastic sheets, etched up to now, are $250 \text{ }\mu\text{m}$ thick Daicel-71 cellulose nitrate (CN). They show well analyzable tracks (fig. 6,7,8).

All sheets carrying biological layers were etched applying the special method (1) in which the biological side of the sheets was sealed against NaOH while the other side could be etched.

Optical scanning with a Leitz-stereomicroscope (2.5 objective and 25 x eyepiece) of CN sheets, positioned at the top and at the bottom of the stack, again showed the absorption of particles by the stack material (table 2), in agreement with the K2 emulsions recordings.

AgCl-detectors normally require irradiation with yellow light during the passage of particles for the stabilization of their tracks. Since this illumination not being achievable, detectors with reduced fading were used in the Biostack II. In these crystals the integral blackness of tracks decreased to values of about 25 % and 15 % respectively, but the geometrical trackwidth remained almost constant. The geometrical trackwidth allows a rough estimate of the charge of the particles.

Tracks of particles with charge $Z < 4$ are recorded only if not relativistic. The surviving tracks were divided into five groups (table 3). Figure 9 shows an example for each of these groups of tracks. The number of surviving nuclear stars was found to be $4\,500 \pm 650$ per cm^3 of AgCl.

c) Biological flight objects

First viability studies of the flight controls - these are flown biological objects not hit by a heavy particle - were performed. Germination and outgrowth of *Bacillus subtilis* flight and ground controls were studied in special incubation chambers on nutrient broth agar at 37° C (15). No significant difference in germination was observed on the flight and ground controls (table 4). The differences in outgrowth and cell elongation rate of the flight and ground controls (fig. 10) were shown to be not significant. The reduction in cell elongation after about 130 minutes of incubation is typical for these rather densely covered spore foils, but it gives no evidence on the viability of the spores. Thus space flight alone exerted no harmful influence on the viability of the spores.

Viability tests of the flight controls of *Artemia salina*, *Tribolium confusum* and *Carausius morosus* were performed with small sections from the rim of the biological foils. Breeding of *Artemia salina* in special salt water with living nutrition (*Dunaliella viridis*) resulted in a hatching of 84.2 % for flight samples in fixed connection with CN and of 90.8 % for flight samples adjacent to nuclear emulsions. Thus, investigation on development of hit eggs is possible. The eggs that have been hit by a cosmic ray particle, were determined from different track detectors positioned adjacent to the biological layers. These are K2 nuclear

emulsions (fig. 11), CN sheets (fig. 12), and AgCl crystals (fig. 13). The last two detectors remained in fixed contact with the biological layers during flight, disassembly and physical evaluation. Investigations on such hit eggs in regard to development anomalies and histological changes are in progress.

Discussion and conclusions

The first data readout of the cosmic radiation detectors of Biostack II was found to agree with the results of the first Biostack analysis flown aboard Apollo 16. The total background dose and the cosmic ray particles fluence per mission hour of the two flights are shown in table 5 .

The visual track detectors recorded in sheets which were close to space about 1.5 times more particles/cm² than in those directed towards the cabin. This decrease in dose and fluence through the stack is due to the absorption of the stack material.

As to the biologics of the Biostack II, they were resistant to the additional space flight factors. This was suggested from first studies on the viability of the flight controls. Concerning Artemia salina eggs, hatching of the flight controls were nearly the same as observed on the relevant eggs of the first Biostack. Likewise a good agreement was observed on germination and outgrowth of Bacillus subtilis spores of the both Biostacks. However after 130 minutes of incubation of Biostack II samples cellular elongation began to decline due to a rather high density of spores. This is different from the Apollo 16 results, where growth was followed up to the first and second cellular division (1). In the layers of the Biostack II the spore density was about three times higher than in the first Biostack layers in order to increase the chance of HZE particles to hit a spore. The observed reduction of the cellular elongation rate was of

no influence on the studied endpoints : germination and outgrowth.

From these observations it is seen that the experiment Biostack II promises a successful evaluation. Thus, the next postflight step will be started on. This is the identification of the biological area which has been penetrated by a HZE particle. Studies on biological radiation effects due to HZE particles and the analysis of the biologically effective particles will follow. These studies will base on the scientific results already obtained from the first Biostack evaluation, yet being in progress. Spores of *Bacillus subtilis* strain 168 flown aboard Apollo 16 have been found to be rather resistant to hits of HZE particles. Therefore Biostack II accomodated a second strain pol⁻ (16) which is very radiosensitive in addition to the more radioresistant strain 168.

Studies on strains of the same species differing in their radiosensitivity have been performed already on *Artemia salina* eggs of the first Biostack experiment. The results were very informative. As to the radiosensitive strain, only 10 % of the hit eggs were able to pass the first step of development, the emergence. In contrast, in the radioreistant strain, the emergence frequency was 61 %. But after successful emergence, the development stopped even in most hit objects of the radioresistant strain showing a hatching decreased to 15 % (table 6). From these observations it

was followed, that the HZE particle induced damage in the encysted blastula of the eggs may influence the gastrula formation and even the hatching process of the nauplius. Many nauplii, which had succeeded to hatch from hit eggs did not survive the stage of first casting of the skin which is accompanied by a high mitose rate. A complexity of malformation was observed in the nauplii from hit eggs. These are shortened extremities or abnormalities of the thorax or the abdomen (fig. 14). The Biostack II studies may confirm these observations and extend them by systematic histological investigations.

As ground controls three stacks were available. Unit S/N 8 is already disassembled and serves as not specially treated ground control. Unit S/N 9 will be irradiated with accelerated oxygen nuclei at the Bevatron in Berkeley. Unit S/N 10 will be submitted to vibration, acceleration and shock at Centre National d'Etudes Spatiales (CNES), Paris, France, in order to study the influence of these launch parameters on the biological objects.

≡ Ap 17?

layer no.	position in the stack	direction towards	dose (mrad)
E 1-1	bottom	space	750
E 8-1	middle		730
E 14-1	top	cabin	715

Table 1. Total dose of cosmic ionizing radiation (background)
during the Apollo space flight measured by LiF TLD
in the Biostack II.(standard deviation $\pm$ 20 mrad)

group	geometrical trackwidth (μm)	estimated charge Z	particle number/cm ²
L (light particles)	< 0.8	≤ 6	254 ± 14
M (medium)	0.8 - 1.2	6 - 9	68.4 ± 6.5
H (heavy)	1.2 - 2.0	9 - 15	17.3 ± 1.9
V (very heavy)	2.0 - 3.0	14 - 26	4.4 ± 0.8
S (super heavy)	> 3.0	> 20	2.4 ± 0.7

Table 3. Cosmic ray particles recorded in AgCl crystals of Biostack II

sheet no.	CN	position towards	etch holes	1 or 2 cones	stopping outside	tracks from inside	all tracks in 20cm ² 1 cm ²	
E 2- 5	Daicel etched 4.0 hrs	space	236	285	27	25	568	28.4
E 13-27	at 40° C	cabin	161	202	25	14	402	20.1
E 2- 1	USF 4b etched 8.0 hrs	space						70±8
E 13-25	at 40° C	cabin						40±6

Table 2 : Number of particles recorded in CN sheets of Biostack II

sheet no.	control	etched	area covered by spores %	germination %	outgrowth %	cell elon- gation begin min	cell elon- gation rate /um/min
E 3-35	flight	yes	23.2	97.7	80.7	80	$4.8 \cdot 10^{-2}$
F 3-41	ground Houston	yes	20.9	96.0	64.0	65	$3.0 \cdot 10^{-2}$
	ground Frankfurt	no	27.8	97.0	63.0	60	$2.1 \cdot 10^{-2}$

Table 4. : Germination and outgrowth of Bac. subtilis spores flight control and ground control.

sample	radiosensitive strain Hayward		radioresistant strain Utah	
	emergence	hatching	emergence	hatching
	%	%	%	%
flight eggs hit by a HZE ion	10	6	61	15
flight controls	30	25	77	46
ground controls	66	62	91	90

Table 6. : Development of Artemia salina eggs of different radiosensitivity, flown aboard Apollo 16 in the first Biostack experiment.

	background mrad/h	particles/cm ² /h recorded in K2 nuclear emulsion	CN directed towards space	cabin
Apollo 16	2.34	0.08	0.12	0.07
Apollo 17	2.41	0.13	0.09	0.07

Table 5. Comparison of the first data on cosmic radiation, obtained in Biostack I and II aboard Apollo 16 and 17.

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to propose to NASA. Group formed to Council of Europe -

April 1970. 1st meeting - Strasbourg later 1970.

^{Kinds of} 3 Meetings to Sept 1972. 1. Formal meeting of working party - formal projects & possible ideas.

2. Reviewed Gen. trends in Physics of N. Then almost irrelevant. 3. Working meetings - prep. of future flts., Apr 16, 17 (Practical very helpful).

2. Surplus for Man (Practical and) How safe places, genetic mutation - are these harmful to man? - Are we sure? No G/B work possible in past. Answer could be given & more - will be given by integrating work - various projects (Brain - Tobacco) Action on N cells, lower, etc. It must be determined. Council of Europe wants investigation of Japanese T-bis (20 km or more) - effects on infant, pregnant women, etc. Are not very - still working on question.

Future collaborations must not - both these directions. Public opinion very sensitive to misfortune of Sci. - good or bad?

Not well prepared for practical conditions. We are preparing other specialists - know more, more to be done. Interdisciplinary activity extremely important, therefore. Need push to gathering work of specialists. Next step is this - to integrate - understand each other's language (discipline).

We are now reconstructing horizontal structure to sci. This is one of technologies of the future.

Apr 17 P. R. R. - Improving - 60 percentages

(4)

150 Eggs - Apr 17
Hit & Van Hit

150 Cystos

154 - 27 - 25

84 - 49

Strain - Apr 17 diff. to Apr 16

Egg - P. R. R.

Hit. Study - R. R. R. V. R. R.
Fixation different. Fixation can't penetrate.

Resistant II - also used a P. R. R. - C. R. R.
= 4 cells in multiplication cyst. After several 1 hr. cyst
breaks → Clpoda → Cyst - Resistant - only one
cell inside

Not yet reduced

Exp. #6 P. R. R. - V. of Marburg - Ad. Lab. Development

Apr 16 Anterior L. R. R.

Napkins - of hit eggs

Short spine after

Enter

Deformed Tails & abdomen

" limbs

Ready death (4th day)

Anterior Annelis - Disrupted

General Rate Normal Head

S. L. almost hit → N. in - non-hit eggs

Hit Eggs → 1 hour - never reach normal.

Exp. #7 P. R. R. - Dr. H. R. R. - V. Frankfurt - B. L. R. R.

1.5 in size

Can see red. Large directly 5 interphase 5 surrounding cells.

Excess det. of point of hit required.

Many participants - R. R. R.

Apr 16 results

Viability of P. R. R. - C. R. R.

Hit Spores - Effect on GERMINATION & OUTGROWTH

Energy loss of P. R. R.

Can dope A_2 $\cup$ - change sensitivity by doping - by
 immediately $\pm UV$
 Doping in daylight.
 No change of layer - change sensitivity by doping
 Cadmium doping - filter out $\therefore$ can select
 latent image alone rapid fading of dark etchings
 In main, α can disappear
 Can replace speed of fading by Temp.
 Can etch by yellow light
 A_2 $\cup$ forgets under etched $\pm$ yellow light

(See Report for complete description)

Tracks $\approx$ to those in K_2
 Can write on a $1/5$ mil.
 i.e. only long silver phase, outside of magnetoplane, etc.
 $1-15^\circ C$ of Temp. $\uparrow$ fading rates $10-100 \times$.

Can etch track density spectroscopically - $\pm$ yellow light.
 Potential sensitive to blue light - $\therefore$ can write on detector.

Q - Max Size of X tells?
 $A = 4.6 \text{ cm}^2$ detector. Can grow right X tells $\rightarrow$
 long as desired.

Exp. #3 - Dr. Beaugleau - Photo Detector - U. of Harv

Used in the way: CV



Etch $\approx 6N NaOH$

6,000 particles counted
 $A1-1 - 32/cm^2$
 $A9-9 - 17.9/cm^2$

Apr. 16

Apr 17 - 50 sheets etched - 16 $\pm$ B. B. Mill.
 Counted then ± 100 particles counted

$122-15 - 28.4/cm^2$
 $\downarrow$
 $1213-27 - 20.1/cm^2$

Unconnected data
 CdO = quartz
 $\neq$ photoconductor
 Ag & K_2 maps
 other small.

Longer exposure times in Apr 17

$2R/x =$ size of particle

Length of track = Energy

Based on 8 CV sheets $O, N, C, Br, Beilstein, \& \text{Thalium}$
 plotted from 10 particles - 7 cm exposed

Biotrack II

Visit to Frankfurt

3-8-73

10 AM

①

Intro - Dr. Buehler

Truck. Picnic - The AGC

Intro Buehler 7 Expts - Apr 16 - 255 H₂ of 1st
10 " " Apr 17 - 305 H₂ of 1st

The 10 Expts.

1. Stairway Team - Nuclear Radiation Expts. - Dr. Pfohl

Apr 16 13 over H₂E soil found

Im middle 30/cm²

A 2 - 8 Expts. Soil 185/cm²

A 9 - 1 Interior Soil 131/cm²

Found some - Li F

Could find to change ± 20 miles from 1st and 2nd.

Compared to Buehler - much more very small good correlation.

Good soil.

Apr 17 - have measured ± 6 , 100 tracks in 60 cm²

E 9-5

9-14

9-17

9-20

Im middle find 40/cm²

(Larger for > Apr 16)

Im E-2-24 140/cm²

500 Very Heavy Ion



E 12-1 110/cm²

30

2. Frankfurt Team - AgCl - Prof. Schopper

Properties of Detectors

Pre same as Na Radiation, but diff. in AgCl x TL.

Yellow - Thin about x thicker AgCl on water glass - produced thin find sheets - will be able to make more sheets soon

Expt #9

⑥

Conclusion of Report. - Preliminary of British I & D

To study & conclude finally

Concl. 3 parts

1. Sci.
2. Policy. 1. Biological Space Res.
3. Aspects Sci. Collab. - Europe.

is 1. - Methods appear to be applicable for → food Sci. results.
Did detect trends & destination resulting.

Provision to fly attack only to Biological field.
Only combat. physical, kind. → Sci. value.

Imp. because no more building provided - plot.

Effect WTL - very small probably.

Concl. to continue in London Lab & others.

Track detector physics can continue into 70's & 80's.

7. Mainly - integrated investigation (Physical & Biol. Demonstrated)

3. Collab. of European countries demonstrated

Professor. Am. to Strasbourg

Sci. collab. in Europe

60-70's has been productive. Period of 70's will be decade of struggle re quality of life. Time to form sci. groups to work in the area - man & his environment. This is esp. program #2

advantage of pool.

1. Biophysics is an infancy. In past density of particles, radiation etc. need - i.e. DENSITY. This decade we hope to go to CORPUSCULAR Biophysics. To form the group we had to rely on lab. & good exposure in the field, but had to rely on people who can collaborate in others & other fields. Only a few such persons in Europe (compared to USA USSR). Saw much done at Berkeley - i.e. Benton - more in Eastern countries. Told they had chance

217.
10.17

⑤

Review on AgCl-Crystals as Visual Detectors of
Nuclear Particles

E.Schopper, F.Granzer, G.Henig, J.U.Schott, K.Dardat
Th.Wendnagel (University of Frankfurt, FRG)

G.Haase, F.Zörgiebel (Techn.University of Munich, FRG)

Introduction:

When we regard the fundamental process, as it occurs in the grain of a nuclear emulsion, which is hit by an ionizing particle, it seems obvious to proceed to greater dimensions of silverhalide crystals and to realize the record of nuclear tracks in macroscopic volumes of a homogenous solid detector. though the idea is clear so far, its realization nevertheless took a rather long time.

We have to remind that the sensitivity of the emulsion grain depends on rather particular conditions of its structure and its chemical composition and on the important influence of the phase boundary to the gelatine. Moreover, the grain hit by a nuclear particle responds to the development as an entity by yes or no, whereas the macroscopic crystal has to react at the path of the particle only. The essential difference between both, though based on the same fundamental properties of the silverhalides, is evident.

A series of investigations, dealing in particular with silver-chloride crystals during the past six years on structural properties (1, 2, 3, 4) on the influence of the chemical composition and of the doping (1, 4, 5, 6, 7) and on the technology of growing doped crystals have succeeded to bring new light into the complex problem and to show up the conditions which determine the formation of tracks in macroscopic crystals.

Paper, presented at the 8th Int. Conference on Nuclear Photography and Visual Detectors, Bukarest, July 1972.

A special technique of growing thin sheets of monocrystals on quartz glass (8), based on a modification of the Clark-Mitchell method (9), was the key for the extended investigations of a large number of doping elements at different concentrations. Among some others, Cd was the most promising and is used at present for our detectors.

With the high concentrations of Cd in our standard types of detectors (600 ppm and 5000 ppm Cd resp) which are above the solubility threshold of Cd in AgCl at room temperature, this method of growing monocrystals is decisive, if not indispensable.

Since the Barcelona conference in 1970 our understanding of the mechanism which leads to the formation of latent tracks in Cd-doped AgCl-crystals has been enlarged by a further important observation: the strong fading of latent tracks from nuclear particles in Cd-doped detectors if they are irradiated in full darkness, and the stabilization of these tracks by an exposure of the detector to in-actinic light during the passage of the particle(10).

Apart from the most interesting consequences, that namely these detectors may be switched on and off for the record of particles for a desired period of time - a unique peculiarity of the AgCl-detectors among the known trackforming solid state detectors - this effect is throwing light on an interesting mechanism caused by the doubly charged Cd-ion in the AgCl lattice.

Dr.Granzer will discuss it in detail in his contribution to this session. J.U.Schott will present in his paper some data concerning the fading-time of latent tracks of different particles and its use for particle-discrimination and time assignment to incoming particles.

The technology of our detectors which are manufactured in our laboratory has now achieved a certain performance, which permits to apply them to experiments in heavy ion and cosmic ray physics, to dosimetry - switched on and

off and - with respect to their good spatial resolution which is not submitted to shrinkage by a wet development - to problems of micro-radiobiology; this field will be shown up in brief with two examples by G.Henig.

Experimental

The detectors used by us as standard types consist of a thin layer of 200 microns of silverchloride crystals on thin quartzglass plates; usually they have a size of 1.5 to 2.5 cm each, subject to the technology of their manufacturing; sizes up to 2.5 x 4.5 cm are, however, achievable. The technology has been described by F.Zörgiebel in his paper on the Barcelona conference (8) in 1970. As aide memoire Fig 1 shows schematically the device for growing the crystals:

At the inner side of two long rectangular bars of quartzglass (A) in a quartz-tube, kept in distance by two pieces D, thin plates of quartzglass (B and C) are slightly fixed.

A droplet of melted doped AgCl is placed on plate C; it creeps between the heated plates by capillary forces and cools down to a polycrystalline layer (E). Melted off again and passing through an adequate high temperature gradient by means of a movable double furnace, these layers form sheets of single crystals. After cooling again, plate C is removed; the free surface of the crystal is polished in order to remove impurities from the glass.

The process occurring with the passage of an ionizing particle through the crystals, analogous to the known fundamental photographic process, consists of two components (Fig 2) :

- a) the fast electronic process: the formation of electrons in the continuum of the conduction band and of holes (Cl^0 , Ag^{++} etc).

Electrons are trapped at disturbances along the path of the particle. The holes should be bound in order to reduce recombination.

- b) the subsequent ionic process which is slower, about 1 millisecond at roomtemperature.

Interstitial Ag_i^+ of rather high mobility is neutralized at the sites of captured electrons along the path of the particle.

A subsequent nucleation of silveratoms leads to the formation of more or less thermically stable Ag_n^0 - specks.

They represent the latent track, which is grainy in the case of weak ionisation on account of the stochastic formation of single discrete specks.

In order to develop, that means to amplify the track to a microscopically visible size, we repeat the described procedure by irradiation of the crystal with ultraviolet light ($\lambda \cong 410 \text{ nm}$), producing photoelectrons and neutralizing interstitial silver at the sites of the track.

The detectors are transparent enough for this wavelength to be revealed throughout a depth of 0.5 mm with a total fluence of 10^{18} quanta/cm². Fig 3 shows the simple device for revealing the tracks.

The sensitivity of the detectors depends upon the concentration of Cd; we are using at present Cd-doped and Cd-Pb-doped crystals in mainly two standard concentrations

5000 ppm Cd

600 ppm Cd + 10 ppm of lead.

Fig 4 shows the thresholds of sensitivity for both types of detectors for particles of different energy, charge and ionization I , in units of the minimum ionization I_0 for $Z = 1$.

Fig 5 shows tracks of slow heavy ions Br and U at energies of 0.3 MeV/Nucl and 0.1 MeV/Nucl and $Z \sim 9$ in an AgCl (600 Cd) detector. They are compact.

No α -particles are recorded in this detector, as below its threshold.

The threshold at $I = 10 I_0$ with the 5000 ppm Cd-detector means an energy of about 30 MeV for protons. Protons of this energy produce grainy tracks (Fig 7). The threshold listed in Fig 4 refers to tracks of an opacity of 0.2 (lacunarity 0.8) as a safe limit of recognizability. Opacity 1 means compact tracks.

In Fig 6 the (compact) track of a ^{16}O nucleus of 200 MeV/Nucl in an AgCl (5000 ppm) detector is presented. Fig 7 shows parts of tracks of different types in this detector from a

- a) slow proton,
- b) slow α -particle,
- c) ^{16}O nucleus at 25 MeV/Nucl ,
- d) fast Fe-nucleus.

We distinguish them in the following way:

<u>type of track</u>	<u>parameter</u>
grainy track (a)	opacity
compact track (b,c)	mean track width MTW
black core	

broad track (d)	density profile:
grey core	optical trackwidth OTW
	+ MTW

Fig 8 explains this definition.

We are measuring the mean track width MTW with a microdensitometer (van-Friesen-type(11); Leitz, Wetzlar) as the equivalent width of a compact track with the opacity 1.

The lateral density profile and the resulting optical track width OTW are determined by a "Quantimet" a device with a movable rectangular slit of variable size, giving digitalized signals from a Video-recorder.

Broad tracks from heavy particles, belonging to the density profile regime, are defined by their MTW and OTW.

The MTW of heavy particle tracks are different by a factor of about 10 in AgCl-crystals and K 5 - emulsion as shown by Fig 9 and 10.

It should be noted that the sensitive AgCl (5000 ppm Cd) detector tolerates the irradiation with a particle density of 10^{10} protons/cm² of 600 MeV, which are at $I = 1,2 I_0$ below the sensitivity threshold, without fogging or loss of sensitivity. The mean linear distance between two protons corresponds to 0.1 micron. This admits the record of particles against a rather high background of radiation which is below the threshold of response.

As already mentioned, latent tracks of particles, irradiated on the detector in full darkness, are unstable in time and are fading. They can, however, be stabilized for months until their later development if the detector

x) Quantimet-System 720
(Metals Research Ltd., Cambridge, England)

is irradiated with inactinic light during or immediately after the passage of the particle, either by permanent yellow light of about 10^{15} quanta/cm² sec or by short light-pulses with a total fluence $I \cdot t \sim 10^{14}$ quanta/cm² ($t > 10^{-3}$ sec).

This exposure to "accompanying" inactinic light does not influence other, already stabilized, tracks nor does it help to stabilize later incoming tracks. Latent tracks not yet stabilized become stabilized at their present phase of fading at the moment of their exposure to light.

This effect, obviously due to a redistribution of minor Ag⁰-complexes at the latent track in favour of more stable ones (viz Fig 2), has presumably an analogy to the stabilizing Herschel-effect on latent proton tracks in C2-emulsion, observed by one of us in 1951 (12), and to the observations by Kartuzhanskii et alii on laminated microcrystals, reported in the proceedings of the Barcelona conference (13). It seems, however, to be only one of several interesting effects of the Cd⁺⁺ ion in the AgCl-lattice which are summarized by F.Granzer.

As a demonstrative example we have irradiated a (5000 Cd)-detector with α -particles (Fig 11)

a) with accompanying light, b) in full darkness.

Development after some minutes shows the eradication of the nonstabilized tracks.

In one of our balloonflights, in cooperation with the Strasbourg group of P.Cuër, R.Kaiser, R.Schmitt(14), we checked the technique of stabilizing or suppressing tracks. We used a combined stack of plastics, K5-emulsion and AgCl(Cd)-crystals. The latter were switched on at a pressure of 10 Torr by means of a pressure gauge. In a parallel set with (switched-off) detectors in full darkness, no tracks were observed at all. Another

detector, flown with Apollo 16 in full darkness
- unfortunately we could not be admitted to the power supply at the late date of our application - has retained some few stars and some corroded tracks of evidently heavier particles.

Though we are now able to reproduce rather well the level of sensitivity of our crystals, we are still observing fluctuations by 2 - 3 orders of magnitude in the lifetime of latent tracks among different specimen of crystals. Lifetimes of 1 millisecond should, in principal, be achievable, as once observed with α -tracks in lead doped crystals (1). This has still to be improved.

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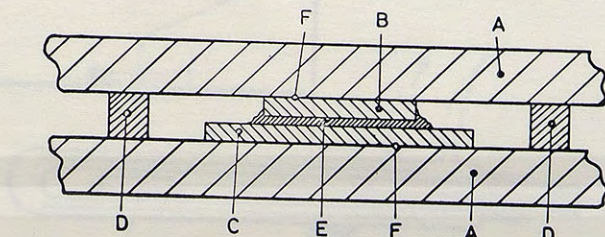
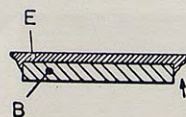
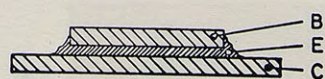


Fig 3: Schematic device for development of AgCl-detectors

Fig 1:
Schematic device
for growing
crystals



0 1 2 3 cm

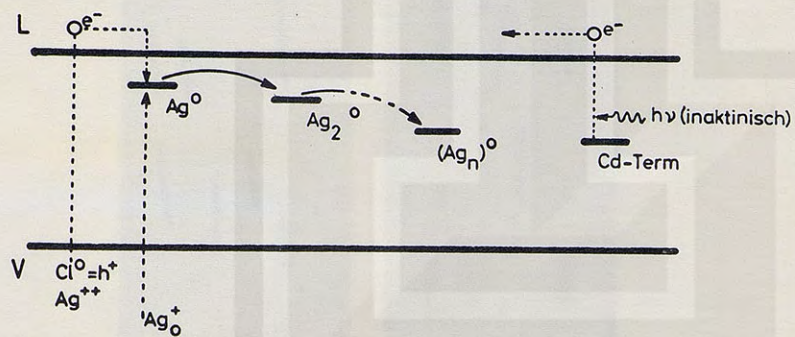


Fig 2:
Scheme of
the formation
of the latent
track

20 μm

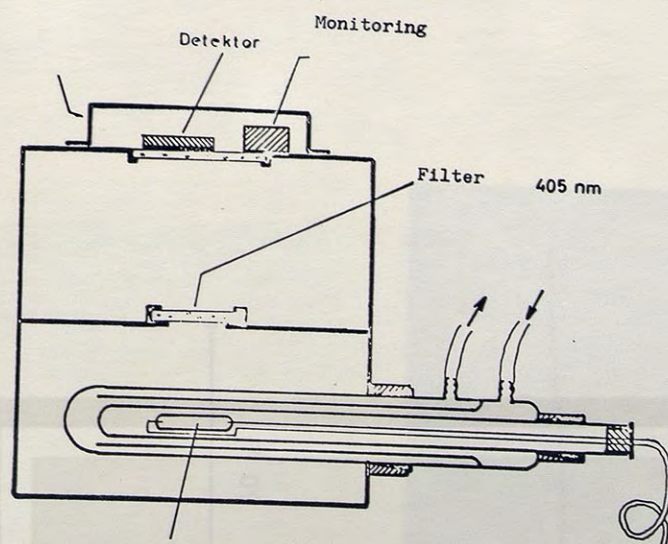


Fig 3: Schematic device for development of AgCl-detectors

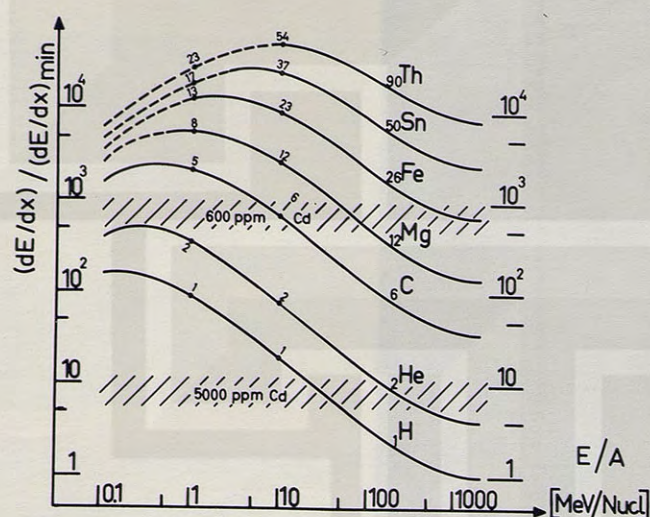


Fig 4: Thresholds of sensitivity of two types of AgCl-detectors
Calculated values of ionization

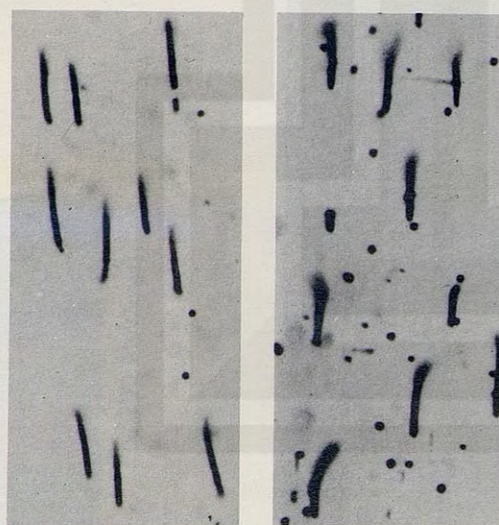


Fig 5: Tracks of slow heavy ions in AgCl(600 Cd)-detector
left: Br 0,3 MeV/Nucl
right: U 0,1 MeV/Nucl



20 μm

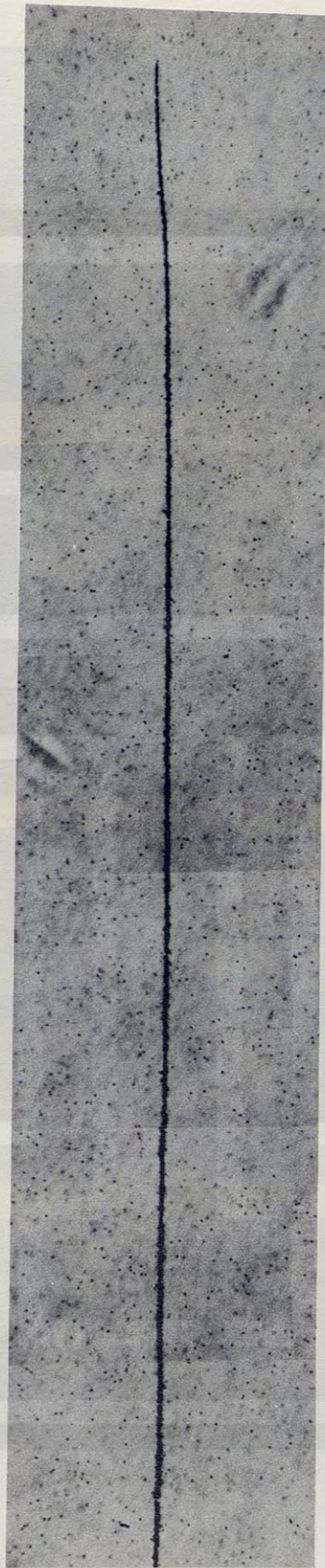


ca. 200 MeV/nucleon.

50 μ

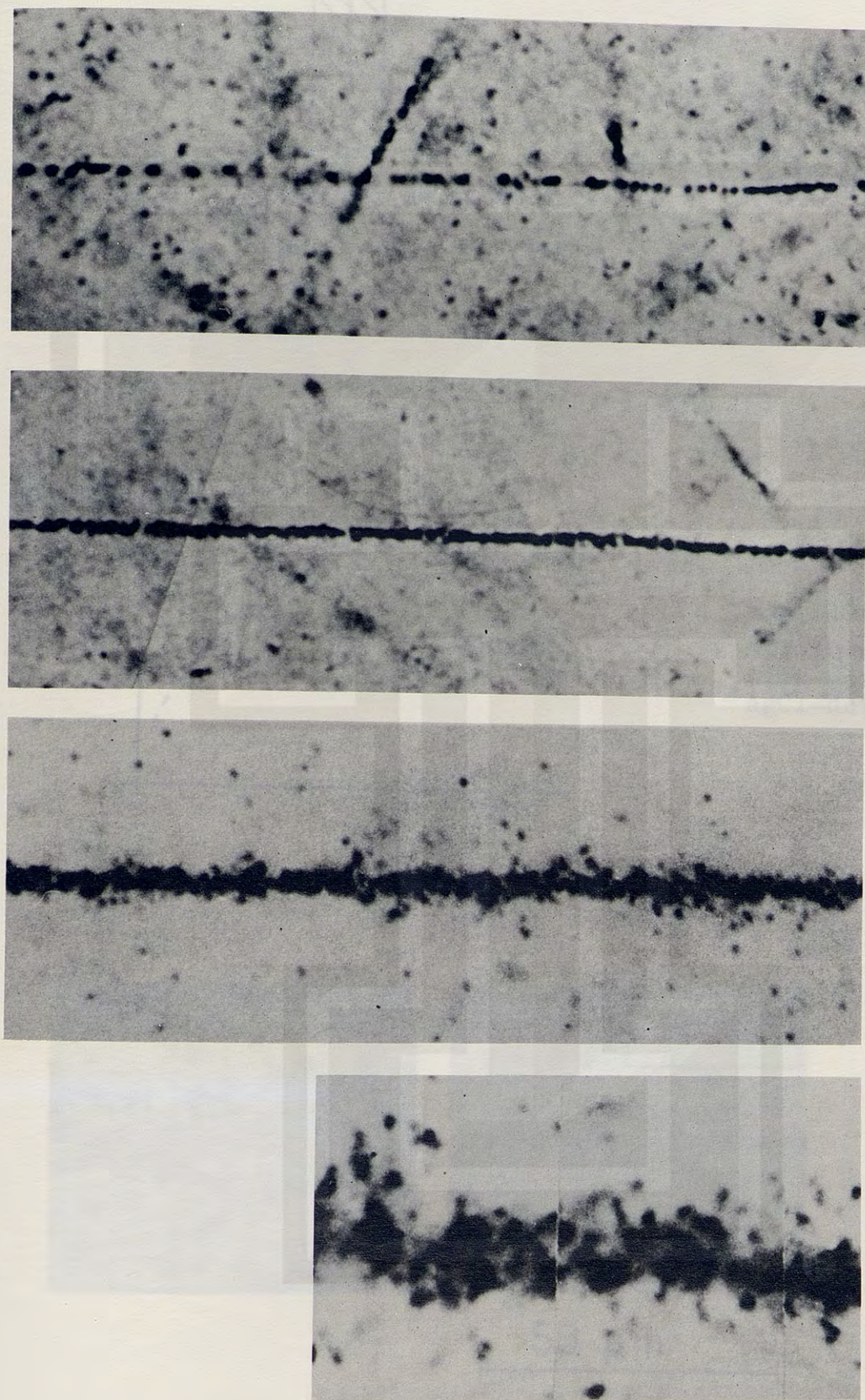
Spuren von ^{16}O in AgCl (5000ppm Cd)

(Bevatron, Law.Rad.Lab., Berkeley)



15 MeV/nucleon. 10 MeV/nucleon. 5 MeV/nucleon. STOP

Fig 6: Tracks of ^{16}O in AgCl (5000 ppm Cd)
(Bevatron, Law.Rad.Lab., Berkeley)



$Z = 1$

$Z = 2$

$Z = 8$

$Z > 25$

Fig 7: Tracks of particles of different charges

Fig 10: Track of a Mg-nucleus in nuclear emulsion AgCl(5000 Cd)detector

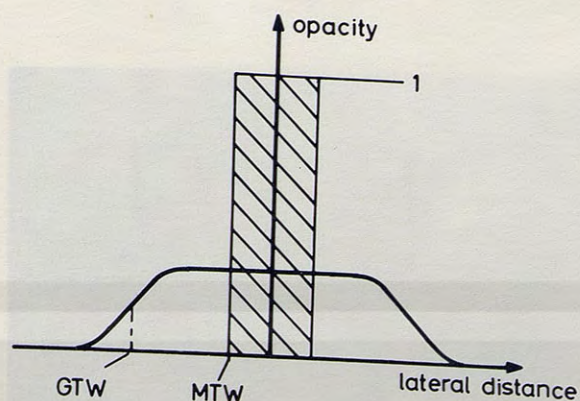


Fig 8 :
Mean track width(MTW)
and optical track
width(OTW)

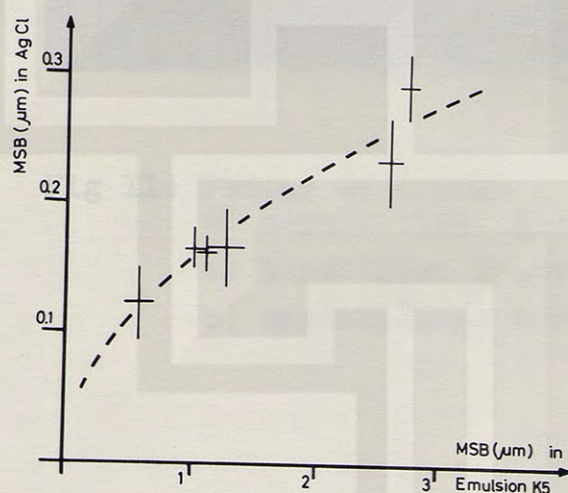
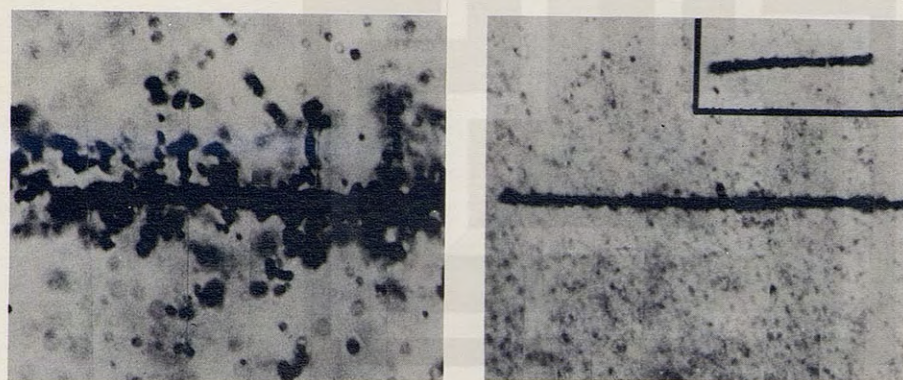


Fig 9:
MTW in nuclear emul-
sion versus MTW in
AgCl-detector



50 μm

Fig 10: Track of a Mg-nucleus in
nuclear emulsion AgCl(5000 Cd)detector

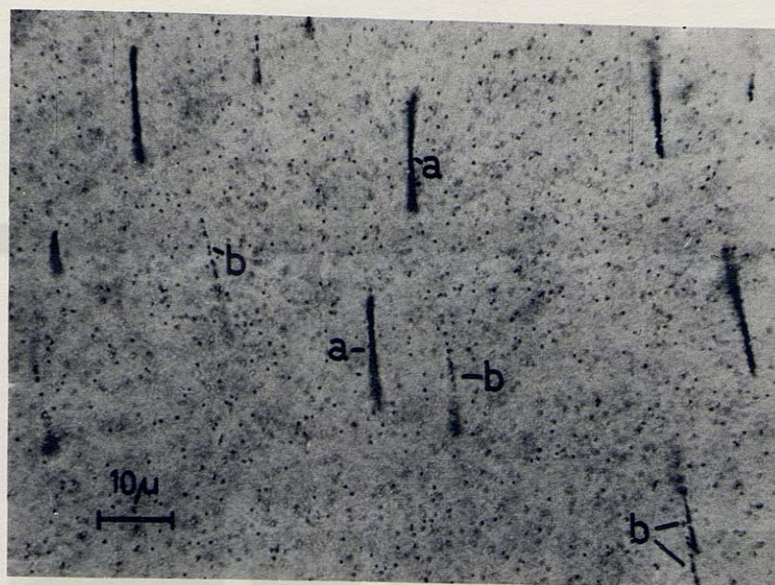


Fig 11: Fading of tracks
of α -particles, 3 minutes after irradiation
a) stabilized tracks
b) unstabilized tracks

On the Mechanism of Track Formation in Cd doped
AgCl Detectors

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Introduction

A series of papers by the Frankfurt-Munich AgCl-Detector Group (1, 2, 3) accentuated the essential role of doping and of simultaneous illumination by non actinic light during the passage of an ionizing particle for the formation and stabilization of the track left behind the particle in doped crystals.

The aim of the following preliminary report is to present in a little more detail some ideas about the mechanism of the track-formation in Cd-doped AgCl-crystals. The procedures involved, being mainly those of solid state physics, will be discussed using well established results of classical photography.

Part I summarizes the structural and chemical properties of the detector crystals. In Part II the situation immediately after the passage of a 6 MeV- α -particle is sketched with the subsequent process of rearrangement and relaxation leading to a latent image of the track. Finally Part III describes the stabilizing influence of a simultaneous illumination on the latent track.

I. Properties of Cd-doped crystals

Thin sheet silver chloride crystals with dimensions of 25 x 15 x 0.3 mm³, containing 5000 ppm Cd⁺⁺ (the concentration of all other elements being less than 10 ppm) were grown by a modified and in some respect improved Mitchell-method described in (4, 5).

The dislocation density in these crystals ranges from 10⁵ to 10⁷/cm² and is thus comparable to that found by Mitchell (6) in crystal-sheets. In pure AgCl as well as in AgBr the intrinsic

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disorder is of the cationic Frenkel-type with equal numbers of positively charged interstitial silver ions $\text{Ag}_\text{O}^\bullet$ and negatively charged silver ion vacancies $\text{Ag}_\text{O}^\ominus$).

Doping of the AgCl-lattice with divalent foreign cations such as Cd^{++} reduces the concentration of interstitial $\text{Ag}_\text{O}^\bullet$ -ions on stoichiometric reasons. On account of the mass action law the number of vacancies $\text{Ag}_\text{O}^\ominus$ is increased and roughly equal to the fraction of substitutionally dissolved $\text{Cd}^\bullet$ -ions (at room temperature).

Because of the low solubility of Cd in AgCl (<600 ppm at room temperature) this will not be the full number of Cd^{++} -ions, corresponding to a doping concentration of 5000 ppm.

A certain amount of cadmium will be clustered or precipitated respectively in the form of small, submicroscopically CdCl_2 matrix. Another fraction of the doped cadmium associates with silver ion vacancies to form neutral $(\text{Cd}^\bullet \text{Ag}_\text{O}^\ominus)$ -complexes. According to rough estimations (5,7) this fraction amounts to about 80 to 90% at room temperature. Hence assuming that the total amount of dissolved $\text{Cd}^\bullet$ is 1000 ppm, the mean distance between neighbouring cadmium ions is about 50 Å.

Summarizing, the influence of Cd with respect to the formation of the latent track of ionizing particles will be the following: The electronic process is favorized by the action of the increased number of $\text{Ag}_\text{O}^\ominus$ vacancies which act as holetraps, forming neutral complexes $(\text{Ag}_\text{O}^\ominus \cdot \Theta)$ with the positively charged holes, and hinder their recombination with electrons.

On the other hand, the detector is desensitized with respect to the subsequent ionic process - the formation of neutral silver specks - because of the lack of interstitial $\text{Ag}_\text{O}^\bullet$ -ions.

This desensitisation-effect also suppresses the development (the decoration) of structural defects of the crystal in favour of the action of the ionizing particles which by their ionization create their own interstitial $\text{Ag}_\text{O}^\bullet$ -ions as a process of "self-sensitisation".

#) " $\bullet$ " and " $\ominus$ " means that the defect is positively or negatively charged with respect to the neutral lattice.

II. Rearrangement- and relaxation processes around the track

Let us assume a 6 MeV- α -particle passing through the crystal; these particles are mostly used by us for checking and standardizing our detectors.

The mean LET along its range of about 20 microns in AgCl is $3 \cdot 10^5$ eV/micron. We estimate the fractions going into primary ions and δ -electrons as follows:

1) Using a mean ionization potential $I_a = 385$ eV (5) for the creation of a primary ion, the number of ions/micron is of the order of $4 \cdot 10^2$; the mean distance between two primary ions comes out as about 25 Å and is comparable with the distance of neighbouring Cd²⁺-ions. The number of interstitial silver ions will be of the order of 10^2 /micron too.

2) The energy transferred to δ -rays has been estimated by Zörgiebel (5) following Katz (8,9) to be about 80 KeV/micron over the energy range of 20 - 2000 eV. If we assume the energy for the formation of an electron-hole pair by δ -rays as 10 eV, the total number of electrons injected into a cube of $1 \mu\text{m}^3$ is of the order of 10^4 and thus exceeds the number of positively charged interstitial silver ions by a factor of 10^2 .

This situation is comparable to a high-intensity exposure to light in the terminology of classical photography. In both cases the latent image consists of fine-dispersed, small specks of neutral silver of minor stability.

The region surrounding the path of the α -particle can be divided into two cylindrical subregions (Fig. 1a). The inner or core-region, as a result of primary ionization events, is characterized by a high concentration of positively charged silver ions. The outer region, given by the range of the δ -electrons, is overflowed by a large amount of electron-hole pairs resulting from secondary, tertiary and higher ionization events.

Now the doping with cadmium becomes important for the following two reasons:

1) The overall reduced concentration of interstitial silver ions as a consequence of doping with divalent cations is locally increased in the core-region of the track: The ionizing particle creates by its ionization a narrow region of its path

which contains $\text{Ag}^{\bullet}_0$ ions and is sensitized with respect to the ionic component of the process.

2) In the outer-region furtheron the direct recombination of electrons and holes is prevented by the trapping of holes at silver ion vacancies. Their concentration is given - as already mentioned - by the amount of substitutionally dissolved $\text{Cd}^{\bullet}$ -ions. Thus, the formation of such neutral V-centres enhances the lifetime and mean free path of the electrons.

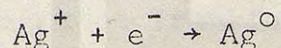
By this way, electrons from the outer region are attracted to the positively charged inner region, finding there silver ions to form a latent track.

As schematically sketched in Fig.2, doping with cadmium improves the signal to noise ratio by desensitizing the outer environment of the track and concentrating the latent image in a narrow region around the path of the particle (1a).

III. The track-stabilizing influence of a simultaneous illumination

As stated in several papers (3, 10) the latent track of an α -particle exhibits strong fading, unless it has been stabilized by irradiation with inactinic light during or immediately following the passage of the particle. It has been pointed out that the effect of rapid fading - an undesired effect in classical photography - can be used advantageously to trigger the recording of tracks in our detector crystals.

The fading or regression of a latent image is generally caused by a thermal disintegration of silver specks into smaller ones which are less stable, an inversion of the step:



and a subsequent recombination of electrons with holes.

In the outer region of a track, because of the lack of silver-ions and of a large supply of electrons, a considerable number of the latter is wasted by forming small silver specks of minor stability. The supply of electrons to the inner region of the track seems not to be sufficient to form an adequate number of stable, larger specks.

The illumination of the crystal during or immediately after the passage of a particle obviously causes a redistribution of the speck-size spectrum in the following way:

Small silver specks constitute, depending on their size and charge, more or less deep electron traps in the forbidden zone of a simplified band-scheme (Fig. 3); they can be ionized by irradiation with visible, nonactinic light: After a certain lifetime in the conduction band the released electrons will be retrapped and finally be captured by sufficiently stable silver specks.

In the course of such a redistribution, larger silver aggregates of higher stability, concentrated in the inner core region, are growing at the expense (Fig. 1b) of smaller unstable ones, thus forming a narrow, stable, latent image of the track. This effect, known in classical photographic emulsions and with nuclear emulsions (11) as the "Positive Herschel" or "Debot"-effect and convincingly demonstrated on large silver halide crystals by Saunders et al. (12) is, in our Cd^{++} -AgCl system, assisted by the presence of a variety of other electron traps. Metallic aggregates of cadmium- and silver atoms as well as phase-boundaries between small CdCl_2 -precipitations (mentioned in part I) and the surrounding AgCl-matrix may contribute additional terms to the forbidden zone.

The distribution of cadmium in the AgCl-matrix - dissolved, clustered or precipitated as CdCl_2 -islands of different sizes, influences too the structure ("graininess") of the track and its stability. The storage of newly-grown detector-crystals, before exposing them to the ionizing radiation, results by some still unknown aging-process in a faster fading.

Our research groups at Frankfurt/M. and Munich are continuing their efforts to elucidate this mechanism of track formation by fundamental physical and chemical investigations.

Acknowledgment:

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Fig 1

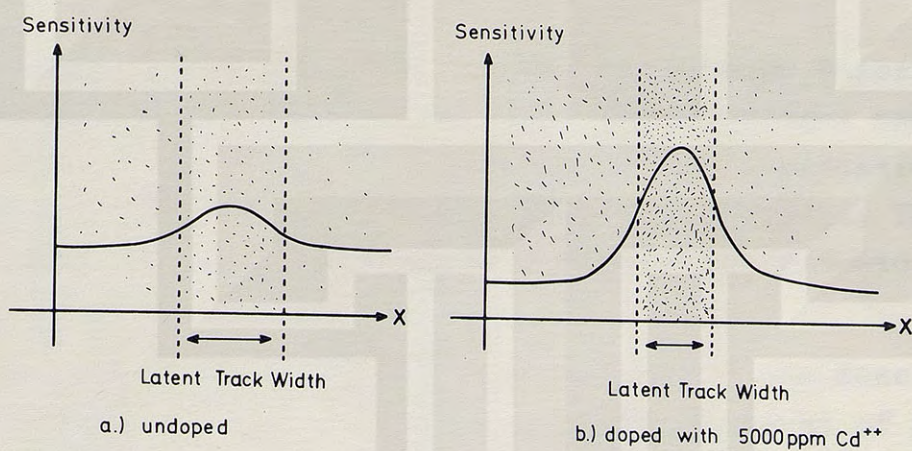
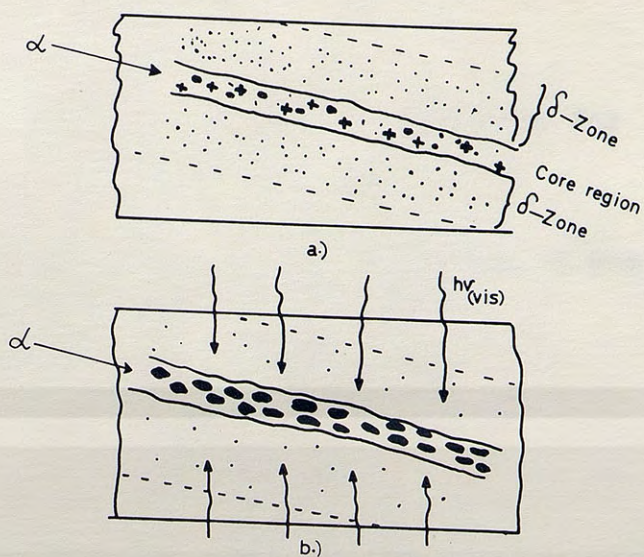


Fig. 1

Fig 2

Fig 3

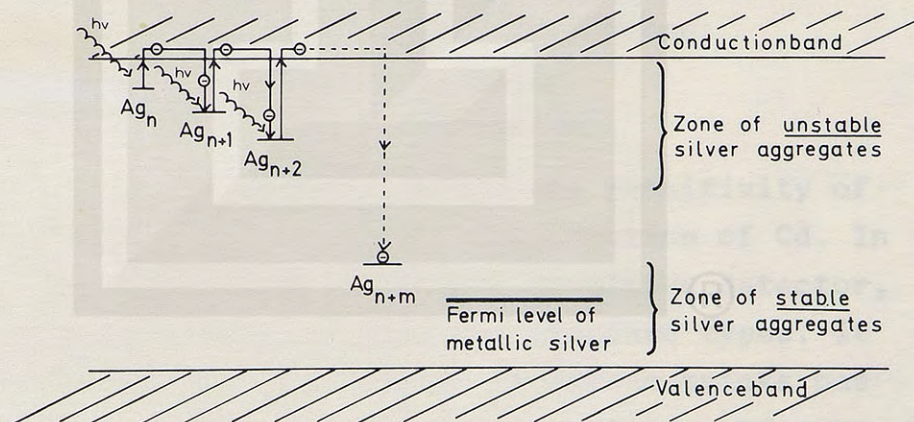


Fig. 3: Band scheme of AgCl, containing small silver aggregates.

Detecting Properties of AgCl(Cd)-Detectors for
Ionizing Particles.

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Introduction

In AgCl-crystals with certain doping components - the most important of which and the best investigated by us is Cd - the latent tracks of ionizing particles are strongly unstable in time.

This behaviour is known from other trackforming detectors too. In AgCl(Cd)-detectors however, these latent tracks can be stabilized by very simple means, namely the irradiation with inactinic light during the passage of the particle. This procedure does not influence the response of the detector to particles passing at a later date.

This behaviour of AgCl(Cd)-detectors means a new concept of trackforming solid state systems, in which tracks of particles can be stabilized and recorded or dropped by fading, in other words, the detectors may be switched on or off for a desired period of time.

With respect to the various interesting applications of these detectors, for instance in combination with electronic devices, we have studied two details of the fading phenomenon:

- a) the time-constant of the fading
- b) the conditions of its inhibition.

As shown in the foregoing contribution (1) the sensitivity of Cd-doped AgCl-detectors depends on the concentration of Cd. In the following we are dealing with the most sensitive detector, doped with 5000 ppm-Cd which is one of our standard types. It may be noted that an analogous behaviour of latent tracks has been observed with detectors of other concentrations and some other components of doping.

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Photography and Visual Detectors, Bukarest, July 1972.

a) Time-constant of the fading

The fading of the latent tracks was investigated for protons, α -particles and ^{16}O -ions. The detectors were exposed to particles in darkness at room temperature. They were stored in darkness for different times T_f , the fading time. The latent tracks are not visible microscopically; they have to be decorated, a procedure of revealing with UV-light (usually at $\lambda = 410 \text{ nm}$). The density of the revealed tracks, represented by the mean track width (1) is a measure for the state of fading of the latent tracks at the moment of their decoration.

Fig.1 and Fig.2 represent the fading of the latent tracks of stopping protons and α -particles. Fig.3 shows the unfaded track of a high-energetic ^{16}O -ion and the slope of the mean track width as a function of the residual track length, measured by micro-densitometry. The fading of the tracks of ^{16}O -ions was measured in the energy range of 25 MeV/nucl. (Fig.3 b). The results are given in Fig. 4.

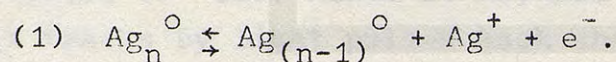
We define as the lifetime of a latent track that time T_f that leads to a latent track which is developable to a final opacity of 0.2.

Fig. 5 shows a comparison of lifetimes for latent tracks of protons, α -particles and ^{16}O ions ($\sim 25 \text{ MeV/nucl.}$).

The energy loss of the ^{16}O -ions is approximately equal to the maximum energy loss of the α -particles, that of the stopping proton is less by a factor of about 4.

b) Conditions for the inhibition of the fading

In a very simplified form the behaviour of the latent track is governed by the reaction



For $n > n_{\text{critical}}$ the reaction is running from the right to the left side of the equation, corresponding to the formation of stable metallic silver specks.

For $n < n_{\text{critical}}$ the equilibrium is given by the concentrations

of Ag^+ and e^- . Carrying electrons to the site of the latent track changes the equilibrium in favour of the left side of the equation: the silver specks are growing, the latent track is stabilized. The mechanism will be discussed in more detail by F. Granzer (2).

The irradiation of latent tracks in a detector to visible in-actinic (not decorating) light of $\lambda > 430 \text{ nm}$ stabilizes these tracks for months. Fig 6 shows the stabilization effect as a function of the wavelength of monochromatic light with a half width of about 15 nm. At an intensity of the stabilizing light of $10^{13} \text{ quanta/cm}^2\text{sec}$ the stabilizing effect depends significantly on the wavelength, whereas at the higher intensity of $10^{15} \text{ quanta/cm}^2\text{sec}$ saturation occurs even in the longwave region.

A brief remark to the experimental procedure: Together with the exposure with 6 MeV- α -particles the detectors were irradiated with a light pulse of 1 sec. Before the decoration procedure the detectors were stored in darkness for more than 5 lifetimes of nonstabilized latent α -tracks.

In order to get information about the mechanism of the stabilization we investigated its time-intensity-dependence.

If the duration of the stabilizing light pulses is shorter than 10^{-2} sec the intensity of the light has to be increased. Fig. 7 shows the ratio of the fluence $I \cdot t$ and the pulse-length for a full stabilization of latent tracks of α -particles. The strong increase of the intensity for pulses shorter than 10^{-3} sec may be caused by the ionic component in the reaction given by equation (1).

The speed of the ionic reaction, depending on the mobility of the Ag^+ -ions, is slow compared to the speed of the electronic component. The transport of Ag^+ to the latent track takes about 10^{-3} sec . Hence it may not be possible to stabilize latent tracks by light pulses much shorter than 10^{-3} sec .

The same behaviour has been observed with the process of decoration. Pulses of 10^{-4} sec of decorating light of adequate intensities are leading to a homogeneous production of photolytic silver only over the whole volume of the detector. No neutral Ag-specks are produced which specifically reveal the latent

track.

The presumed upper limit of the time resolution of 10^{-3} sec of the detectors has not yet been achieved with the detectors investigated.

As the lifetime of tracks in our detectors depends on the charge and energy of the particles, the time resolution available in a certain experiment is determined by the lifetime of the most stable tracks occurring.

This obviously disadvantageous property of the Cd-detectors may be helpful with another type of experiments: to discriminate different particles by means of the lifetime of their latent tracks.

Fig 8 shows the conditions of the discrimination of ^{16}O -ions against α -particles or of α -particles against protons resp.

The track of the α -particle which was stabilized $3 \cdot 10^3$ sec after the exposure has almost completely faded. If the fading of the latent tracks of α -particles and ^{16}O -ions is stopped 10^4 sec after exposure of both particles, the latent track of the α -particle has completely faded, whereas the latent track of the ^{16}O -ion is stabilized in a state of about 30 % fading. The corresponding time for the discrimination of α -particles against protons is $5 \cdot 10^2$ sec.

It should be mentioned, that the lifetime of tracks in our present, laboratory manufactured detectors fluctuates from one sample to the other by 2 - 3 orders of magnitude. The data reported in this paper are mean values, observed at room temperature. The lifetime of latent tracks strongly depends on the temperature of the detector during irradiation and storage. At 50°C for example, the lifetime decreases to $\tau < 1$ sec. The track can, however, be stabilized in the usual way.

From recent experiments we know that the lifetime of tracks also decreases with the age of the detector, presumable due to an effect of structural conversion with time.

Our efforts are now directed towards the understanding of the mechanism of this phenomenon and to influence it in two different directions: short lifetimes of the latent tracks for trigger-

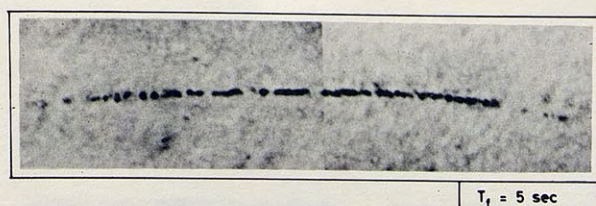
experiments, and long lifetimes with large spread for different particles, which enables us to discriminate them by means of their different time of fading.

Figure captions

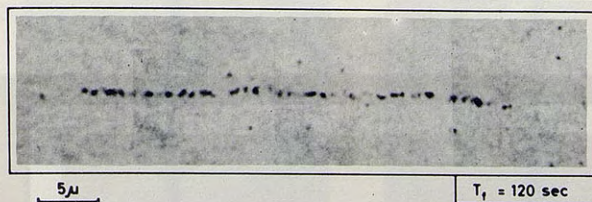
- Fig 1 Fading latent track of a stopping proton
- Fig 2 Fading latent track of a stopping α -particle (6 MeV)
- Fig 3 Track of an ^{16}O -ion
- Fig 4 Fading of the latent track of a ^{16}O -ion with an energy of about 25 MeV
- Fig 5 Lifetime of the latent tracks of protons, α -particles and ^{16}O -ions
- Fig 6 Influence of the wavelength of the stabilizing light on the decoration of latent tracks
- Fig 7 Stabilization effect as a function of intensity and time of the irradiation
- Fig 8 Particle discrimination by fading

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$T_f = 5 \text{ sec}$



$T_f = 120 \text{ sec}$

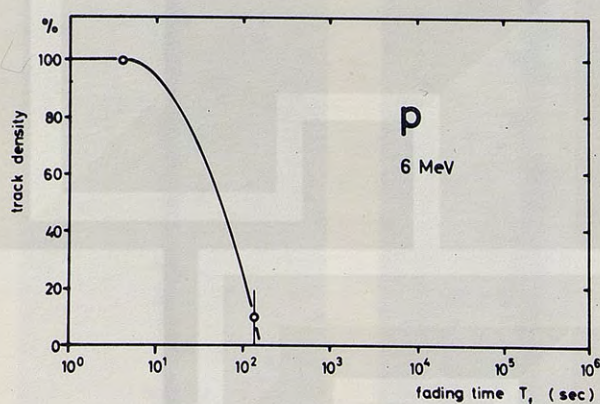


Fig 1
Fading of the latent tracks of a stopping proton



$T_f = 10 \text{ sec}$

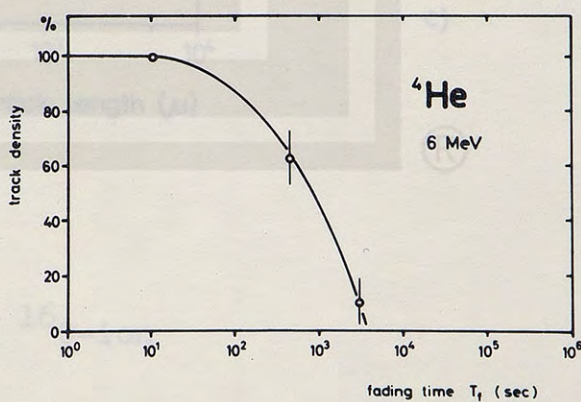


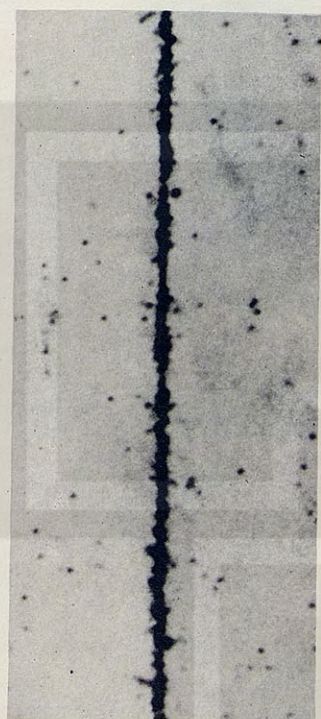
$T_f = 500 \text{ sec}$



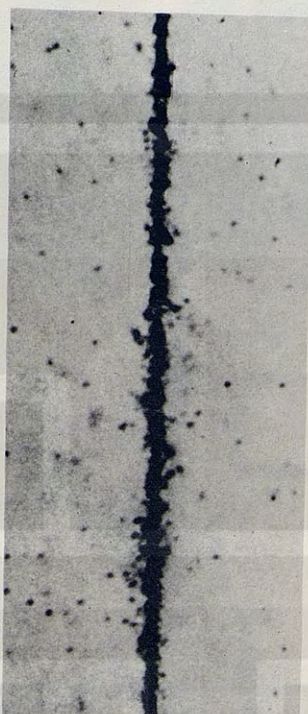
$T_f = 3000 \text{ sec}$

Fig 2
Fading of the latent tracks of stopping α -particles





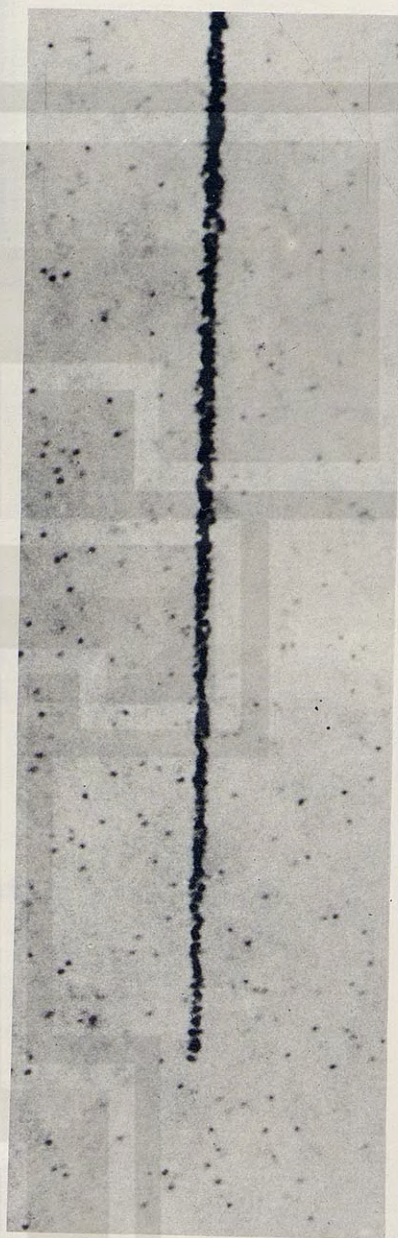
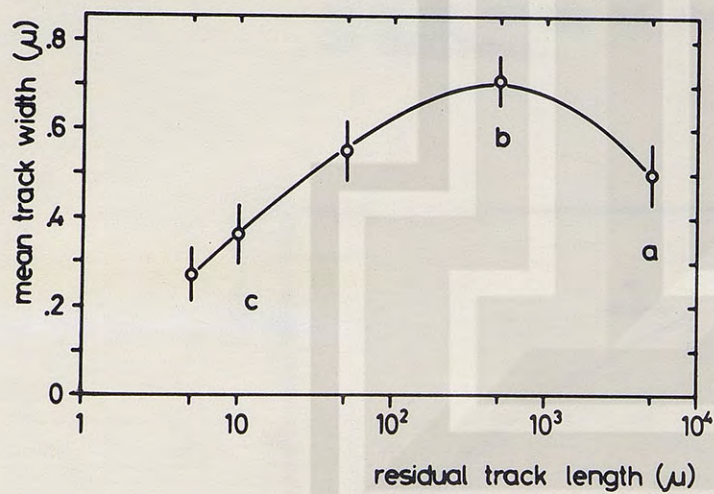
a) 90 MeV/nuc



b) 25 MeV/nuc

^{16}O

10 μ



c)

Fig 3 Track of an ^{16}O -ion

Fig 3
Lifetime of the latent
tracks of protons,
 α -particles and
 ^{16}O -ions

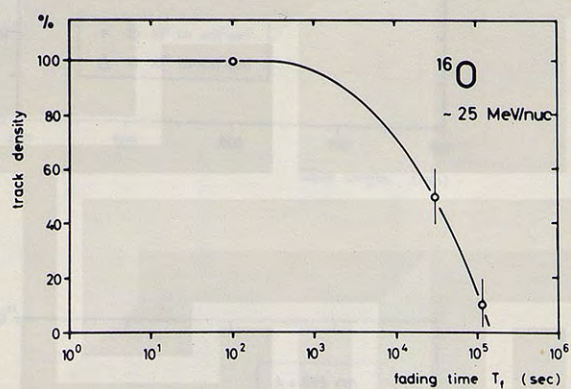
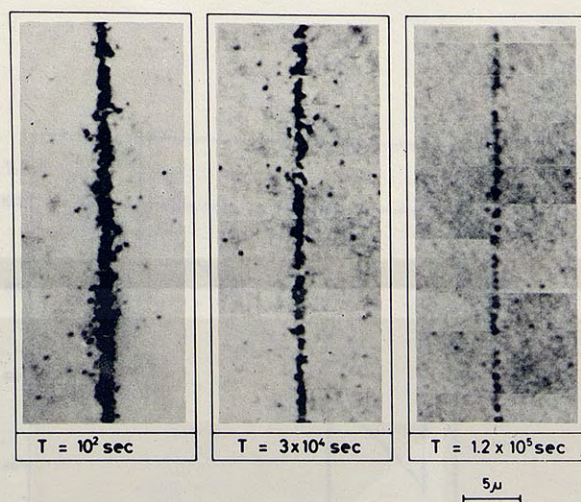


Fig 4 Fading of the latent track of an ^{16}O -ion with an energy of about 25 MeV/nuc.

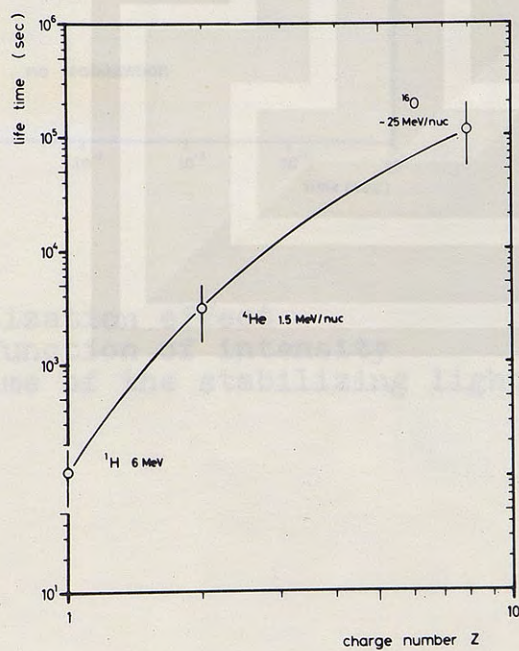


Fig 5 Lifetime of the latent tracks of protons, α -particles and ^{16}O -ions

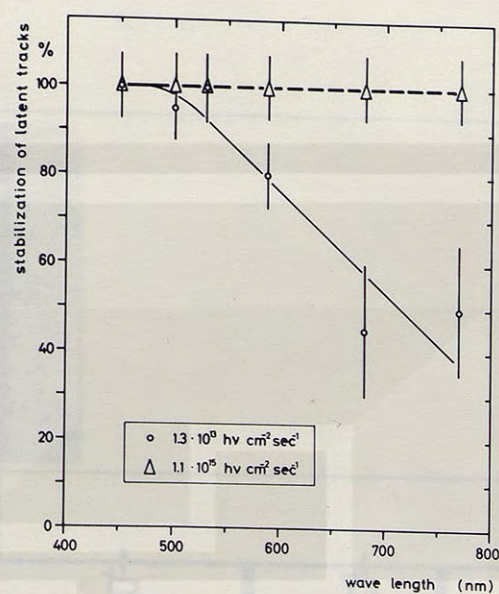


Fig 6
Influence of the
wavelength of the
stabilizing light
on the stabilization
effect

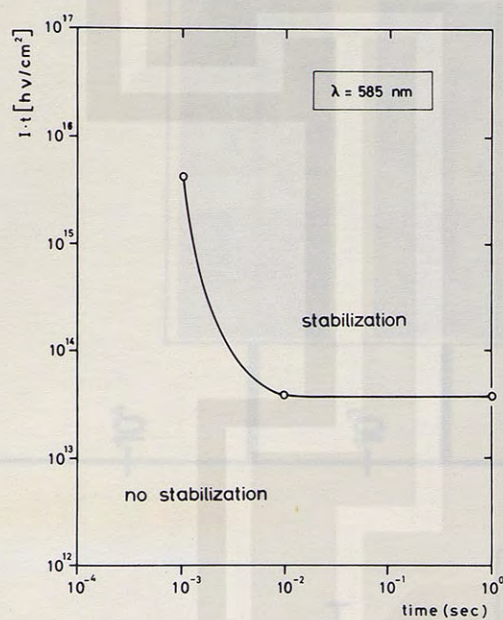


Fig 7
Stabilization effect
as a function of intensity
and time of the stabilizing light

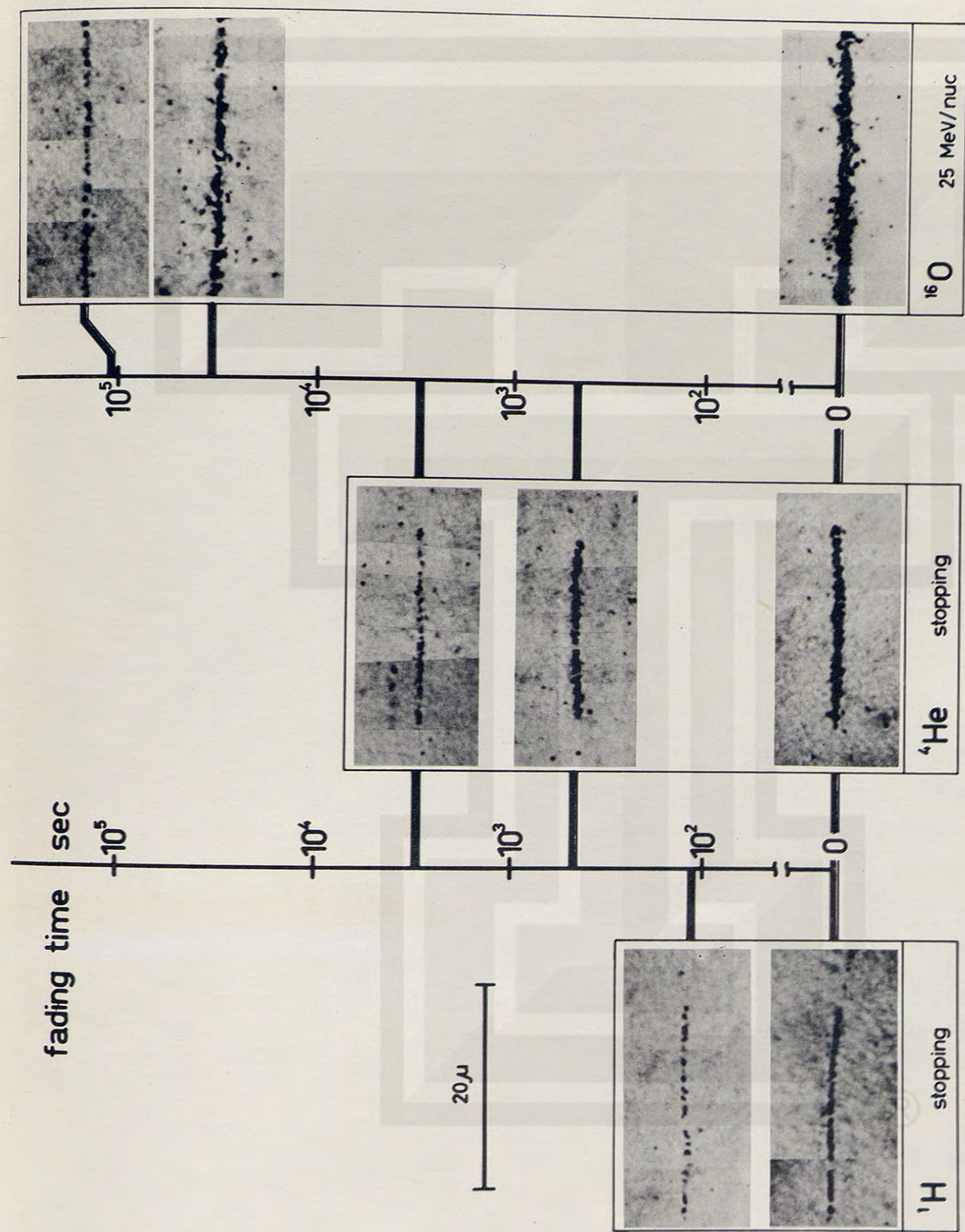


Fig 8 Particle discrimination by fading

Radiobiological and Dosimetric Applications of AgCl-Detectors

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Abstract

Two examples of applications of AgCl-detectors are presented.

1) Combination with biological objects

Spores of *Bacillus Subtilis* are glued with PVA on the surface of AgCl-Detectors. The spores are irradiated by ionizing particles. By a simple dry development the tracks of these particles are made visible in the detector with a spatial resolution better than 1 micron without removing the spores and without damaging them. As the spores have a size of merely 1 micron, their fixed position and the high spatial resolution of the AgCl-detectors is most important for the assignment of tracks and hit spores.

2) Neutron dosimetry

AgCl-detectors were irradiated by neutrons with doses of 3×10^6 to 3×10^9 neutrons/cm², the neutron energy being 1.2, 5.5 and 16.1 MeV. The reactions $\text{Cl}(n,\alpha)$, $\text{Cl}(n,p)$, $\text{Ag}(n,\alpha)$ and $\text{Ag}(n,p)$ within the crystal volume resulted in tracks of protons and of α -particles according to the different cross sections. Number and length of these tracks permit measurements of the neutron rate and of the maximum neutron energy. The influence of γ -radiation on the detector response was investigated. Accompanying γ -radiation does not influence AgCl-neutron-dosimetry at doses below 200 r.

As the formation of stable tracks in these detectors requires simultaneous illumination with yellow light, the record of incoming radiation can be limited to a chosen period of time or suppressed by switching the illumination on or off.

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1. Radiobiology

In order to study the effects of single ionizing particles on biological objects, these objects must be combined with physical detectors which localize the path of the particle against the object.

In the case of the European BIOSTACK experiment during the Apollo 16 mission, the investigators used 4 different objects: root pieces of VICIA FABA, eggs of ARTEMIA SALINA, seeds of ARABIDOPSIS THALIANA and spores of BACILLUS SUBTILIS. All of them were combined with nuclear emulsions and plastics as particle track detectors. For the development it was necessary to remove the objects from the nuclear emulsion; in the case of plastics the objects could remain upon the detectors, but the plastics could be etched from their backsides only. In the first three cases, where the single pieces have sizes not less than 100 . microns, there does not arise any problem.

The situation is different in the case of the spores, which have a diameter of 1 micron only. The spatial resolution of the detectors is not high enough to point out single events; the evaluation must be restricted to summary effects of the radiation.

We examined the combination of such spores with our AgCl-detector. The spores were glued with PVA in a thin layer of 1 or 2 microns on the surface of AgCl-detectors and afterwards were irradiated by ionizing particles. The particles penetrate the spores and produce latent tracks in the detector.

The detector is developed by ultraviolet light of quantum energy of 3 eV and with about 10^{18} photons/cm². The number of photons corresponds to the fluence of some seconds of normal sunlight; the quantum energy is not high enough to cause observable damage in organic material, which as a matter of fact begins at 5 eV approximately. The tracks are made visible in the detector without removing the spores, without damaging them and without shrinkage of the detector as in the case of nuclear emulsions. The tracks reach up to the surface of the detector directly beneath the spores.

After growing the spores in a nutritive solution, it is possible to assign non-surviving spores to the tracks in the detector

beneath with a spatial resolution better than 1 micron. In cases where the size of the objects is about 1 micron, their fixed position and the high resolution of the AgCl-detector is most essential.

2. Neutron Dosimetry

The lack of hydrogen in the AgCl-detectors permits to apply them for neutron dosimetry by means of the (n,p) and (n, α) reactions at the Ag and Cl-nuclei. AgCl consists of the four isotopes ^{35}Cl , ^{37}Cl and ^{107}Ag and ^{109}Ag , with different cross sections and Q-values. Table 1 shows the data of the isotopes involved, their cross sections at neutron energies of 14 MeV and their Q-values.

As the cross section of chlorine is much higher than that of silver, 86% of the particles originate from reactions of the chlorine.

Table 1 : Neutron-reactions with AgCl, cross sections at $E_n = 14$ MeV, and Q-values

Isotop (abundance)	Reaction	Product	Cross-section at $E_n = 14$ MeV	Q - value
Cl^{35} (75.5 %)	(n, α)	P^{32}	150 mbarns	+ 1.0 MeV
Cl^{37} (24.5 %)	(n, α)	P^{34}	50 mb	< 0.1 MeV
Ag^{107} (51.4 %)	(n, α)	Rh^{104}	3 mb	
Ag^{109} (48.6 %)	(n, α)	Rh^{106}	25 mb	+ 3.5 MeV
Cl^{35} (75.5 %)	(n,p)	S^{35}	130 mb	+ 0.7 MeV
Cl^{37} (24.5 %)	(n,p)	S^{37}	30 mb	- 3.6 MeV
Ag^{107} (51.4 %)	(n,p)	Pd^{107}	35 mb	
Ag^{109} (48.6 %)	(n,p)	Pd^{109}	14 mb	- 0.3 MeV

	$\sigma(n,\alpha)$	$\sigma(n,p)$	$\sigma(n,\alpha) + \sigma(n,p)$
Cl	125	105	230 mb
Ag	13	25	38 mb
AgCl	138	130	268 mb

Lit.: A.Chatterjee; Nucleonics 23,8,112
D.G.Gardner and Yu-Wen Yu; Nucl.Phys. 60,49

Fig 3 contains micrographs of α -particles and protons, which can easily be distinguished by their different track density.

Positive Q-values permit dosimetry also for slow neutrons. We have irradiated AgCl-detectors with neutron doses from $3 \cdot 10^6$ neutrons/cm² up to $3 \cdot 10^9$ neutrons/cm² at neutron energies of 5.5 and 16.1 MeV resp. The number of α -particles and protons and their ranges were measured within an AgCl-layer of about 100 microns thickness.

Fig 4 shows the cross-sections evaluated for the (n,p) and (n, α) reaction resp; which at 14 MeV are in rather good agreement with the predicted values of table 1. In Fig 5 and Fig 6 the integral energy distributions of protons and α -particles are plotted for the different neutron energies mentioned.

The admissible number of tracks per cm² lies between 10/cm² as minimum on account of the very low background, and about 10^6 /cm² for both, proton and α -tracks, with a range of neutron doses between

$$3 \cdot 10^5 \text{ neutrons/cm}^2 \text{ and } 3 \cdot 10^{10} \text{ neutrons/cm}^2$$

corresponding to 10^{-2} rem up to 10^3 rem.

The AgCl dosimeter seems therefore to be well adapted for human dosimetry - though it is not tissue-equivalent - up to doses which are higher by a factor of 100 than the maximum admissible dose.

The influence of a simultaneous dose of γ -rays which normally accompany neutrons begins to become evident at about 10^2 r.

Fig 7 and 8 elucidate the influence of a simultaneous or subsequent irradiation with 1,2 MeV γ -rays to undeveloped tracks of α -particles.

Tracks which are already developed are not influenced by γ -radiation.

As long as the detectors are kept in full darkness, the latent tracks of particles are fading; those of protons and α -particles disappear in the course of minutes or fractions of minutes. The detector remains free from background accumulated with time.

The fact that tracks are stabilized by illumination of the detector with yellow light during the passage of the particles,

permits to make a time assignment to particle tracks and to switch the detector on or off for a certain period of time. Illumination with a small bulb of 0.1 watt is sufficient to make of it an accumulating dosimeter.

Acknowledgement: This work has been supported by the German Federal Ministry for Education and Research (St. Sch 0504).

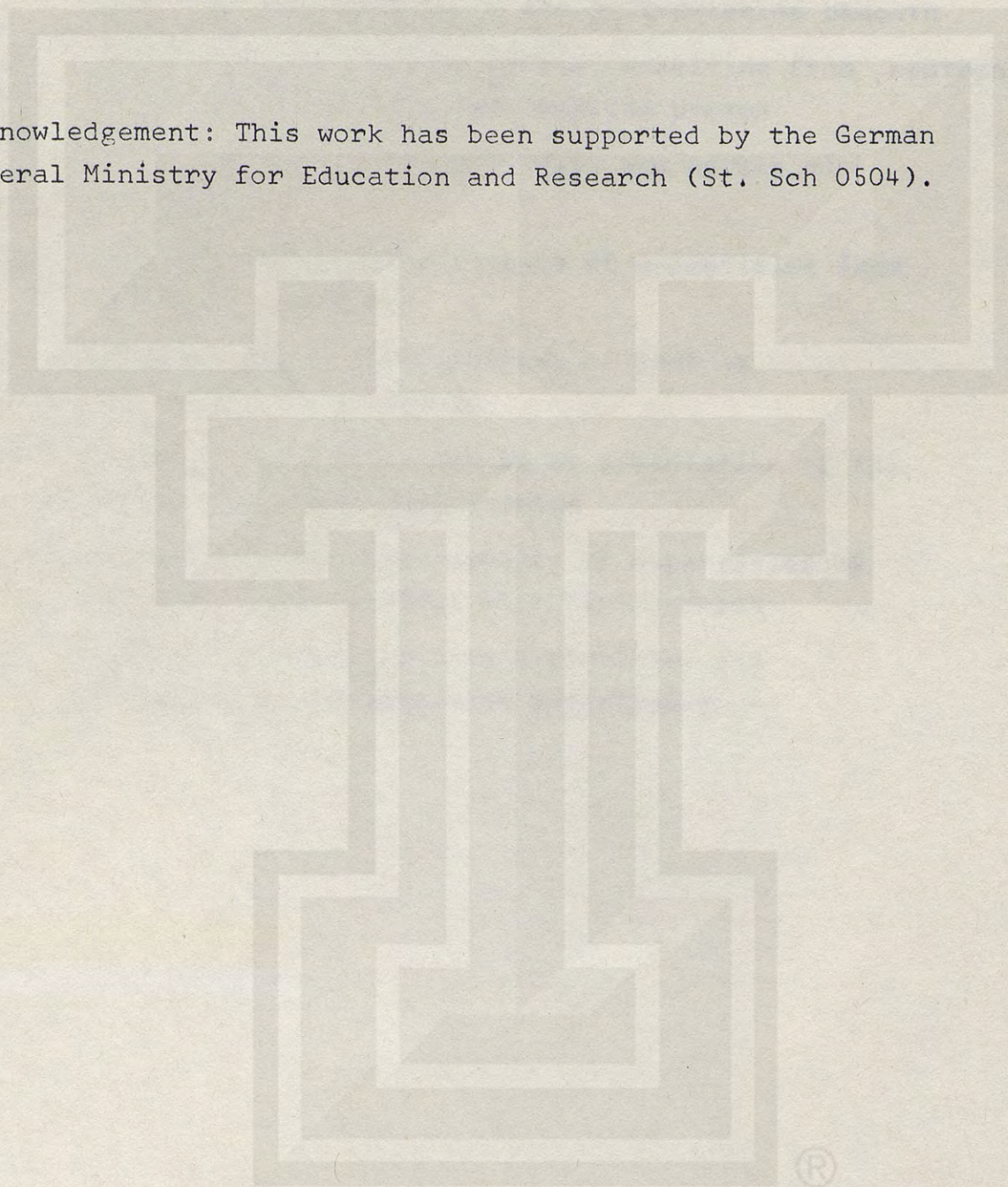


Figure captions

- Fig 1: Arrangement of spores of *Bacillus Subtilis* on the AgCl-detector
- Fig 2: Spores of *Bacillus Subtilis*, irradiated by α -particles, which are made visible in the AgCl-detector beneath
- Fig 3: α -particle and stopping proton, resulting from neutron-reactions; α -particle and crossing proton
- Fig 4: Cross sections of the $\text{AgCl}(n,p)$ and $\text{AgCl}(n,\alpha)$ reactions
- Fig 5: Integral energy distributions of α -particles from $\text{AgCl}(n,\alpha)$ reactions
- Fig 6: Integral energy distributions of protons from $\text{AgCl}(n,p)$ reactions
- Fig 7: Damage of α -particle tracks by irradiation of the latent image with high γ -doses
- Fig 8: Decrease of the track density of α -particles by irradiating the crystal with high γ -doses
- a) after irradiating with α -particles and
- b) before irradiating with α -particles

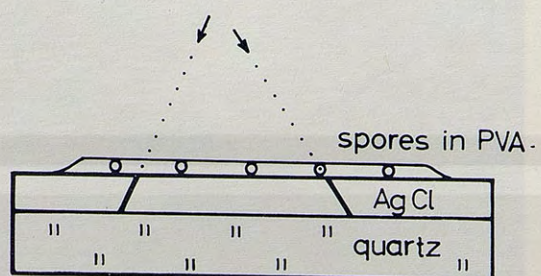
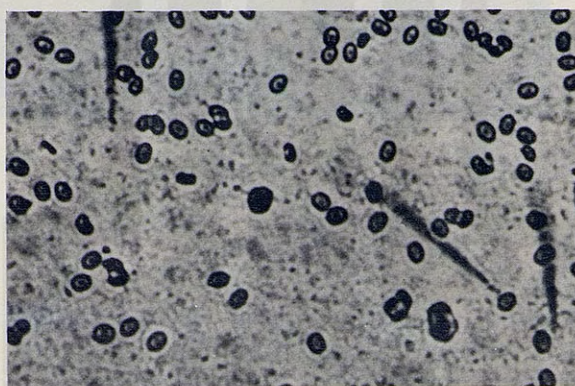


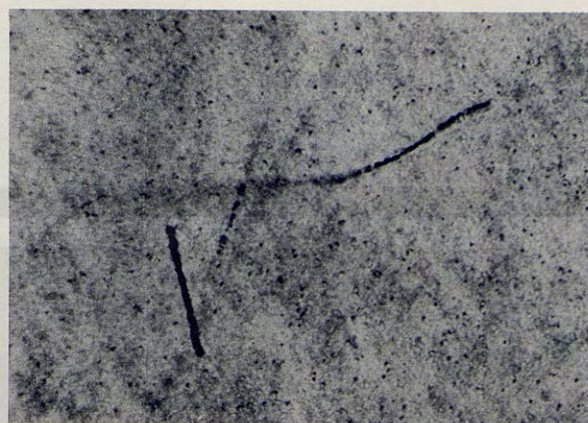
Fig 1

Arrangement of spores of
Bacillus Subtilis on the AgCl-detector

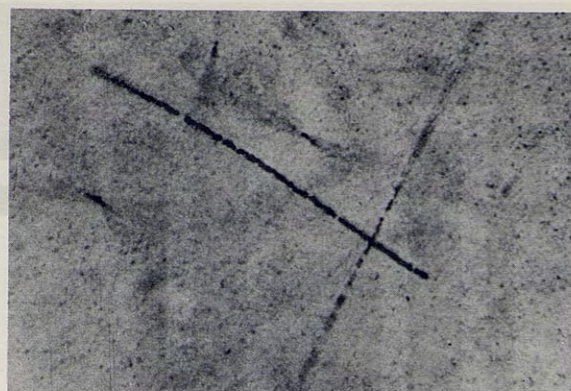


10 μ m

Fig 2 Spores of Bacillus Subtilis,
irradiated by α -particles, which are
made visible in the AgCl-detector
beneath



20 μm



20 μm

Fig 3 α -particle and stopping proton,
resulting from neutron-reactions;
 α -particle and crossing proton

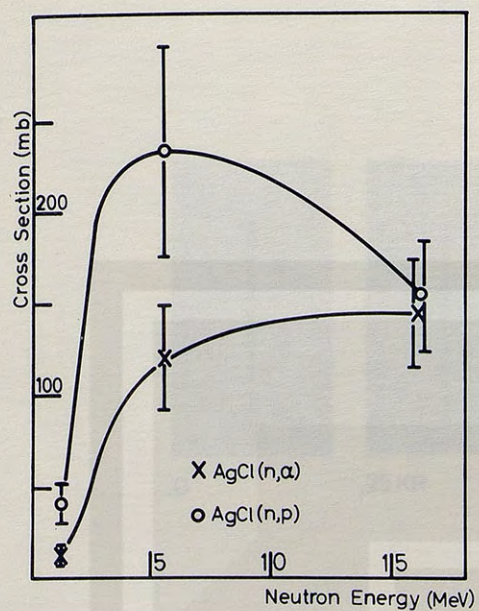


Fig 4
Cross-sections of the
 $\text{AgCl}(n,p)$ and $\text{AgCl}(n,\alpha)$
reactions

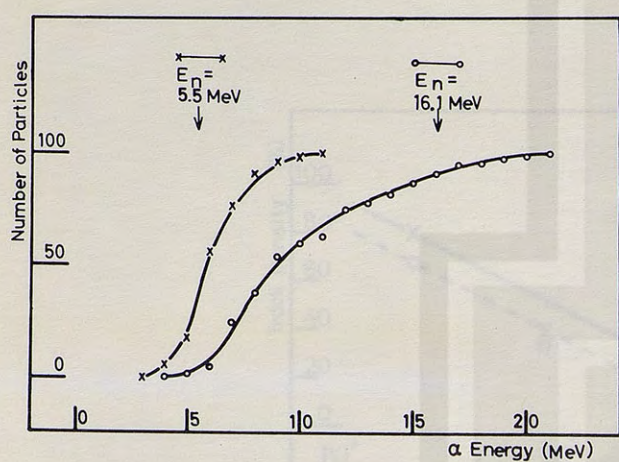


Fig 5
Integral energy distributions
of α -particles from
 $\text{AgCl}(n,\alpha)$ reactions

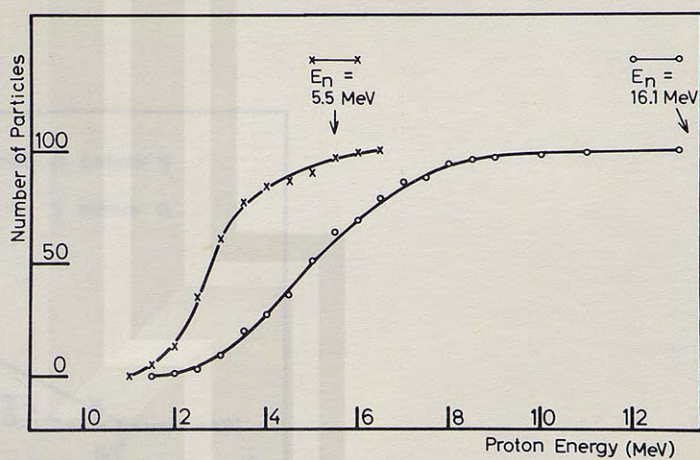


Fig 6
Integral energy distributions
of protons from
 $\text{AgCl}(n,p)$ reactions

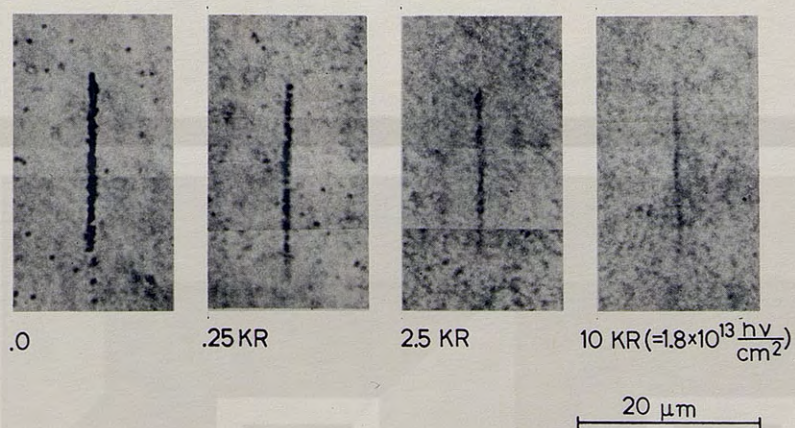


Fig 7 Damage of α -particle tracks by irradiation of the latent image with high γ -doses

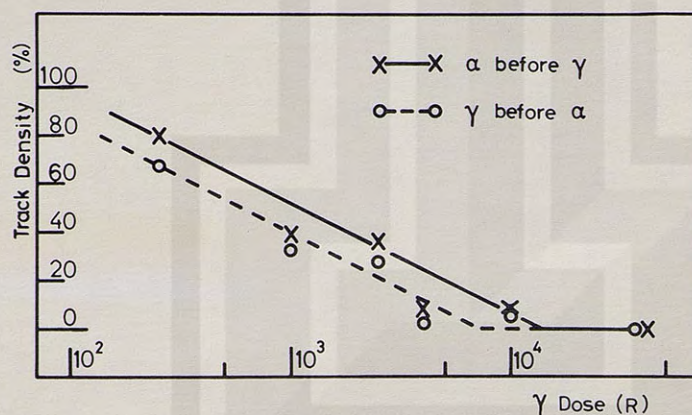


Fig 8 Decrease of the track density of α -particles by irradiating the crystal with high γ -doses

- a) after irradiating with α -particles and
- b) before irradiating with α -particles