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Proposal for the continuation of experiment PS 203 at LEAR

"Antiproton induced fission and fragmentation of nuclei"

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Abstract: In order to investigate the antiproton-nucleus interaction and the processes following the antiproton annihilation at the nucleus, we propose the following experiments:

A) Measurement of several fragments from fission and from multifragmentation in coincidence with particle spectra, especially neutrons and kaons.
B) Precise spectra of π, K, n, p, d and t with time-of-flight techniques.
C) Installation of the Berlin 4π neutron detector with a 4π Si detector placed inside for fragments and charged particles. This yields neutron multiplicity distributions and consequently distributions of thermal excitation energies and decay properties of hot nuclei at low spins.

D) Determination of the neutron halo in nuclei from residual nuclei after antiproton annihilation. Radioactive residual nuclei are identified from their γ-spectra. Investigation of the competition between fission and spallation in very hot nuclei with low spin using residual nuclei.
E) A complementary measurement to the neutron halo experiments will be the observation of antiprotonic x-rays with Ge detectors to obtain information on proton and neutron densities and on the antiproton-nucleus potential.
F) Distributions of residual nuclei after annihilation of fast antiprotons will shed light on very high excitations of nuclei (1 GeV).

All these experiments will be done with a series of target nuclides.

1. Introduction

Interaction and annihilation of antiprotons and nuclei have many interesting aspects. Antiprotonic x-ray transitions provide information on the antiproton-nucleus potential. We investigated previously especially the E2-resonance effect, an unusual coupling of atomic and nuclear states. The annihilation process deposits very localized an energy of about 2 GeV at the nuclear surface. In contrast to heavy ion reactions this takes place with low angular and linear momentum transfer and without compression. Therefore essential and complementary results are expected for the understanding of processes in nuclei with up to 1 GeV excitation energies. The particles created during annihilation, especially pions (on average 5) but also kaons, start an intranuclear cascade with particle emission, multifragmentation, fission or evaporation. These processes can be simulated with Monte Carlo calculations. Comparison of experimental results with calculations gives very detailed knowledge of the various reaction mechanisms and of the time scale of very hot nuclei with low spin. This information which includes also strangeness production cannot be obtained with other methods.

2. Results of PS 203

2.1. Antiproton induced fission (Munich)

A completely new apparatus had been constructed essentially consisting of two PIN-diode arrays (each 12x12 diodes of 1 cm^2) at opposite sides and distances of 60 cm from the target. This measurement provides for each event the energy, the time-of-flight and the folding angle of two coincident fragments. Many quantities can be deduced for each event such as fragment masses, total masses, total kinetic energies and momentum of the fissioning nucleus. From the correlation between total mass and total kinetic energy the ratio of the number of prescission nucleons to the total number of emitted nucleons is obtained as a function of the excitation energy. In contrast to heavy ion induced reactions with large angular momentum, the number of postscission nucleons is increasing with excitation energy indicating faster fission for higher excitation energies. Asymmetric fission for low excitation energies, symmetric fission for higher excitation energies and also scission before thermalisation was observed. These unexpected results are very important for the understanding of very hot nuclei with low spin and require further investigations. Monte Carlo calculations are being developed to reproduce the measurements.

A special measurement was performed to determine absolute probabilities of stopped antiproton induced fission. Values of (77±4) % for ^{238}U, (70±4) % for ^{232}Th, (3.1±0.2) % for ^{197}Au and (1.1±0.6) % for ^{165}Ho were obtained and compared with calculations.

2.2. Particle spectra from time-of flight techniques (Berlin)

In a test experiment spectra of π, K, n, p, d and t were obtained with several large scintillation detectors (NE 213, 12.5 cm diameter, 10 cm thickness) and time-of-flight measurements at 172 cm and 182 cm distance from the target. These very interesting first K spectra give information on the early stage after annihilation in nuclei. The neutron spectra of a U target consist of at least three components from the fast cascade, preequilibrium emission and evaporation, respectively.

2.3. Distribution of residual nuclei and the neutron halo (Warsaw)

Targets consisting of Cu, Au and Th were irradiated with antiprotons and the induced radioactivity was measured off-line with Ge detectors. The deduced distribution of residual nuclei gives information on the energy deposition in nuclei after antiproton annihilation. It is compared with results from relativistic ion reactions and with Monte Carlo calculations. Similarities and specific differences were observed.

Jastrzebski proposed recently to use the yield of residual nuclides with only one proton and with only one neutron missing from the target nuclide to determine the neutron density in the periphery of nuclei (neutron halo). With a certain probability the antiproton annihilates with a neutron or proton of the nuclear periphery without any additional nuclear reaction. In this case, from the target nucleus (Z_t, N_t) the residual nuclei (Z_t, N_t-1) and (Z_t-1, N_t) are produced and their ratio is a measure for the neutron halo. For ^{232}Th a halo factor (excess of neutrons in the periphery corrected for the $\bar{p}n$ and $\bar{p}p$ cross section ratio and Z_t/N_t) of 6.8±1.9 was obtained.

3. Proposal for improved and new experiments.

Project A) Fragments and particle spectra in coincidence (Munich).

The purpose of this experiment is twofold. One purpose is the direct determination and distinction of particles emitted before and after scission. This result gives reliable information on the time scale of the fission process with low angular momentum. This determination can be made if the particle spectra, especially neutron spectra, are measured as a function of the angle to the fission axis. The second purpose is the direct identification of multifragmentation, i.e. the coincident observation of three and more fragments.
The experimental arrangement has to make a compromise between good energy, mass and angular resolution, a large solid angle and affordable electronics. We shall start with six PIN-diode arrays (each 6x12 diodes of 1 cm^2) surrounding the thin target (about 1 mg/cm^2, area about 2 cm^2) at a distance of about 20 cm in a vacuum chamber (50 cm diameter, 50 cm height). The start signal for the time-of-flight measurements will be given by the antiproton telescope (thin scintillation detector). The antiprotons are moderated to stop in the target. The energy resolution for fragments is about 1 MeV and the mass resolution about 10-15 u. The solid angle is about 10 %. Outside the vacuum chamber between 5 and 10 liquid scintillation detectors (NE 213, 12.5 cm diameter, 10 cm thickness) will be placed at various angles around the target at distances between 1 and 2 m. Pulse shape discrimination, energy deposition and TOF will allow to determine energies and identify neutrons and charged particles. The PIN-diode arrays provide the fission axis or the multifragmentation event in coincidence. Particle spectra can be obtained for various total masses (related to total excitation energies) or total kinetic energies.

Experimental details:
Area at the beam: 4x4 m^2
Area for electronic equipment outside: 20 m^2
Targets: about 1 mg/cm^2, 2 cm^2 area, U, Th, Bi, Au, Ho, Ag.
$\bar{p}$-beam: 100 (200) MeV/c; (20-200)$\cdot 10^3$ $\bar{p}$/s; 1 h spills.
Beam time request: about 2 weeks per year
Data evaluation: at home.
All equipment will be brought from Munich and Berlin.

Project B) Time-of-flight spectra (Berlin)

Precise particle spectra provide much information on the annihilation process, the fast intranuclear cascade, preequilibrium processes, and evaporation. Test experiments showed that very good π, K, n, p, d and t spectra can be measured with large liquid scintillation detectors (NE 213, 12.5 cm diameter, 10 cm thickness, time resolution about 1 ns). Energies and particle discrimination are obtained by TOF, pulse height and pulse shape. Thick targets will be used to stop all antiprotons in the target (100 mg/cm^2 or more). Vacuum is not necessary. A thin scintillation detector for the incoming antiprotons provides the start signal. Six large detectors are placed at a distance of about 2 m from the target.

Experimental details:
Area at the beam: 4x4 m^2
Area for electronic equipment outside: 20 m^2
Targets: about 100 mg/cm^2, 2 cm^2 area; C, ^{40}Ca, ^{48}Ca, ^{63}Cu, ^{92}Mo, ^{144}Sm, ^{154}Sm, ^{165}Ho, ^{197}Au, ^{209}Bi and ^{238}U.
$\bar{p}$-beam: 200 (100) MeV/c; (20-200)$\cdot 10^3$ $\bar{p}$/s; 1 h spills
beam time request: about 1 week for 1993
Data evaluation: at home.
All equipment will be brought from Munich and Berlin.

Project C) 4π neutron and 4π fragment and particle detector (Berlin)

We propose to install the Berlin 4π neutron detector which measures event by event the total neutron multiplicity and in addition a 4π detector for charged particles positioned inside of the neutron detector. With this unique device we intend to measure (i) the thermal excitation energy distribution of antiproton induced reactions in heavy nuclei and (ii) the decay properties of hot nuclei at low spins: evaporation, multifragmentation and fission as function of excitation energy.

In heavy-ion induced reactions it is possible to heat nuclei to very high excitation energies and to study the decay properties of hot nuclei produced in this way. This was done in many recent investigations (1,2). However, in these reactions the nuclei are not only thermally heated but also collective, compression and in particular rotation degrees-of-freedom are excited which are of great importance for the decay properties of these nuclei (3). Thus it is of great interest to heat nuclei without exciting these collective and compression degrees-of-freedom and study their decay properties and compare it with various theoretical models (4).

There exist two possibilities to achieve this objective: (i) to heat nuclei with highly energetic protons (0.5-3 GeV) or (ii) by annihilation at rest or finite energies (100-1000 MeV) in heavy nuclei (5). In antiproton induced reactions the mean spin is only 15 to 20 $\hbar$ (6) compared to more than 80 $\hbar$ in heavy ion reactions. The method (i) is followed by experiment 243 at SATURNE by a HMI-GANIL-IPN-Orsay-LNS-ANU collaboration which will have its first data taking run in November 1992.

Though the proton and antiproton induced reactions do not excite compression and collective degrees of freedom in the initial stage of energy dissipation there are many pre-equilibrium particles emitted prior to the attainment of thermal equilibrium. This makes it mandatory to measure the thermal excitation energy of the decaying nuclei. This observable by itself is of great interest to test several INC models (6,7).

In order to measure both the thermal excitation energy as well as the decay properties of nuclei (evaporation, multifragmentation and fission) in antiproton induced reactions event by event we propose to install at LEAR the Berlin 4π neutron detector and the 4π Silicon multidetector in order to measure the decay properties of antiproton induced reactions on heavy nuclei of U, Bi, Au, and Ho.

The 4π neutron detector measures event by event the total neutron multiplicity with high efficiency for evaporativ neutrons and with considerable smaller efficiency for highly energetic neutrons. This property makes it possible to deduce the thermal excitation energy from the measured total neutron multiplicity. This has been demonstrated in many heavy ion induced reactions (1,2,8). At LEAR there is a complication which was of no concern for the heavy ion reactions. This is due to the large multiplicity (about 2.5) of charged pions in antiproton induced reactions (40 % of all emitted charged pions are stopped in the scintillator material of the Berlin neutron detector). If a negative pion is stopped in the scintillator it will be captured in a carbon nucleus and can thus produce additional neutrons. Whereas the decay of a stopped positive pion can also cause problems which might be, however, identified and rejected electronically. The n-background due to pion capture will be in the order of one or two neutrons compared to 20 to 30 neutrons from nuclei excited to 300 to 500 MeV.

The 4 π detector for fragments and charged particles consists of 160 Si-detectors with a thickness of 500 μm (9). The radius of the sphere is 10 cm. Fragments from fission and multifragmentation can be identified. Charged particles are distinguished by energy and time-of-flight and possibly also by pulse-shape discrimination (10). This will furthermore enable us to study the pre- and post-scission emission of charged particles as a function of excitation energy providing additional and important information on the dynamics of the fission process studied previously at LEAR by detecting fission fragment - fragment correlations (11) and pre- and post-scission neutron emission (12).

Due to the characteristic of the neutron 4π detector which has a dead time of about 50 microseconds the acceptable reaction rate is only 1.000 reactions/seconds. Depending on the fraction of captured antiprotons in the target and whether it will be possible to transfer the not captured antiprotons out of the neutron sphere the acceptable rate of antiproton will be 1.000 to 500.000 per second for low and high energy antiprotons, respectively. Detailed beam requirements can only be made after a test run at LEAR.

The above described experimental set-up con be available for experiments starting fall 1993 with stopped antiprotons.

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Experimental details:
Target thickness: ≈500 μgr cm^{-2}.
Space-requirements for the detctor at the target position 2.5 m x 2.5 m and 4 m high. For the high energy beam a beam tube of about 3-4 m to beam dump behind the detector will be necessary.
Present beam hight of the detector is 1.80 m, reduction to 1.66 m is possible.
Space for electronic 4-5 racks, 3-4 in the cave and 1 in the data taking room, plus space for computer (table top vaxstation) and 4-5 terminals.
Data taking: multiparameter CAMAC system with a vax station.
Beam requirements: 1) 100 (200) MeV/c with 1000 $\overline{p}$/s
2) 600-1600 MeV/c with 2-5 x 10^5 $\overline{p}$/s
beam-time: 1) 1993 1 week; 2) 1994 2-3 weeks / year

Project D) Neutron halo and residual nuclei (Warsaw)

The possibility of an increased neutron to proton density on nuclear surface has attracted a considerable theoretical and experimental interest for decades. The huge "neutron halo" observed in light nuclei close to the neutron drip line was certainly one of the most spectacular discoveries in nuclear structure of the last years. More subtle effects are expected to show up in heavy nuclei close to the beta stability line. After first, rather qualitative arguments (1) advocating a neutron excess on the surface of heavy nuclei, Hartree-Fock calculations (2) of matter and charge distributions have indicated, that e. g. in ^{208}Pb the rms radius is 4 % larger for neutrons than for protons. However, at large nuclear distances, such a small difference in the rms radii, if present, would lead to much more pronounced differences in neutron and proton densities due to the Coulomb wall for protons. The detection of these differences using the nuclear absorption of strongly interacting particles was reported by Davis et al. (3,4) who studied K^- meson interaction with nuclei in nuclear emulsions. The differences in the characteristics of hyperonic and mesonic reaction products after the kaon annihilation on proton and neutron were used as a signature of the neutron excess effect. The data of heavy emulsion nuclei were normalized to those of light nuclei, for which similar neutron and proton density distributions were assumed. It was found (5) that in heavy nuclei the annihilation of a K^- on a neutron is 4.25 ± 1.00 times more probable than in light nuclei.

Besides kaons, antiprotons were also used for the search of a neutron halo in heavy nuclei. In 1973 Bugg et al. (6) presented the results of their experiment in which the Brookhaven National Laboratory 30 inches hydrogen bubble chamber was exposed to a beam of slow antiprotons. In this chamber the mesonic prongs from carbon, titanium, tantalum and lead targets were investigated. The physics of the experiment was derived from the fact that $\bar{p}p$ and $\bar{p}n$ annihilations produce events with a net charge of 0 and -1, respectively, and from the assumption that the nuclear capture and annihilation process occurs in the nuclear periphery. After numerous experimental corrections the net result was expressed as "halo factor", f, (in which corrections for the differences in the $\bar{p}n$ and $\bar{p}p$ interaction potentials and trivial N/Z differences were taken into account). This factor showed an increasing tendency as a function of the target mass and for Pb target was equal to 2.3±0.5 to be compared with 1.0 value for C target. The experiment indicated the enhancement of neutron events compared with the expectation for identical neutron and proton distributions.

It did not, however, give direct information on the magnitude and distribution of the neutron halo effect in heavy nuclei. To answer these questions a theoretical model should be employed. Such a model was proposed by Leon and Seki (7). These authors have shown that the answer strongly depends on the average value of the complex $\bar{p}p$ and $\bar{p}n$ interaction potentials, which are not well known.

In what follows we propose a new method for the detection of the neutron halo in heavy nuclei, using antiproton annihilation. The method uses the identification of nuclear rather than mesonic products of antiproton - nucleus interaction. As yet, the necessary corrections we foresee are small and probably easy to calculate.

After the annihilation of a stopped antiproton on the nuclear surface a fraction of created particles (mainly pions) enters the nuclear volume and initiates an intranuclear cascade. However in some cases only the annihilated proton or neutron is missing and no further interaction takes place. Two reaction residues of interest for the method proposed are the (Z_t,N_t-1) and (Z_t-1,N_t) nuclei, where Z_t and N_t are target proton and neutron numbers, respectively. The determination of their relative yields should therefore be a sensitive method for the detection of differences between neutron and proton concentration in the nuclear periphery. Contrary to Bugg's experiment, which was sensitive to the total neutron to proton absorption ratio the proposed method is sensitive to the absorption at large distances. Therefore it should be, in principle, able to detect even smaller effects of the neutron halo in heavy nuclei. The obvious limitation of the method is that it can only be used for targets for which both annihilation products one mass unit lighter than the target are radioactive. A first successful experiment was performed with ^{232}Th (see above). The resulting halo factor of 6.8 is in very good agreement with very recent calculations by S. Wycech indicating that the assumed neutron density in the far periphery and the assumed p-nucleon interaction was correct.

However, this agreement is not trivial and the neutron halo has to be tested for a series of isotopes with various neutron excesses. We propose the following targets for these investigations: ^{58}Ni, ^{96}Ru, ^{96}Zr, ^{144}Sm, ^{147}Sm, ^{149}Sm, ^{152}Sm, ^{154}Sm, Te, YB, U, Au, Sc, Eu. Each target has to be irradiated with about 10^9 $\bar{p}$ in short spills (5-15 min). The measurement of the γ-spectra takes place off-line.

Another very interesting and open question which can be studied by measuring γ-spectra of targets irradiated with antiprotons is the competition between fission and spallation for highly excited nuclei. Careful evaluation of such measurements can yield the ratio of fission to spallation as a function of the excitation energy up to several hundred MeV. The targets can be placed between catcher foils to distinguish fission fragments from spallation residues in order to enhance the effect. Electronic x-ray spectra of the residual nuclides give clear indications of the produced elements. These investigations started with Au and Th targets. We like to continue with U, Bi, Ta and other targets.

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Experimental details:

Experimental area at the beam: 1 m^2

Targets: about 100 mg/cm^2, area about 2 cm^2

Simple $\bar{p}$-telescope in front of the target to count $\bar{p}$'s.

$\bar{p}$ Beam: 200 MeV/c; several spills per target, each spill for 5-15 min a total of $4 \cdot 10^9$ $\bar{p}$.
Measurement of γ-spectra: Short half-lives at CERN with Ge-detectors, long half-lives in Warsaw
Beam request: 10 days per year, 3-5 spills per day.

Project E) Antiprotonic x-rays (Warsaw)

Measurements of the lowest observable antiprotonic x-ray transitions yield information on the antiproton-nucleus potential and on proton and neutron densities in the nuclear periphery. Therefore, these experiments are complementary to the neutron halo experiments described in project D. For selected targets which are also studied in project D we would like to measure antiprotonic x-rays. Detailed theoretical interpretations of the neutron halo experiments require this information. We intend to place several Ge detectors close to the target.

Experimental details:
Experimental area: 3x3 m^2
Targets: ca. 100 mg/cm^2, area 2 m^2
$\bar{p}$-telescope, $\bar{p}$-moderator, several Ge detectors
$\bar{p}$-beam 200 MeV/c, 1 h spills, $(10\text{-}100) \cdot 10^3$ $\bar{p}$/s
beam request: about 5 days per year.

Project F) Nuclear excitation from energetic antiproton annihilation (Warsaw)

The annihilation of antiprotons with energies of 0.5 to 2 GeV takes place more inside the nucleus and the resulting pions move more in the direction of the nucleus. Therefore higher thermal excitations of the nucleus are expected without increasing the angular momentum and without compression. This very interesting effect has to be carefully investigated and compared with intranuclear cascade calculations. We plan to irradiate targets with fast antiprotons and measure off-line the γ-spectra in order to determine the distribution of residual nuclei. This distribution is expected to be shifted to lighter residues compared to stopped antiproton annihilation due to higher excitations. These experiments require only a parasitic beam behind another experiment, e.g. behind the Crystal Barrel. Preliminary discussions took already place.

Experimental details:

Experimental area: parasitic position behind another experiment, ca. 0.5x0.5 m^2

$\bar{p}$-beam: 0.5-2 GeV; 5 10^5 $\bar{p}$/s; 1 h spills, several days per target.

Targets: U, Th, Bi, Au etc.; area 2 cm^2, thickness: 1 g/cm^2.

Measurement of γ-spectra: short half-lives at CERN, long half-lives in Warsaw

Beam request: Several weeks per year, parasitic mode.

Beam-Time Request 1993 - 1995
for PS 203

Project	Momentum (MeV/c)	Intensity $\bar{p}$/s	1993 days	1994 days	1995 days
A fission and multifragmentation (Munich)	100(200)	(20-200)·10^3	10	5	-
B TOF spectra (Berlin)	200(100)	(20-200)·10^3	5	-	-
C 4π detectors (Berlin)	100(200)	1000	7	14	-
	500-2000	10^5	-	10	14
D n halo (Warsaw)	200	4 10^9/spill 3-5 spills/day	10	10	-
E $\bar{p}$ x-rays (Warsaw)	200	(10-100)·10^3	3	5	5
F fast $\bar{p}$ (Warsaw)	500-2000	10^5 parasitic	14	21	21

Till v. Egidy
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Supplement to the Proposal for the continuation of
Experiment PS 203 at LEAR
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Ph.D. and Diplome theses from the Physics Department of the Technical University Munich at LEAR / CERN 1983 - 1992

1986	W. Kanert
Ph.D.	Antiproton-nucleus interaction and the E2 nuclear resonance effect in Mo and Nd isotopes
1987	E. Moser
Ph.D.	Investigation of the distribution of residual nuclei in ^{95}Mo, ^{98}Mo and ^{165}Ho after antiproton annihilation
1987	P. Hofmann
Diplome	Spectra of charges particles from antiproton annihilation
1987	W. Markiel
Diplome	Particle spectra after antiproton annihilation
1991	Th. Haninger
Diplome	Fission fragment measurements with PIN diode arrays
1992	M.S. Lotfranaei
Diplome	Angular distribution of fission fragments
1992	Y.S. Kim
Ph.D.	Antiproton induced fission of ^{238}U
1992	W. Schmid
Diplome	Absolute probabilities of fission induced by stopped antiprotons
1992	P. Hofmann
Ph.D.	Antiproton induced fission of ^{232}Th and ^{209}Bi

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Antiprotonic molybdenum: resonant coupling of atomic and nuclear states and the impact of annihilation on the nucleus (PS 186)

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Antiprotonic atom spectroscopy at LEAR (PS 176)

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Nucl. Phys. A, submitted
Production of light particles after antiproton–nucleus annihilation and their interpretation with statistical models

28) J. Jastrzebski, W. Kurcewicz, P. Lubinski, A. Grabowska, A. Stolarz,
H. Daniel, T. von Egidy, F.J. Hartmann, P. Hofmann, Y.S. Kim,
A.S. Botvina, Ye. S. Golubeva, A.S. Iljinov, G. Riepe, H.S. Plendl
Phys. Rev. C, submitted
Interaction of stopped antiprotons with copper

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Physics Letters B, submitted
Signature of a neutron halo in ^{232}Th from antiproton absorption

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F.J. Hartmann, M.S. Lotfranaei, H. Plendl
Nuclear Instruments and Methods A, to be submitted
A double–arm fission fragment spectrometer with pin diode arrays

31) T. Haninger, M.S. Lotfranaei, T. von Egidy, F.J. Hartmann, P. Hofmann,
Y.S. Kim, H. Märten, A. Ruben
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Folding angle and excitation energy of fragments from ^{235}U(n,f)
and ^{252}Cf(sf) reactions

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Nucl. Phys., to be submitted
Antiprotonic atoms of heavy nuclei

Additional publications on antiproton induced fission are in preparation.

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München

2.1.9 Dynamics of nucleon evaporation in antiproton induced fission of ^{238}U and ^{232}Th

Y.S. Kim, P. Hofmann, H. Daniel, T. von Egidy, F.J. Hartmann

The dynamical evolution of highly excited nuclei is one of the most challenging topics in modern nuclear physics. Many recent experiments with heavy ions report the discovery of the dissipative effects in nuclear fission [1]. Hilscher et al. have compiled data of neutron counting experiments and concluded that fission is a relatively slow process and that the fissioning nucleus is almost cold at the scission point [2].

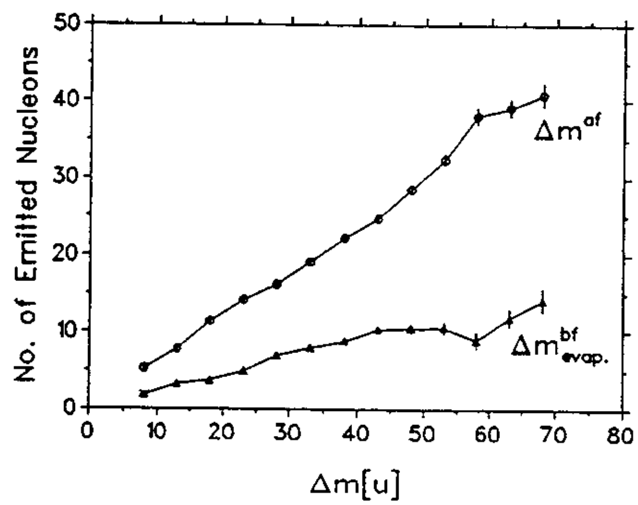

Fig.1: Pre- ($\Delta m^{\mathrm{bf}}_{\mathrm{evap}}$) and postscission ($\Delta m^{\mathrm{af}}$) evaporation nucleon multiplicities as functions of the total mass loss of two coincident fission fragments from antiproton induced fission of ^{238}U. (The scaling of the mass loss to the thermal excitation energy (MeV) is given by excitation energy $\approx 10\times$ mass loss.) The lines are only for guiding the eye.

Experimentally, the dissipative effect in the fission process can be best demonstrated by measuring the nucleons evaporated before and after scission. If the effect is large enough, it should manifest itself in an enhanced number of prescission evaporation nucleons in contrast to statistical model predictions. The time scale of fission can be extracted by establishing the correlation between time and the prescission neutron multiplicity by statistical calculations [3]. The determination of pre- and postscission neutron multiplicities has been performed most frequently by the direct neutron counting method where the neutron spectra are taken at several angles with respect to the fission axis and by unfolding the spectra with various assumed neutron specta. Thus the analysis of the data is largely dependent on the assumptions of the shapes of the source spectra and the complex iteration procedure.

We have developed a new method to obtain the number of pre- and postscission evaporation nucleons exploiting the correlation of the Total Kinetic Energy (TKE) and total mass of two coincident fragments based on the fact that prescission evaporation and postscission evaporation have different consequences to the TKE [4, 5], and applied it to the case of antiproton induced fission of ^{238}U and ^{232}Th. Figs. 1 and 2 show the number of prescission evaporation nucleons ($\Delta m^{\mathrm{bf}}_{\mathrm{evap}}$) and the number of postscission nucleons (Δm^{af}) as functions of mass loss (Δm), thus excitation energy [4], for these nuclei. It is clearly seen that Δm^{af} increases linearly with increasing excitation energy whereas $\Delta m^{\mathrm{bf}}_{\mathrm{evap}}$ has the trend to saturate with excitation energies greater than about 400 MeV ($\Delta m \approx 40$) in both cases. The absolute number of the prescission evaporation nucleons is certainly larger than the prediction of the statistical model (about two nucleons almost independent of the excitation energy for those nuclei) for high excitation energy, which qualitatively proves the role of the dissipative effect. On the other hand our results show a remarkable difference compared with those of heavy ion experiments where much larger angular momentum is involved (Fig. 3) [3]. Hinde et al. have interpreted Fig. 3 as a clear evidence that the fission fragments are rather cold at scission almost independent of the initial excitation energy. This argument is, however, not supported by our result. Our results indicate that the fragments are still very hot at the scission point with their excitation energies linearly proportional to the initial excitation energy. Our result is supported by the previous measurement of protons after the antiproton annihilation on ^{238}U [6], where about 17% of the fragments are measured to evaporate a proton. If the fission fragments are cold, they can hardly evaporate protons.

It is a puzzling question why antiproton induced fission yields a smaller number of prescission evaporation nucleons than the heavy ion induced fission, because one would expect normally a slower fission time in the case of antiproton induced fission where a smaller angular momentum is involved. Thus our results suggest very interesting physics involving the angular momentum dependence of the nuclear viscosity and the level densities.

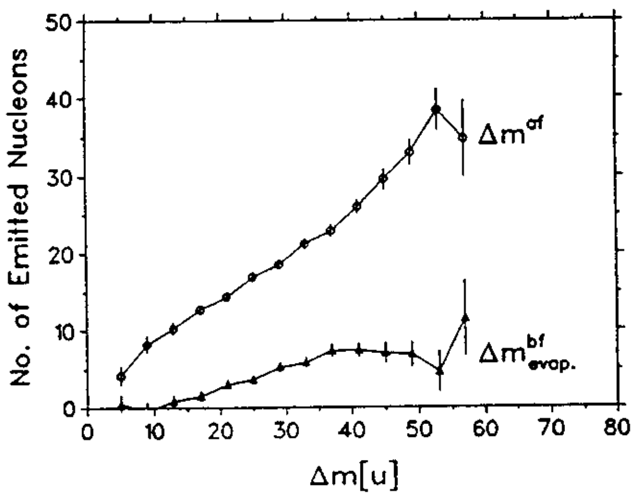

Fig.2: Pre- (Δm^{bf}_{evap}) and postscission (Δm^{af}) evaporation nucleon multiplicities as functions of the total mass loss of two coincident fission fragments from antiproton induced fission of ^{232}Th. The lines are only for guiding the eye.

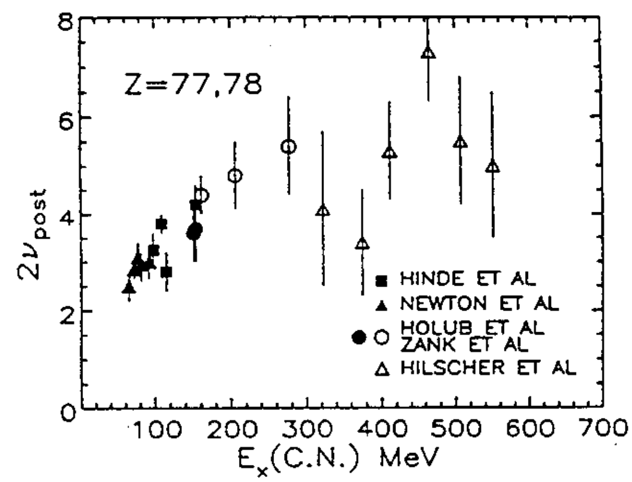

Fig.3: Postscission neutron multiplicities ($2\nu_{post}$) for Z = 77,78 compound nuclei formed in heavy ion reactions as a function of excitation energy. The picture is taken from ref. [3].

[1] J.O. Newton, Sov. J. Part. Nucl. **21** (1990) 349
[2] D. Hilscher et al., Phys. Rev. Lett. **62** (1989) 1099
[3] D.J. Hinde, D. Hilscher and H. Rossner, Nucl. Phys. **A502** (1989) 497c
[4] Y.S. Kim, PhD thesis, TU München, 1992
[5] P. Hofmann, PhD thesis, TU München, 1992
[6] W. Markiel et al., Nucl. Phys. **A485** (1988) 445

2.1.10 Production of light particles after antiproton-nucleus annihilation and their interpretation with statistical models

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Energy spectra of protons, deuterons and tritons from stopped-antiproton annihilation in targets of Li, Si, Ca, Ni, Ge, Mo, Ho, Yb and Th have been measured with a Ge detector telescope at LEAR/CERN. The shapes and the yields of these spectra were analysed and compared with statistical calculations. Previous measurements of p, d, t, ^{3}He and ^{4}He spectra following antiproton annihilation in targets of C, Ca, Cu, Mo and U [1, 2] are included in the discussion. The theoretical analysis of the data was carried out with the statistical approach which comprises the multipion-nucleus interaction described by the intranuclear cascade model including the coalescence mechanism for complex particle production, the preequilibrium emission of complex particles with the exciton model, multifragmentation and evaporation. The comparison of experimental and calculated particle spectra identifies the principal mechanisms of particle production. As an example fig. 1 shows the experimental p and ^{3}He spectra from a ^{98}Mo target together with theoretical spectra calculated for various reaction contributions.

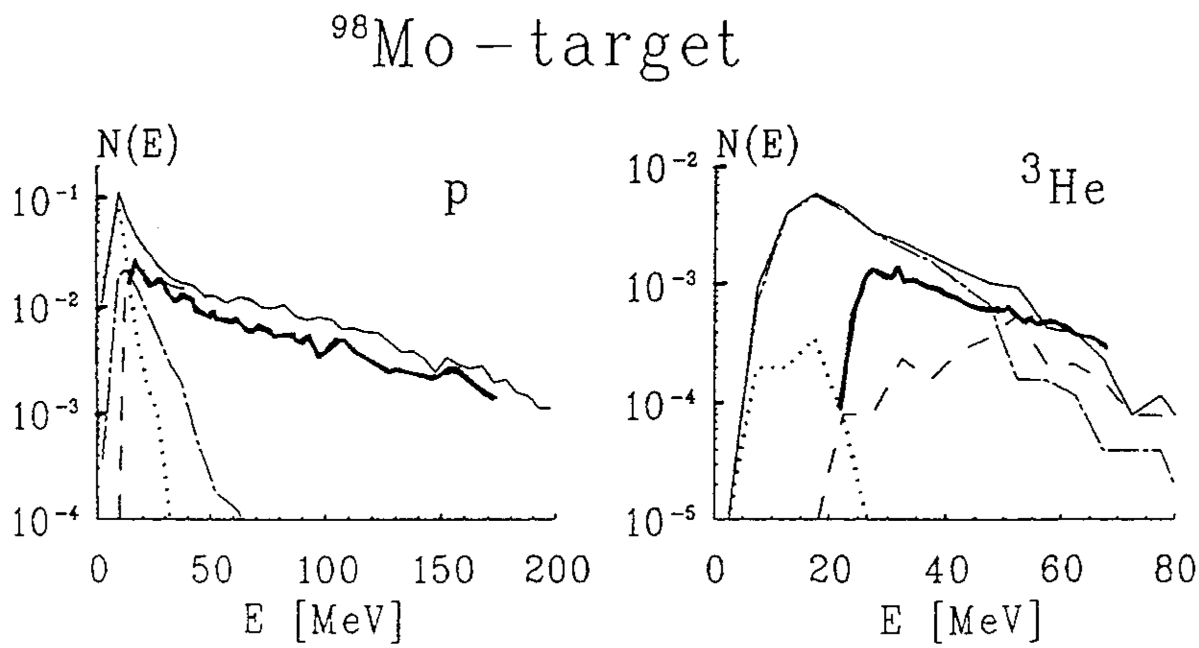

Fig.1: Energy spectra of p and ^{3}He after $\bar{p}$-annihilation on ^{98}Mo (number of particles per MeV and stopped $\bar{p}$). Bold curves present experimental spectra, the other curves are calculated. The dashed curve is the cascade and coalescence contribution. The dot-dashed curve gives the preequilibrium emission, and the dotted curve the evaporation. The thin solid curve includes all contributions.

[1] W. Markiel et al., Nucl. Phys. **A485** (1988) 445
[2] P. Hofmann et al., Nucl. Phys. **A512** (1990) 669

2.1.11 Neutron emission induced by antiproton annihilation at rest on uranium nuclei

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F.J. Hartmann, P. Hofmann, Y.S. Kim, M.S. Lotfranaei, W. Schmid
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The dynamics of the fission process in heavy-ion induced fission has been studied extensively in recent years by measuring the multiplicity of neutrons which evaporate before and after scission. These investigations resulted in the finding that the fission time scale is rather long ($(1\text{-}5)\times10^{-20}$ s) and consequently the temperature at scission is low [1] (1.5 to 2.5 MeV). Since the spin in heavy-ion induced fission is very large ($\sim$70 to 100 $\hbar$) it is interesting and necessary to investigate the dynamics of the fission process at low spin by other methods. According to nuclear cascade calculations [2] the mean spin in antiproton induced fission is about 15 $\hbar$. Kim et al. [3] approached this subject by measuring the total kinetic energy and mass of the fission fragments. From these observables they deduced a relatively small number of pre-scission evaporation nucleons at high initial excitation energies. In order to obtain an independent information on the pre-scission time scale we intend to measure the pre- and post-scission neutron multiplicities in antiproton induced fission. To this purpose we started studying the antiproton induced neutron emission at LEAR/CERN.

A beam of (2 to 5)$\times10^4$ antiprotons/s with an energy of 21 MeV (200 MeV/c) was slowed down in Mylar and Kapton foils and a thin scintillator and stopped in the center of the U target. The scintillator signal was used as a start for the time-of-flight measurements with two NE213 neutron detectors (12.5 cm diameter and 10 cm thick) which were positioned 182. and 172. cm from the target at 0° and 90° with respect to the direction of the $\bar{p}$ beam, respectively. 2 cm in front of each neutron detector a thin (3 mm) plastic scintillator (paddle) was positioned in order to identify charged particles. The time resolution as taken from the gamma peak was 1.2 ns.

With this setup we measured the time-of-flight spectra of n, p, d, t, π^{+-} and K^{+-}. The pulse shape signals of the NE213 scintillators were exploited in order to identify particles with low and high ionisation density, which is mandatory for the identification of the various particles. The time-of-flight spectra of neutrons and protons were converted into energy spectra and are shown in Fig.1.

A preliminary analysis of these spectra has indicated that about 14 neutrons are evaporated per $\bar{p}$-capture on average in a thick U target whereas about 3.5 and 1.0 highly energetic neutrons and protons, respectively, are emitted prior to the attainment of thermal equilibrium. The proton multiplicity is consistent with previous charged particle measurements by Hofmann et al. [4]. The neutron multiplicity of highly energetic neutrons agrees with an earlier measurement of neutrons by Angelopoulos et al. [5] who quoted 3.3 neutrons, whereas their value of low energetic evaporation neutrons is only 2.5 which is much smaller than our value. Our value for the charged pion multiplicity is approximately 2.5 per antiproton capture which also agrees reasonably well with previous experimental and theoretical values [2].

[1] D. Hilscher et al., Phys. Rev. Lett. **62** (1989) 1099

[2] A.S. Iljinov, V.I. Nazaruk and S.E. Chigrinov, Nucl. Phys. **A382** (1982) 378

[3] Y.S. Kim, PhD thesis, TU München, 1992; P. Hofmann, PhD thesis, TU München, 1992; Y.S. Kim et al., Jahresbericht 1991, p. 18

[4] P. Hofmann et al., Nucl. Phys. **A512** (1990) 669

[5] A. Angelopoulos et al., Phys. Lett. **B205** (1988) 590

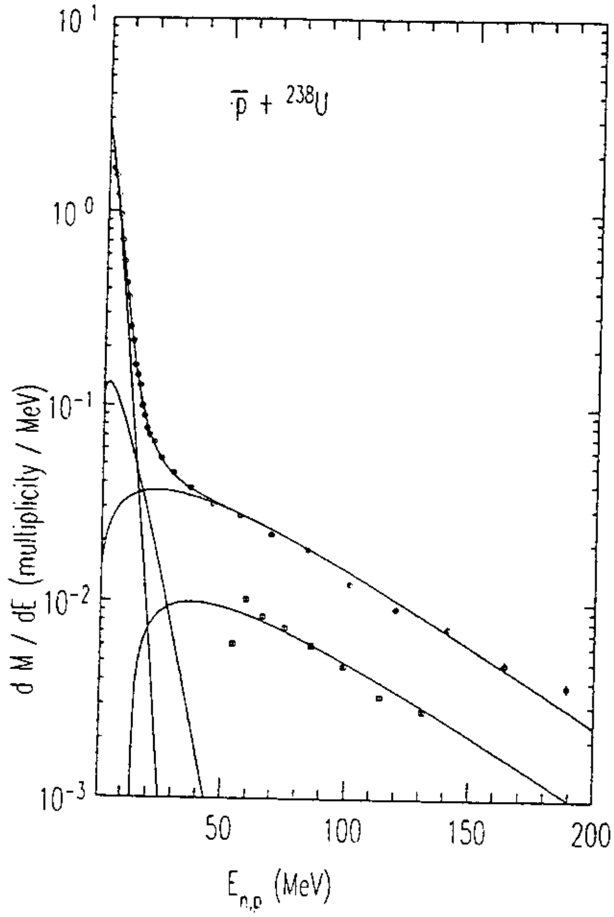

Fig.1: Experimental energy spectra of neutrons (upper points) and protons (lower points) induced by $\bar{p}$ capture in a thick U target.The fitted spectral shape is assumed to be given by

$$\frac{dM}{dE} = \sum_{i=1}^{k} \frac{2M_i}{\pi^{1/2} E_{0i}^{3/2}} \sqrt{E_n} exp(-E_n/E_{0i}),$$

where k is the number of sources: $k = 3$ for neutrons and $k = 1$ for protons. For protons E_n was replaced by $(E_n - B_c)$ where B_c is the Coulumb barrier of a proton in U. M_i and E_{0i} are fit parameters.

2.1.12 Absolute fission probabilities by stopped antiprotons

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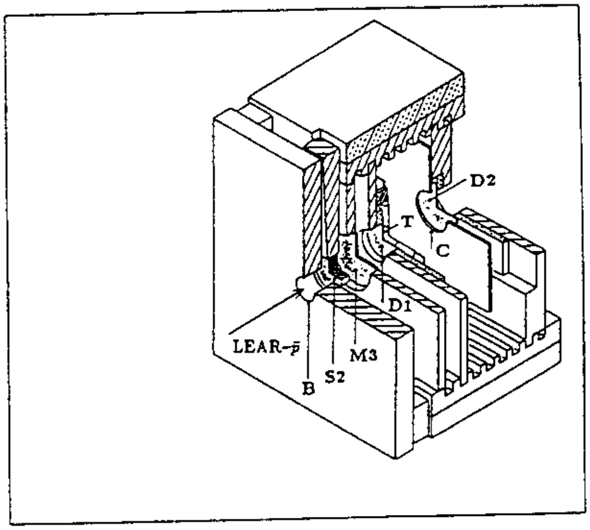
Absolute fission probabilities of ^{238}U, ^{232}Th, ^{209}Bi, ^{197}Au, ^{165}Ho, ^{nat}Ag and ^{nat}Cu after the annihilation of stopped antiprotons were measured at LEAR/CERN. The experimental setup is shown in Fig. 1. The antiprotons with 200 MeV/c were monitored by a scintillation counter and slowed down by a moderator. They passed through a PIN diode and stopped in the targets. The targets were sandwiched between two PIN diodes and the fission events were identified by simultaneous signals in both diodes. The number of antiprotons stopped in the targets was determined by γ activation measurements [1]. The feasibility of the experimental concept was tested by measuring the ^{238}U(p,f) reaction at the Tandem accelerator of University and Technical University of Munich. By keeping a low bias voltage at the diodes, big signals were obtained for fission fragments while noise from the passing-through protons was suppressed.

The results are shown in Fig.2 together with results of intranuclear cascade calculations (curves)[2]. Our results show a reasonable agreement with the calculation. Since our setup cannot distinguish fission fragments from multifragmentation fragments, the probability for ^{165}Ho should be understood as the probability of the both processes. Our results are very similar to the case of 1 GeV proton induced fission [3] implying that the involved excitation energies and the angular momenta are similar. ^{nat}Ag and ^{nat}Cu did not show a significant amount of fission.



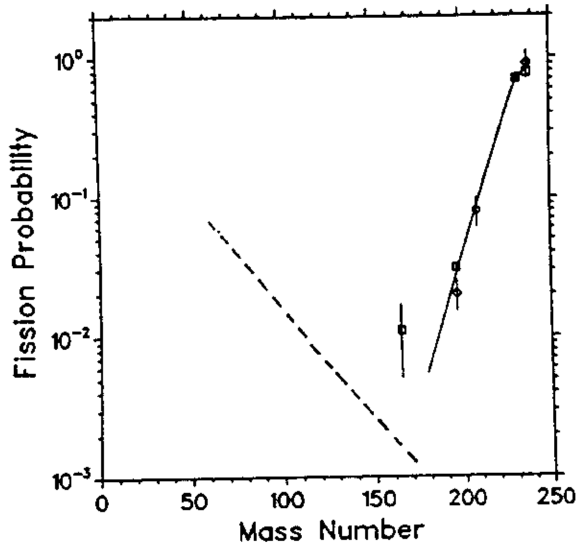


Fig.1: Experimental setup. S2: Scintillation counter; M3: Moderator; D1,D2: PIN Diodes; T: Target; B,C: Collimators.

Fig.2: Fission probabilities by stopped antiprotons. Rectangles: this measurement; circles: measurements of ref. [4]; curve: calculation for fission (full) and multifragmentation (dashed).

[1] W. Schmid, Diploma thesis, TU München, 1992
[2] A.S. Botvina and A.S. Iljinov, private communication
[3] L.N. Andronenko et al., Sov. J. Part. Nucl. **18** (1987) 289
[4] Ye.S. Golubeva, A.S. Iljinov and M.V. Mebel, Nuovo Cimento **A103** (1990) 781

2.1.13 Comparison of residual nuclei from relativistic ion and antiproton reactions with nuclei

T. von Egidy, H.H. Schmidt

The annihilation of antiprotons deposits nearly 2 GeV very localized at the nuclear surface. Produced fast pions start an intranuclear cascade and consequent particle evaporation. In contrast to relativistic ion reactions with nuclei the angular and linear momentum transfer and the compression are small. The comparison of the distributions of residual nuclei after stopped antiproton annihilation and after relativistic ion reactions can shed light on the differences of these two reaction processes. Sümmerer et al. [1] proposed recently an universal empirical formula for the distribution of residual nuclei after relativistic ion reactions which depends only on the target mass A_t and charge Z_t and not on the kind of projectile or on its energy. We compared this formula with recent distributions measured after stopped antiproton annihilation in targets of Cu, Mo, Ba and Ho [2, 3, 4] and found that the formula can also be applied if some parameters are adjusted, if the shape of the mass distribution is assumed to be Gaussian instead of exponential and if the so-called memory effect is modified [5].

Fig. 1 shows that the maximum of the charge dispersion Z_{max} for a given A is very close for antiproton and relativistic io reactions. However fig. 2 demonstrates the different widths z of the charge dispersions of both reactions.

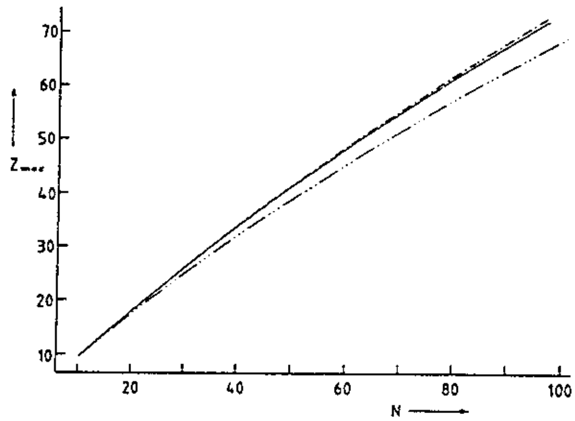


Fig.1: Maximum of the charge dispersion Z_{max} of residual nuclei after antiproton (full) and relativistic ion (dot-dashed) reactions together with the valley of β-stability.

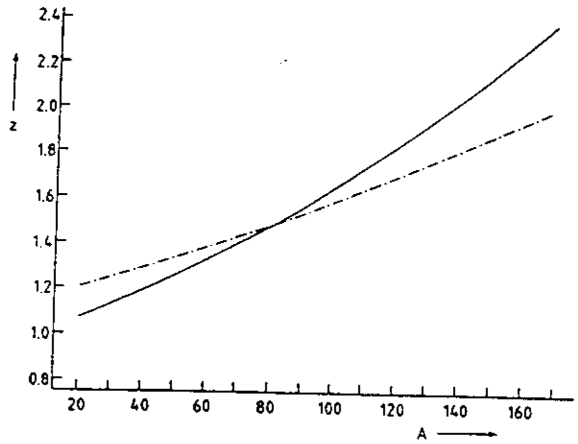


Fig.2: Widths z of the charge dispersions of residual nuclei after antiproton (full) and and relativistic ion (dot-dashed) reactions.

[1] K. Sümmerer et al., Phys. Rev. **42** (1990) 2546
[2] E.F. Moser et al., Z. Phys. **A333** (1989) 89
[3] T. von Egidy et al., Z. Phys. **A335** (1990) 451
[4] J. Jastrzebski et al., to be published
[5] T. von Egidy, H.H. Schmidt, Z. Phys. **A341** (1991) 79

2.1.15 Interaction of stopped antiprotons with Au

A. Grabowska [a], J. Jastrzebski [a], W. Kurcewicz [a], P. Lubinski [a], A. Stolarz [a], P. Baumann, H. Daniel, T. von Egidy, F.J. Hartmann, P. Hofmann, Y.S. Kim, M.S. Lotfranaei, W. Schmid
[a] Warsaw University, Warsaw, Poland

The annihilation of stopped antiprotons at the nuclear surface is a very special process which can excite nuclei to several hundred MeV with small linear or angular momentum transfer and without nuclear compression. The distribution of residual nuclei after antiproton annihilation provides information on the nuclear heating by the intranuclear cascade which is started by the annihilation pions. This distribution had been previously determined for targets of Cu, ^{92}Mo, ^{95}Mo, ^{98}Mo, Ba and Ho using off-line gamma-ray spectroscopy techniques [1, 2, 3]. In heavy hot nuclei fission, spallation and particle evaporation compete. This competition yields information on the time scale of the processes.

We irradiated several Au targets with antiprotons at LEAR/CERN and measured the induced radioactivity. Stacks of foils including catcher foils were used in order to separate fission fragments and products from secondary reactions.

An interesting survey of the residual nuclides is provided by the measurement of electronic x-rays of the fragments. The x-ray spectrum in fig. 1 shows lines from Xe up to Pt. The lines below 40 keV are partly due to fission fragments. The results will be compared with intranuclear cascade calculations [4].

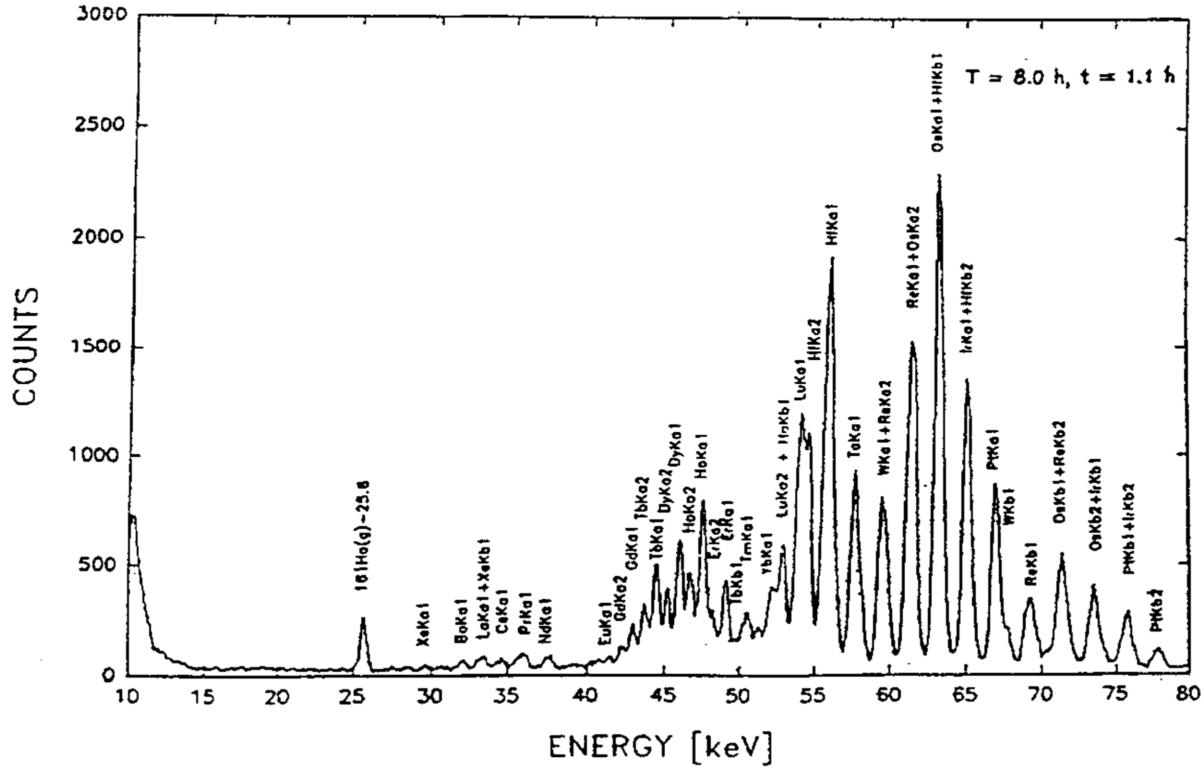


Fig.1: Electronic x-ray spectrum of residual nuclei after antiproton annihilation on Au.

[1] E.F. Moser et al., Z. Physik **A333** (1989) 89

[2] T. von Egidy et al., Z. Physik **A335** (1990) 451

[3] J. Jastrzebski et al., to be published

[4] A.S. Iljinov et al., Nucl. Phys. **A382** (1982) 378

2.1.16 Exotic trapping of antiprotons in gaseous helium

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After forming hadronic atoms, negative hadrons like π^-, K^- or $\overline{p}$ are expected to vanish immediately by nuclear absorption. It was observed recently, however, that a few percent of kaons stopped in liquid He show free decay (lifetime 10 ns). Very recently, an experiment with antiprotons [1] revealed that the time distribution of the annihilation products after $\overline{p}$ stop in *liquid* helium contains delayed components with trapping times between 3.7 ns and 3.0 μs. No such delayed components were found for $\overline{p}$ in liquid nitrogen or in liquid argon. One explanation for the trapping in hadronic helium may be that the neutral hadronic atom can only slowly deexcite by radiative transitions from high-lying states with large angular-momentum quantum number, because Auger effect and Stark mixing are not possible [2].

To answer the question how trapping time and trapping fraction depend on the phase of the stopping substance, an experiment was performed at LEAR/CERN stopping antiprotons in *gaseous* helium at pressures between 2 and 10 bar and in Ne at a pressure of 2 bar, respectively. Annihilation was detected by observing charged pions with the aid of scintillation counter hodoscopes and telescopes.

The time spectra for $\bar{p}$He showed delayed components with pressure independent trapping time and trapping fraction, which, moreover, were nearly the same as observed for liquid He. Differences between ^{3}He and ^{4}He were detected which can be qualitatively explained by differences in the reduced mass of the $\bar{p}$. Admixture of only 0.04 at.% of H_2 to He changed the trapping time drastically. Admixtures of 5 at.% Ne, on the other hand, had only little effect.

[1] M. Iwasaki et al., Phys. Rev. Lett. **67** (1991) 1246, and references quoted therein.
[2] G.T. Condo, Phys. Lett. **9** (1964) 65.