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LEAR PS 203 Project for 1994/95. Part I

Absolute probabilities of antiproton induced fission of medium heavy nuclei

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1. Physical motivation

Fission of medium heavy nuclei is a very complicated process and the details are not well understood. In particular the increase of the fissility for nuclei lighter than Ag has to be investigated. Antiproton-nucleus interaction offers the unique possibility to study fission under very special conditions. The multipion process excites nuclei with low angular-momentum transfer and without compression. Angular momentum is an important parameter in fission. Elaborate intranuclear cascade codes are available for comparison with theoretical assumptions. Therefore, the measurement of absolute probabilities of antiproton-induced fission of medium heavy nuclei will substantially increase our knowledge of low and high energy fission in a large mass range. With our experiment we would like to continue and finish our previous investigation [10] where we measured absolute fission probabilities of Au, Th and U at LEAR.

2. Theoretical description

It is well known that stopped-antiproton absorption by nuclei is a multistep process [1]. The deexcitation of the $\overline{p}$ atom is the first stage. Then, pions are produced during the annihilation at the nuclear surface and start an intranuclear cascade (INC).

The INC-stage is fast and takes place in the time scale of $\tau_o = 10^{-22}$ s. As a result, a residual nucleus is produced which acquires a definite excitation energy E^*, a momentum p, and an angular momentum I. Such a system reaches thermodynamical equilibrium rather quickly within the time of $\tau_{eq} = (5 - 10)\tau_o$. During the last slow stage ($\tau_{ev} >> \tau_o$) the produced compound nucleus emits successively particles or undergoes fission. Standard fission is accompanied by strong rearrangement of the nucleonic structure and is a slow process ($\tau_f > 10^{-20}\,\mathrm{s}$), and consequently it is a natural signature of the thermodynamical equilibrium. Therefore, it is possible to study the characteristics of the compound nucleus by means of fission.

The 1st and 2nd stages of the $\bar{\mathrm{p}}$-nucleus annihilation were calculated with the model described in detail in ref. [1]. The characteristics of the fission process were averaged over all produced compound nuclei. The probability of fission for the compound nucleus was calculated using the modified evaporation model [2]. The parameters for this model were chosen in such a way that they reproduce a large amount of the information on the statistical properties of nuclei excited by low-energy particles and heavy ions. In particular, this model takes into account the damping of shell effects in excited nuclei in the correct manner.

To describe the data on the fissility by stopped antiprotons we used as the only free parameter of the model the ratio of α_n/α_f of the level density parameter for a nucleus with the configuration corresponding to the fission saddle point and for a nucleus with equilibrium deformation. In order to calculate the fission barrier heights (B_f) of the compound nuclei we used the standard liquid drop model (LDM) [3]. The details of the calculation of the fissility were described elsewhere [4]. The result of a calculation with the value $\alpha_f/\alpha_n = 1.020$ fits the experimental data on the fissility of the heavy nuclei Au, Pb, Bi, Th and U rather well (fig. 1). However, the experimental fissility for the Ho nucleus is much higher than the calculated one. The same discrepancy was observed in the study of the fissility of nuclei by intermediate energy projectiles (γ, p, π, α)[4]. Probably, the reason of such disagreement is that the standard liquid drop model [3] predicts too high fission barriers for medium heavy nuclei ($A = 100 - 150$). Indeed, the modified liquid drop model [5] gives the fission barrier heights for nuclei with $A \sim 100$ about 10 MeV lower than the standard LDM. The fissilities by antiprotons are higher by about an order of magnitude in the region of $A \sim 100 - 150$ if they are calculated with the modified LDM than if they are calculated with the standard LDM. The model predicts an increase of the fissility of nuclei heavier than Pr. It is interesting to check this prediction by the experiment. It is very important to verify the increase of the fissilities with decreasing mass for nuclei with $Z^2/A < 23$.

The speciality of antiproton induced fission is the multipion interaction and the low angular and linear-momentum transfer. Since this plays an essential role in fission, results can be expected which are different from experiments with other projectiles. Much higher energy transfer to the nuclei will take place with 1-2 GeV/c antiprotons because more annihilation pions will penetrate the nuclei with higher energies. However, the cross sections for these processes are smaller. We plan to perform experiments with the same or with a similar detector in 1995 using 1-2 GeV/c antiprotons at LEAR.

3. Choice of fission detector

A fission detector based on multiwire proportional chambers (MWPC) [6] is proposed to measure antiproton induced fission probabilities. The *windowless* MWPC has a sensitive area of $80\,\mathrm{mm} \cdot 72\,\mathrm{mm}$ and a size of $120\,\mathrm{mm} \cdot 120\,\mathrm{mm}$ to provide a maximum solid angle ($\sim$ 10%). The MWPC anode is prepared from gold plated W wires ($20\,\mu$

diameter, 4 mm apart). The cathodes are made from the same wires (1 mm spacing). The distance between the anode (central electrode) and the cathode planes is equal to 5 mm.

The volume of the whole target chamber is filled with pure isobutane at 0.1 atm. A permanent gas flow is not necessary, but desirable.

This arrangement has the following advantages: Combination of large solid angle ($0.12/2\pi$), high discrimination factor for fission fragments against α particles (10^{-5}) and other background, and fast enough timing (20 ns) will be provided by MWPC's specially adjusted for this measurement.

Practically complete separation of fission fragments from α particles was obtained due to a relatively low anode voltage (800 V) and a correspondingly low gas amplification factor. This was achieved even for measurements of single fragments with strong alpha active targets such as ^{237}Np ($10^5\,\alpha/s$) at fission counting rates in the beam of less than 0.1 s^{-1}. Some limitations in geometry were found to be necessary to guarantee such a performance, namely, the distance between the target and the MWPC's should be 3-5 cm at an isobutane gas pressure of 0.1 atm, and the angle of emission should be less than 45°. At such conditions the amplitude response function does practically not depend on the angle of emission (fig. 2) and the peak of the fission fragments is separated from the α peak very clearly. In addition, a special unfolding technique allows the evaluation of the symmetric and asymmetric mass component ratio for fission fragments even without coincidence measurements.

The thickness of the targets is also limited for such performances (less than 1.0 mg/cm^2). For higher target thicknesses the peak from fission fragments will be too broad due to energy loss of the fragments within the target.

A supplementary method to obtain more detailed information and decrease the background could be used without efficiency loss (with the same target thickness up to 1 mg/cm^2): the installation of two semiconductor detectors behind the MWPC's to measure the total energy of the fission fragments and deduce Z.

An individual mass evaluation is possible by the use of two MWPC's placed at the opposite sides of the target to measure complementary fission fragments in coincidence with a mass resolution of about 7 u. This will also provide a position measurement of the fission fragments to reproduce the beam profile on the target, to obtain angular correlations, and to suppress background, if necessary.

The position information of the MWPC is obtained by delay lines from the cathodes. Four TDC channels for two MWPC's will be required in addition to two ADC channels for two anode planes.

The fission fragments are measured in coincidence with antiproton telescope counters (beam monitors). For this purpose a fast anode signal could be used. It has a rise time near 20 ns. A time resolution of 15 ns was obtained with a simple discriminator (without constant fraction operation) in the dynamic range 1:10, corresponding to fission fragments amplitudes. This resolution seems to be reasonable for the antiproton induced fission measurements because of the relatively low count rates.

4. Scheme of the experiment

The experimental set-up is shown in fig. 3. The antiproton beam is slowed down in a mylar moderator. Antiprotons are identified and counted as described earlier [7]. An additional counter within the volume with a ^{252}Cf source is convenient to control the gas quality during the measurement.

The acquisition system includes 8 TDC and 2 QDC (or ADC) channels.

We emphasize again that MWPC's are transparent for the beam. The source of background particles originates from the beam entrance window and the isobutane gas inside the volume. At a gas pressure of 0.1 atm the density of gas is 0.267 mg/cm^3. The energy loss ΔE of fission fragments within the MWPC gaps has a wide distribution from 6 to 18 MeV, near 10 MeV on average, for the fixed geometry (the ΔE signal decreases rather sharply as the fission range increases). Also, a distance of 5 cm between the moderator and the target (1.3 mg/cm^2), respectively, is essential to determine background events. The rest gas volume upstream of the target is an additional moderator.

So, the relative number of antiproton absorptions in the gas (0.5 mg/cm^2 within MWPC and some mg/cm^2 upstream) will be comparable with the one in the target (1 mg/cm^2 thickness). The MWPC discrimination factor (10^{-5} against α particles) seems to be sufficient to eliminate such background taking into account the fissility parameter for medium heavy nuclei which is of the order of 10^{-3}.

The background from recoils (C nuclei mostly) seems to be negligible, because the MWPC is not sensitive for light nuclei, and the secondary effect (fission by recoils) would be suppressed by the relatively low cross section (in comparison with the antiproton-fission one) and the large solid angle.

The solid angle could be determined precisely for absolute measurements by Monte-Carlo simulations and with a ^{252}Cf source.

5. The targets

In accordance with the physics motivations the targets should be prepared in the A range from Ag ($Z^2/A = 20$) to U ($Z^2/A = 36$). For example, Ag, La, Nb, Ho, Ta, Bi, Au, Pb, Th, U could be considered. The optimal thickness of targets should be near 1 mg/cm^2 (self supporting). If necessary, light backing material (for example C) could be used. In principle, targets thicker than 1 mg/cm^2 could be also used, but a special calibration technique has to be developed then.

6. Counting rate estimate

Results with stopped antiprotons obtained by Bocquet, Polikanov et al. [8] for U, Bi, Pb, and Au nuclei show a good agreement with fission data obtained by various intermediate energy projectiles (fig. 1). We can extrapolate the fissility for lighter nuclei up to Ag (fissility parameter $Z^2/A = 20$) by the phenomenological formula:

$$P_f = \exp[0.682(Z^2/A - 36.25)] \text{(see ref. [9])}.$$

So, the expected yield of fission events in the slow antiproton beam, which has a minimum for nuclei near Ag, should be close to 0.1% as compared with uranium.

Taking into account the antiproton fission data obtained for ^{238}U by our group [10] we can estimate the count rates for various nuclei, an antiproton beam of 100 MeV/c and an intensity of $2 \cdot 10^5$ $\bar{p}$/s:
Solid angle 10%,
target thickness 1000 μg/cm^2,
stopped antiprotons in the target 1.25%.
Yield for

U	($P_f = 0.8$)	200	(fissions/s)
Th	($P_f = 0.7$)	175	"
Bi	($P_f = 0.08$)	20	"
Au	($P_f = 0.03$)	8	"
W	($P_f = 0.01$)	2.5	"
Ta	($P_f = 0.008$)	2	"
Ag	($P_f = 0.001$)	0.25	"

So, the exposition time for the Ag target with stopped antiprotons could be 1-2 hours about and 10 different targets could be irradiated during one day.

We intend to use the same detector to measure fission probabilities with 1-2 GeV/c antiprotons in 1995. It is expected that high energy antiprotons transfer much higher excitation energies to the nuclei.

References

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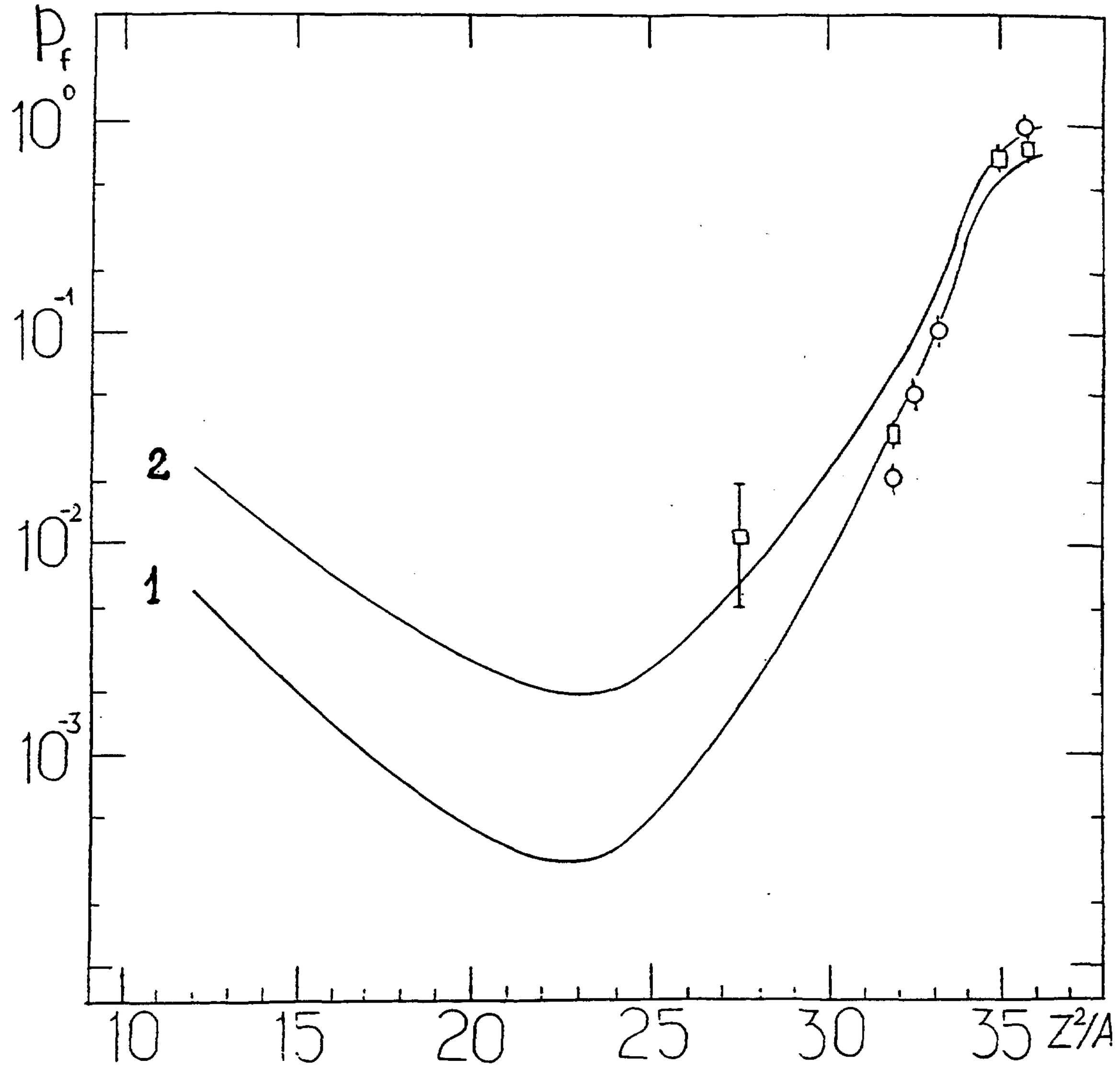

Fig. 1: Calculated and measured fission probabilities by stopped antiprotons as a function of the fissility Z^2/A. Curve 1: Myers, Swiatecki [3]; curve 2: Krappe, Nix, Sierk [5]; open circles: Bocquet et al. [8]; open squares: Schmid et al. (our group) [10].

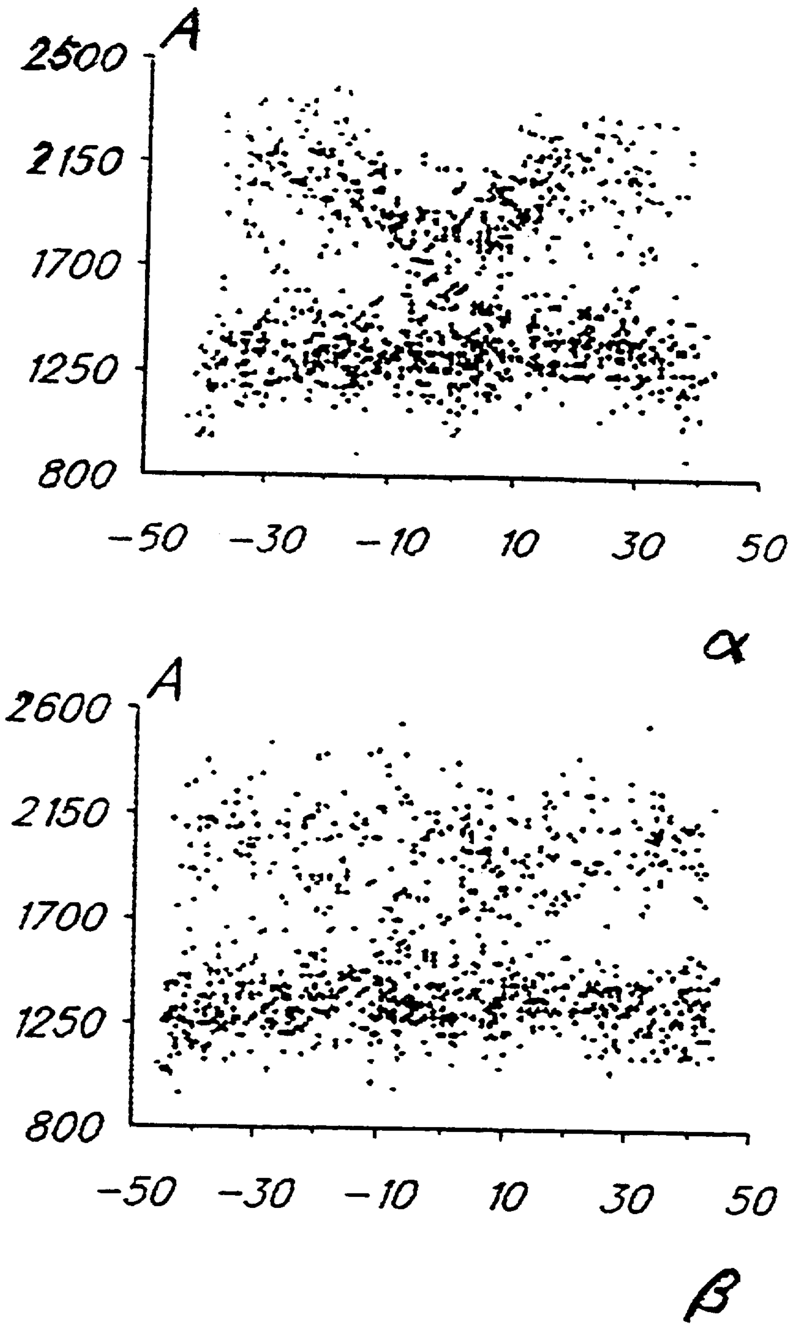

Fig. 2: Amplitudes A of the ΔE signal of fission fragments in the MWPC. α and β are the emission angles vertical and parallel to the anode wires, respectively.

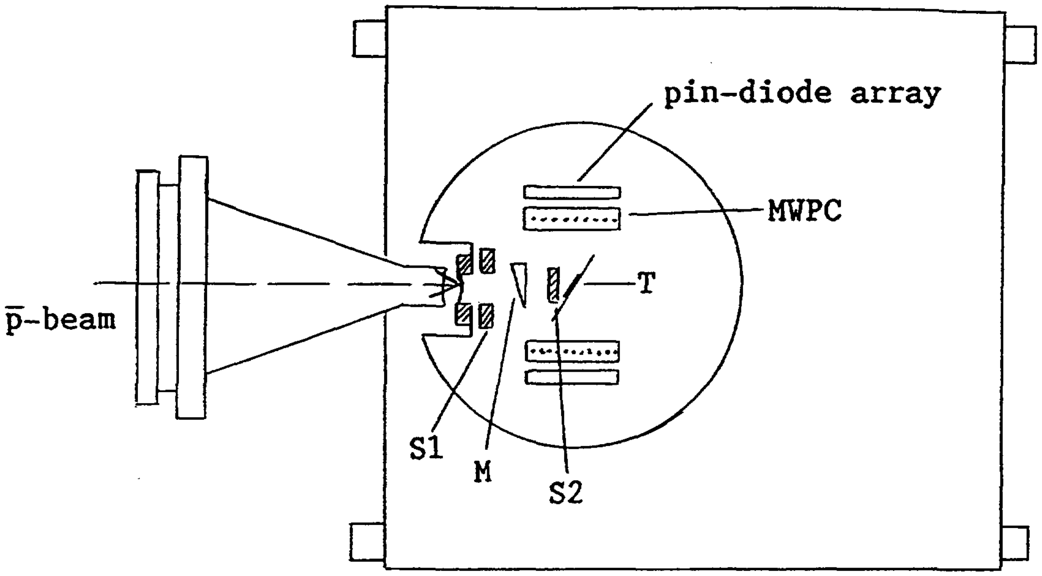

Fig. 3a: Schematic view of the target chamber mounted at the beam line. The chamber is placed on a moveable table.

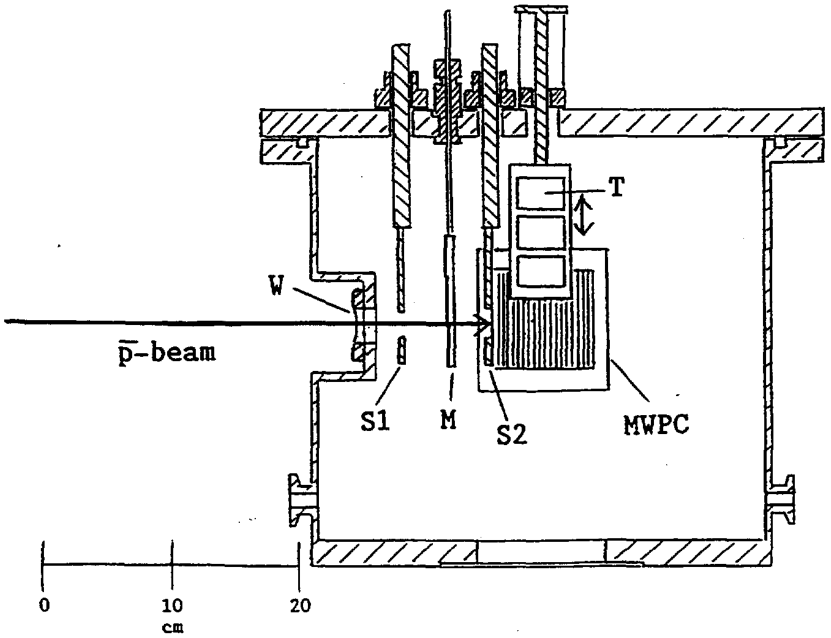

Fig. 3b: Section through the target chamber. The antiproton beam comes from the left. W: entrance window; S1: ring scintillation counter; S2: beam scintillation counter (0.1 mm thick); M: adjustable degrader (mylar); MWPC: multiwire proportional chamber; T: target.

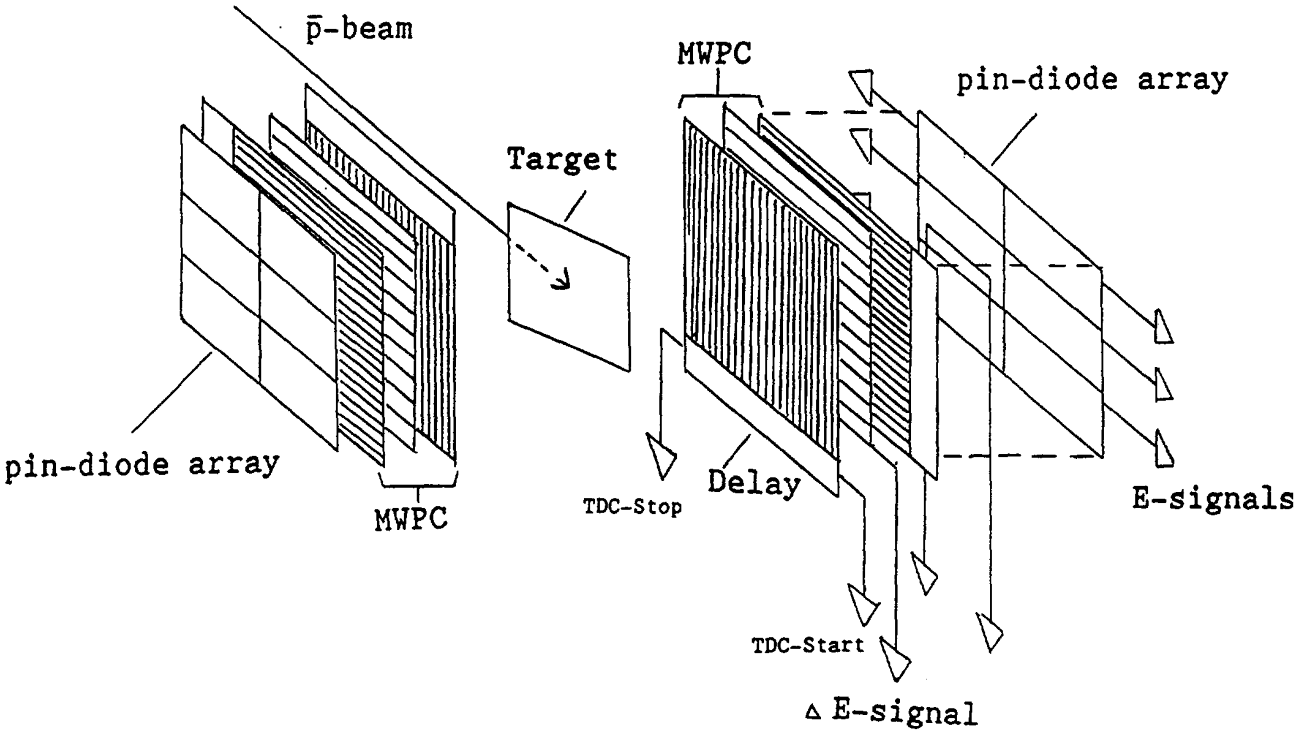

Fig. 3c: Perspective view of the whole fission-detector assembly. For one detector part of the wiring is also indicated.

LEAR PS 203 Project for 1994/95. Part II.

Nuclear structure and nuclear excitations from antiproton-nucleus interaction

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1. Introduction

During our investigation of the antiproton-induced fission and fragmentation we found it useful to extend the in-beam counter methods to off-line radiochemical studies. These methods are extremely unexpensive concerning the needed beam when the interactions of stopped antiprotons are investigated (our last Phys. Rev. paper [1] in which these methods were used was based on $8 \cdot 10^8$ $\bar{p}$ delivered in 3 ten-min. spills). They provide, however, complementary and often very useful information on high nuclear excitations followed by spallation, fission or fragmentation.

As a by-product we have recently discovered that the same radiochemical methods can be successfully applied to nuclear structure studies. More precisely, in ref. [2] we have proposed and demonstrated a new method for the investigation of the nuclear periphery using antiprotons.

In this part II of the PS203 project we propose the continuation of the nuclear periphery study using antiprotons as well as the investigation of nuclear excitation ("heating") using antiprotons available from the LEAR facility. Both subjects are a direct continuation of what we have done during the last two years.

2. The nuclear-periphery study using antiprotons

What was done in 1992-1993: A new and simple method for the detection of differences between the neutron and proton densities at the nuclear surface was proposed. The method, based on nuclear spectroscopy techniques, was applied to about 10 different isotopes of heavy nuclei. A clear neutron-halo signature was observed in some of the nuclei studied. The neutron-halo effect was found to be correlated with the neutron separation energy. A proton-halo effect was probably observed in some very neutrondeficient isotopes.

The new method was introduced and placed in the historical background in our ref. [2] (see a copy of the first page at the end of this proposal). It is shortly summarized below.

New method for the nuclear surface investigation using antiprotons

Stopped antiprotons annihilate on the nuclear surface. For distant annihilations there is a large probability, P_{missing}, that all pions created during the annihilation miss the target nucleus. As a result a cold nucleus with mass $(A_{\mathrm{target}} - 1)$ is produced. The ratio of produced nuclei with one neutron less than N_{target} to nuclei with one proton less than Z_{target} is a simple function of the neutron-to-proton density ratio at distances where $P_{\mathrm{miss}} > 0$. If $(N_{\mathrm{target}} - 1)$ and $(Z_{\mathrm{target}} - 1)$ products are radioactive their production rate can be easily determined using gamma spectroscopy methods. This enables us to extract a "halo factor"

$$f = \frac{N(\bar{\mathrm{p}}\mathrm{n})}{N(\bar{\mathrm{p}}\mathrm{p})} \cdot \frac{\mathrm{Im}(a_p)}{\mathrm{Im}(a_n)} \cdot \frac{Z_t}{N_t}$$

where a_p and a_n are $\bar{\mathrm{p}}\mathrm{p}$ and $\bar{\mathrm{p}}\mathrm{n}$ scattering lengths, respectively.

Figure 1 gives the presently determined neutron-halo factor in heavy nuclei as a function of the neutron separation energy. Figure 2 shows the calculated (Hartree-Fock model with Skyrme force) neutron to proton density ratio as a function of the nuclear distance. Although the theoretical data are preliminary they clearly indicate that the observed neutron-halo can be expected.

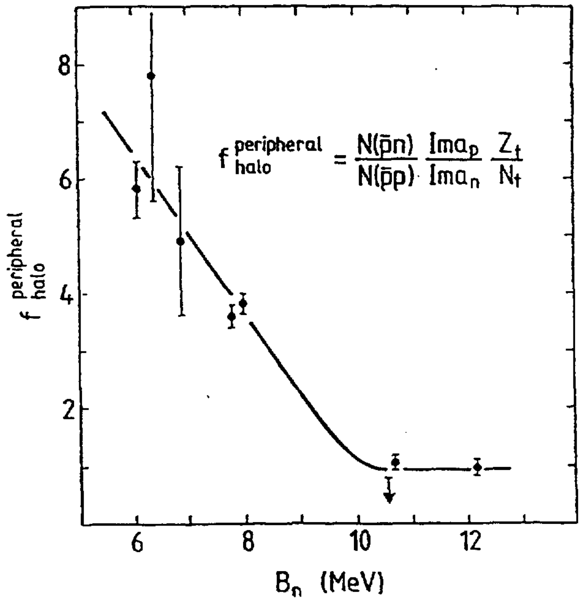

Fig. 1 : Experimental values for the halo factor as a function of the neutron binding energy. The nuclei presently studied were: ^{58}Ni, ^{96}Zr, ^{96}Ru, ^{144}Sm, ^{154}Sm, ^{176}Yb, ^{232}Th and ^{238}U.

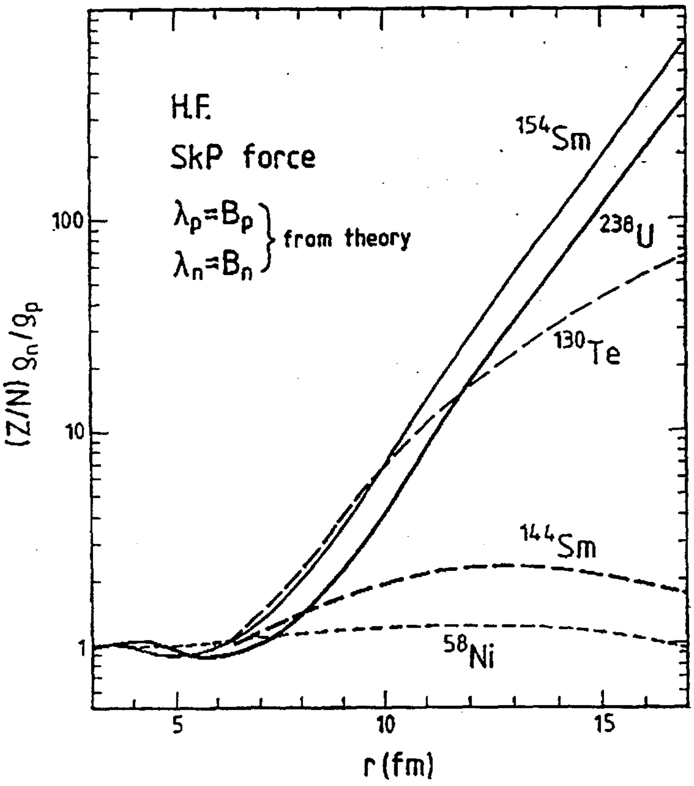

Fig. 2: Neutron-to-proton density ratio calculated for some nuclei studied in this experiment

What can be done more by the same techniques? Continuation and verification of the neutron-halo study for a few more cases; testing the nuclear wave function at large distances studying the isomeric ratios of $(A_{\mathrm{target}}-1)$ nuclei after $\bar{p}$ absorption; determining the importance of charge exchange effects, studying the production rate of $(Z_{\mathrm{target}}+1)$ nuclei.

Another method for studying the nuclear periphery using $\bar{p}$: Levels of antiprotonic atoms in their last orbits are sensitive to the matter distribution in nuclei. The observables of this effect are the antiprotonic x rays. It is proposed to investigate with modern HPGe detectors and a BGO anti-Compton shield the antiprotonic x rays for the same targets which were previously (see above) studied with new methods for neutron-halo detection. In this way it is expected to obtain an independent and complementary information on the neutron and proton densities at the nuclear surface. In the previous experiments related to the n/p ratio the state of absorption was assumed (calculated with optical potential). The x-ray data would check these calculations. We have a strong theoretical support for these studies (S. Wycech).

Experimental details

a) For radiochemical studies:

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 the $\bar{p}$,
$\bar{p}$ beam: 200 MeV/c; several spills per target, each spill for 5-15 min with 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.

b) For antiprotonic x rays:
Experimental area: 3x3 m^2,
Targets: ca. 100 mg/cm^2, area 2 cm^2,
$\bar{p}$ telescope, $\bar{p}$ moderator, one or two Ge detectors, probably with BGO shield,
$\bar{p}$ beam 200 MeV/c, 1 h spills, $(10-100) \cdot 10^3$ $\bar{p}$/s,
beam request: about 10 days per year.

3. Heating of nuclei by energetic antiprotons

One of the experimental observables strongly depending on the temperature of the product formed in nuclear reactions is the mass-yield distribution (see Ref. 3). Our previous investigations of this observable in the interaction of stopped antiprotons with Cu, Ag and Au targets indicate that the excitation energy deposited in nuclei after stopped $\bar{p}$ annihilation is similar to that after about 1-2 GeV/c proton interaction. One hopes that energetic antiprotons can heat the target nuclei much more due to the closer annihilation site and kinematical focusing of the produced pions.

We propose to investigate this possibility comparing the previously determined mass yield distribution gathered with stopped antiprotons with those, obtained using energetic antiprotons (up to 1.8 GeV/c).

Contrary to the stopped antiprotons, in the case of energetic $\bar{p}$ the beam intensity is the most serious problem in this experiment. Therefore, we can no longer run in a parasitic mode, but the full beam intensity is requested during a 48h period.

We assume to have during this time:
100 spills of 10 min. duration each,
$7 \cdot 10^9$ $\bar{p}$ in LEAR for each spill,
30% extraction and beam transport efficiency,
total $2 \cdot 10^{11}$ $\bar{p}$ on target (about 30 nCb).

With 1 g/cm^2 targets we will produce about $2 \cdot 10^9$ nuclei ($\sigma_{tot} = 1\,\mathrm{b}$ assumed). The detection of products with 0.1-1% yield will be possible. This is necessary for the mass yield determination.

The $\bar{p}$-energy dependence will be investigated during the same irradiation, using beam degraders and consecutive target stacks. Cu, Ag and Au targets will be investigated.

References

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LEAR Beam-Time Request 1994

1a) Absolute probabilities of antiproton-induced fission:
Period: September – December,
duration: 10 days,
$\bar{p}$ momentum: 100 or 200 MeV/c,
intensity: 200 000 $\bar{p}$/s,
condition: 1h spills.
1b) For about seven days we shall ask for 2 short full spills per day as in July 1993 for irradiation.

2) Irradiation of Au, Ag and Cu targets with high energy $\bar{p}$:
Period: any,
duration: 2 days,
$\bar{p}$ momentum: 1-2 GeV/c,
intensity: max. intensity,
condition: 10 min spills.

LEAR Beam-Time Request 1995

1) Absolute probabilities of antiproton-induced fission:
Period: any;
duration: 10 days,
$\bar{p}$ momentum: 1-2 GeV/c,
intensity: max. intensity,
condition: 1h spills.

2) Irradiation with high energy $\bar{p}$:
Period: any;
duration: 2 days,
$\bar{p}$ momentum: 1-2 GeV/c,
intensity: max. intensity,
condition: 10 min spills,

3) Antiprotonic x rays:
Period: any,
duration: 5 days,
$\bar{p}$ momentum: 100 or 200 MeV/c,
intensity: 200 000 $\bar{p}$/s,
condition: 1h spills.