Short report on experiments at LEAR on antiproton–nucleus interaction
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1. Collaborations

Our experiments PS 186, PS 203 and PS 205 and the proposed experiments at LEAR for the next years require relatively small experimental arrangements and about ten to fifteen physicists to prepare, install and handle them at the antiproton beam. We apply semiconductor and scintillation detectors to measure particle or fragment energies including time–of–flight and to obtain on–line and off–line γ–spectra. These experimental set–ups can be easily adapted to special and new problems.

Presently we collaborate with several groups which focus their interest on various questions of antiproton interactions: Hahn–Meitner–Institut, Berlin (D. Hilscher, D. Polster, H. Rossner), KFA Jülich (H. Machner, G. Riepe), University Bonn (P. David), Florida State University, Tallahassee (H.S. Plendl), University of Virginia, Charlottesville (K.O. Ziock), Warsaw University (J. Jastrzebski, W. Kurcewicz, S. Wycech), Russian Academy of Sciences, Moscow (A.S. Ilijinov, A.S. Botvina, N.G. Nedorezov, A.S. Sudov) and University of Tokyo (T. Yamazaki, E. Widmann, R.S. Hayano, M. Iwasaki, S.N. Nakamura, K. Shigaki).

The Munich group consists of: H. Daniel, F.J. Hartmann, J. Hoffmann, W. Schmid, T. von Egidy et al..

2. Interesting processes during antiproton–nucleus interaction

a) Antiprotonic atoms: The last antiprotonic x–ray transitions provide
information on the antiproton–nucleus potential which is not yet well understood, especially inside the nucleus. The E2–resonance effect represents an unusual coupling of atomic and nuclear states and is a tool to investigate the potential.

b) Exotic storage of antiprotons in He: Yamazaki et al. (Univ. Tokyo) showed that a fraction of the antiprotons stopped in He annihilate with a delay time of a few μs. The reason is that antiprotons captured in atomic orbits with large angular momentum proceed only slowly to lower orbits by radiative transitions. The measurements with gas mixtures show unexpected results for H\textsubscript{2} admixtures. Antiproton storage is interesting for the production of antihydrogen.

c) Annihilation process: It is still an open question whether the presence of nuclear matter influences the annihilation. It has been proposed that strangeness production and consequent kaon yields increase with the target mass.

d) Signature of the neutron halo of nuclei: Jastrzebski (Warsaw University) proposed recently to use antiproton annihilation to obtain information on the ratio of neutron to proton density in the periphery of nuclei. 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. It can be determined by γ–lines of residual nuclei.

e) Intranuclear cascade and nuclear heating: The annihilation pions have energies close to the Δ–resonance and interact strongly with the nucleus starting an intranuclear cascade with particle emission. These processes heat the nucleus up to about 800 MeV excitation energy without compression and with small linear and angular momentum transfer. Therefore, this excitation is quite different from heavy ion reactions and complementary to it. The intranuclear cascade has been calculated with Monte Carlo methods by Ijînov et al. and Cugnon et al.. Detailed comparison of the experimental results with these calculation yields very specific
information on the intermediate processes involved such as fast intranuclear
cascade, pre-equilibrium reactions, coalescence emission, multifragmentation,
trawling effect (non-linear nuclear density reduction), competition of evaporation
and fission and the time scale of these reactions.

f) Particle emission: Mainly neutrons and some protons but also d, t, 3He, 4He
and heavier ions are emitted during the above mentioned processes. Their yields
and energy spectra characterize the reactions.

g) Fission: Heavy nuclei undergo with a certain probability fission after
annihilation. Mass, energy and folding angle of fission fragments allow to
determine the mass of the fissioning nucleus and the particle emission before and
after scission. The energy equilibration of the fissioning nucleus can be
investigated. These experimental results provide the time scale of the reactions.

h) Multifragmentation: Very hot nuclei may undergo multifragmentation.
Liquid-to-gas phase transition of the nucleus could cause it. Multifragmentation is
therefore a very interesting field of research.

i) Hypernuclei: Nifenecker, Polikanov et al. studied the production of
hypernuclei after antiproton annihilation in very heavy nuclei. These experiments
raised more questions than they could answer until now.

j) Residual nuclei: Finally, residual nuclei are left which are frequently
radioactive and can be identified from their γ-spectra. They reflect the impact of
the annihilation on nuclei.

3. Projects to be studied at LEAR during the next years

a) Multifragmentation sheds light on the highest thermal excitations of the
nucleus (larger than 500 MeV excitation energy). We intend to measure it with a
special arrangement of twelve 6 x 6–PIN–diode arrays (each PIN–diode has 1 cm²
area) and to determine mass, energy and angle of three fragments. Due to the low
angular momentum and absent compression the results are expected to be very
different from heavy ion reactions.

b) With the same PIN-diode arrangement we shall detect fission fragments and in coincidence with them the neutron spectrum. The neutron spectra are measured with scintillation counters and time-of-flight techniques. This gives direct information on the number of emitted neutrons before and after scission and on the velocity of the fission process. Our recent results on antiproton induced fission show that the number of neutrons emitted after scission increases with the excitation energy indicating faster fission for higher excitation energies. These findings are at variance with heavy ion induced fission where the number of post-scission neutrons is rather independent of the excitation energy (Hilscher et al.). Consequently we hope to solve this problem by direct measurement of the neutron spectra together with Hilscher et al. and his neutron detectors.

c) The scintillation detectors of Hilscher et al. yield not only neutron spectra but also proton, deuteron and especially pion and kaon spectra. Kaon spectra have not yet been measured. They give information on the annihilation process itself and on the influence of nuclear matter on it.

d) The Warsaw group (Jastrzebski et al.) will continue the activation analysis of targets irradiated with antiprotons. The investigation of the neutron halo with this method seems to be a very promising new technique and systematic studies are necessary.

e) Antiproton storage in He has to be investigated in more detail as a function of the density and temperature and of gas admixtures in particular H₂.

f) The production of hypernuclei with antiproton annihilation was shown to be a powerful tool to study hypernuclei. There is a wealth of open questions concerning especially the Λ attachment to fission fragments. H. Nifenecker, Grenoble, and G.E. Belovitsky, Moscow, are very interested in these investigations.

g) The above described experiments are performed with stopped antiprotons. We plan to continue these experiments with antiprotons of 0.5 to 2 GeV energy.
It can be expected that much more thermal energy is transferred to the nucleus and that multifragmentation increases with antiproton energy. The reason is that the annihilation of fast antiprotons takes place closer to the nucleus and that the annihilation pions move more in the direction of the nucleus.

4. Summary

We think that there are many exciting problems left which justify the continuation of experiments on antiproton nucleus interaction. Our investigations concern the extreme heating of nuclei without large angular momentum or compression. Multifragmentation, fission, particle emission and residual radioactivity provide specific experimental information on these processes. Comparison with intranuclear cascade calculations elucidates many details of these reactions. Experiments on the neutron halo, hypernuclei and antiproton storage are additional fascinating research areas.
Publications of the Experiments PS 186 and PS 203
at LEAR in the years 1989 — 1992

Z. Physik A333 (1989) 89—105
Residual nuclei after antiproton annihilation in Mo and Ho

Charged particle emission and fission following antiproton annihilation at rest

Z. Physik A 335 (1990) 451—457
Yield of residual nuclei after antiproton annihilation in Ba

Charged—particle spectra from antiproton annihilation at rest in A = 12 to 238 nuclei
in "6th Int. Conf. on Nucl. Reaction Mechanisms" Varennna, June 1991
Antiproton induced fission and fragmentation

6) T. von Egidy, H.H. Schmidt
Z. Physik A 341 (1991) 79–82
Comparison of residual nuclei from relativistic ion and antiproton reactions with nuclei

Z. Physik A, accepted
Fission fragment distribution following antiproton absorption at rest on $^{238}$U

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

Interaction of stopped antiprotons with copper
   Physics Letters B, submitted
   Signature of a neutron halo in $^{232}$Th from antiproton absorption

   Nuclear Instruments and Methods A, to be submitted
   A double–arm fission fragment spectrometer with pin diode arrays

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

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

Additional publications on antiproton induced fission are in preparation.