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ANTIPROTON-NUCLEUS INTERACTIONS AT LEAR

C. GUARALDO
INFN - Laboratori Nazionali di Frascati C.P. 13, 00044 Frascati (Rome) Italy

Abstract

The most recent results on low-energy antiproton-nucleus interactions are discussed. Further investigations beyond the conventional intranuclear cascade scenario are considered.

Key Words Annihilation dynamics, deep annihilation, multinucleon annihilation, quark-gluon blob, strangeness production, antiproton-nuclear states, residual nuclei.

INTRODUCTION

It can be considered a well established matter of fact that nuclear physics results are among the more interesting scientific outputs of the first generation of LEAR experiments. In what follows, we shall choose a few of the most recent results, focussing the attention on typical aspects of the low-energy antiproton-nucleus interaction, carefully explored at LEAR:

- the dynamics of the dominant process, i.e. the annihilation, with its mechanism of energy transfer and the role of the particles involved;
- the problem of the penetration of antiproton inside a nucleus, identifying peripheral and deep events and possibly selecting a specific annihilation radius;
- the fascinating field of the new physics beyond the "conventional" annihilations, with its typical predicted signatures, in particular strangeness production;

- the search for antiproton-nucleus states bound by the strong interaction, which are different from the well known antiprotonic atom states bound by the Coulomb interaction;
- and finally what is left to a nucleus after that reorganization of hadronic matter that is the annihilation process, i.e., the yield of residual nuclei.

DYNAMICS OF LOW-ENERGY ANTIPROTON ANNIHILATION IN NUCLEI

The pion and proton momentum spectra and the rapidity distributions obtained by the PS 187 experiment (Mc Gaughey et al., 1986a) from 608 MeV/c antiproton annihilation on^{12}C, ^{89}Y and ^{238}U targets, clarify, together with the good agreement with intranuclear cascade calculations, many aspects of the dynamics of the annihilation, stressing the role of pions in transferring energy to the nucleus and identifying how many nucleons participate in the annihilation and subsequent cascade in nuclei.

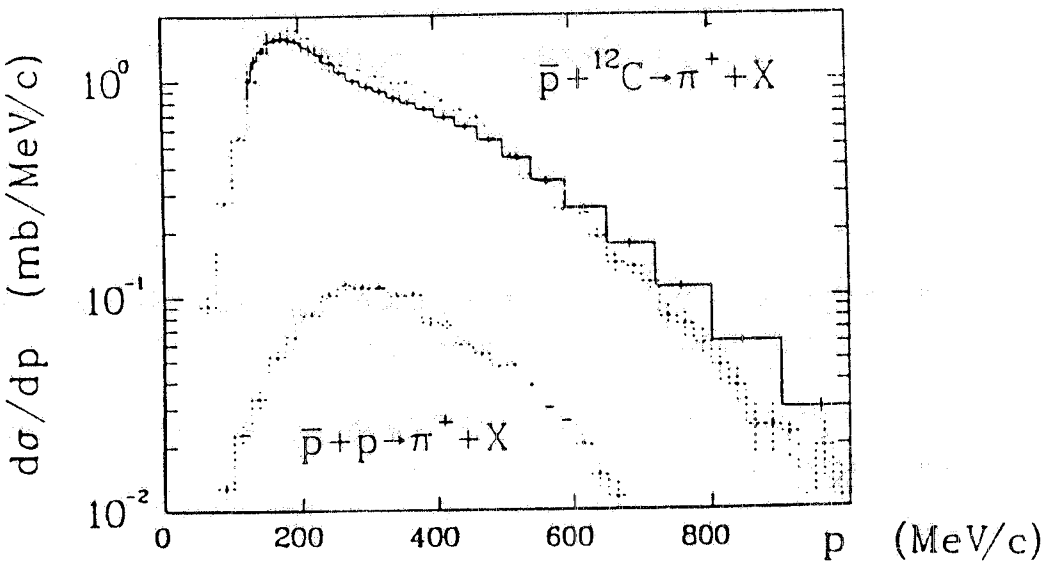

FIG. 1 - Inclusive momentum distribution for π^+ from 608 MeV/c antiproton annihilation on ^{12}C. The solid histogram are the data and the dashed histogram represents the INC calculation. The second dashed curve represents the pion momentum distribution from $\bar{p}$-p annihilation at the same energy (PS 187 experiment).

The inclusive pion momentum spectrum of Figure 1 shows a typical two-bump structure: above 300 MeV/c the $\bar{p}$-nucleus data are similar in shape to the free $\bar{p}$-N distribution (also reported for comparison), reflecting non-interacting pions from peripheral annihilation ("primordial" pions). A lower momentum peak is essentially due to the pions that have interacted, formed deltas and reappered with lower energies ("secondary" pions).

The kinematic origin of ejectiles, pions and protons, distinguishing between different momentum regions, were deduced from the rapidity distributions, and helped to determine the number of nucleons participating in the process. The pion rapidity spectra for $P_T \geq 120$ MeV/c and $P_T \geq 500$ MeV/c clearly show, for the latter, the quasi-free $\overline{N}$-N origin ($y \approx 0.3$), while low-energy pions come from a system involving many more nucleons ($y \approx 0$).These features confirm what inferred from the inclusive spectra. Assuming that nothing unusual is occurring, the method for energy deposition is pion absorption (via delta) and scattering. Thus large energy depositions correspond to production of low-energy "thermalized" pions and necessarily it will happen deeper within the nucleus, involving many nucleons in the process. On the contrary, high energy "primordial" pions are associated to peripheral annihilations, which happen on a single nucleon.

In the case of protons, both low and high momenta clearly originate from the target system. The high-P_T data show, in addition, some structure at positive y, not well reproduced by the INC calculations, which could be due to fast protons from $\pi N \rightarrow \pi N$ inelastic scattering, or perhaps from annihilation occurring on more than one nucleon.

In conclusion, these results give information on the dynamics of low-energy $\overline{p}$ annihilation in nuclei and confirm its essential peripheral character. The agreement with cascade calculations is indeed significant, but, at the same time, somewhat disappointing, due to the assumption, underlying the INC model, that only "conventional" reactions take place. One might hope, on the contrary, to go beyond this scheme, looking for new physics, which might be favoured by "unusual" behaviors. Hunting for new phenomena, certainly a special role must be deserved to multinucleon annihilations, as firstly envisaged by Rafelski (Rafelski, 1980). Enhanced strangeness production and a tail of high momentum protons would be the signature of annihilations with baryon number $B>0$. Perhaps, in the deviation from INC calculation seen in the high momentum region of the proton rapidity spectra, some hint of this may be supposed.

IDENTIFICATION AND TAGGING OF CENTRAL ANNIHILATIONS

There are two good reasons to focus a particular attention on central or "deep" annihilations. By definition, one may expect that any significant difference between antinucleon-nucleon and antinucleon-nucleus processes, which constitues one of the objectives of nuclear physics research with antiprotons, are most likely to show up in such events. Moreover, the signals of the new physics which might be discovered in annihilations on more than one nucleon, the probability of which increases going deeply within the nucleus, could in principle be enhanced if these events could be distinguished from the background of peripheral annihilations on a single nucleon.

The bubble/streamer chamber measurements do provide a profile of the entire (limited to charged particle) event. High statistics counter experiments are necessary to be drawn quantitative conclusions. In this sense the two approaches are complementary. The streamer chamber group of the PS 179 experiment has firstly shown simple selection criteria between surface and central annihilations from charged prong and final products characteristics (momentum, angle, rapidity) distributions. The PS 187 experiment has found a clean way to determine the average annihilation radius, which allowed to perform high statistics measurements of true central annihilations.

Identification of central annihilations (PS 179 experiment)

These results of the streamer group were obtained on ^{20}Ne at 200, 300, 600, MeV/c and at rest and on nuclear emulsion (Ag/Br) at 300, 400, 500 MeV/c and at rest (Batusov et al., 1986; Balestra et al., 1986; Balestra et al., 1987b). Central from peripheral annihilations have been clearly identified from:

a) Multiplicity distributions of charged prongs.

Low-and high-multiplicity events present typical opposite behaviors. Consider the reaction cross section σ_R in Neon: for events with multiplicity $M \leq 9$, σ_R follows the energy behavior of the $\bar{p}$-N cross section, which increases as the energy decreases. This is typical of surface annihilations. For events inside the nucleus, one expects a quite different behavior versus energy, due to Pauli blocking, Fermi motion and the attraction produced by the Coulomb potential. In fact, for high multiplicity, the reaction cross section is independent on energy. Moreover, in this case, for $M>9$ the average multiplicity is $\overline{M}\sim 10.7$, $\bar{n}_{\pi^-}\sim 1.75$ so that the number of heavy prongs must be ~7.5, on average, which means that a nucleus with atomic number 10 is almost disintegrated in free nucleons due to a transfer of energy greater than its total binding energy. This is possible when a deep penetration has occurred. Finally, it is remarkable that the percentage of the central events is increasing with energy: from some percent for a $\bar{p}$ at rest up to about 15% at 600 MeV/c.

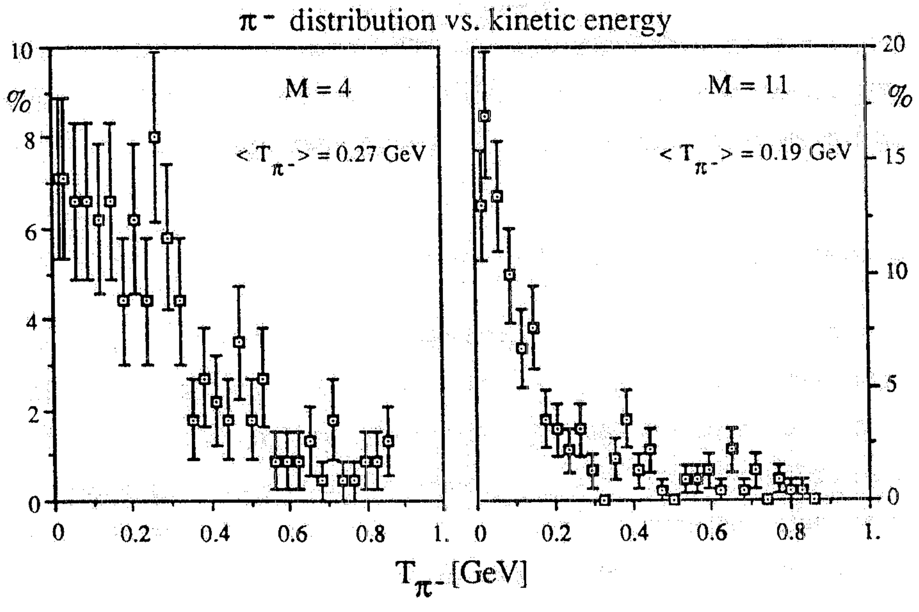

FIG. 2 - Negative pion distributions vs kinetic energy for 607 MeV/c antiproton annihilation on ^{20}Ne (PS 179 experiment).

b) Final products characteristics.

A comparison between momentum, angle and rapidity distribution of π^- and nuclear fragments for low- and high-multiplicity events (in the case of Neon: M=4 and M=11, respectively) has been performed. The results can be summarized as follows: the high-multiplicity events present, respect to the low-multiplicity ones, a lower number of negative pions, which have lower mean energy (Figure 2) and are isotropically emitted from a kinematical source involving many nucleons (Figure 3). On the contrary, the negative pions associated to the low-multiplicity events are forward emitted in annihilations involving only one nucleon (Figure 3). As far the nuclear fragments are concerned, their number and their mean energy is higher for M=11 than for M=4, while the kinematical sources involve, in both cases, a number of nucleons. The overall degree of isotropy (jet parameter) of the charged prongs is higher for high multiplicity.

Recalling the discussed dynamics of annihilation we can conclude that all these features are clearly contained in a scenario in which low-multiplicity events correspond, on average, to annihilations occured on the surface of the nucleus, while high-multiplicity events correspond, on average, to deep annihilations inside the nucleus.

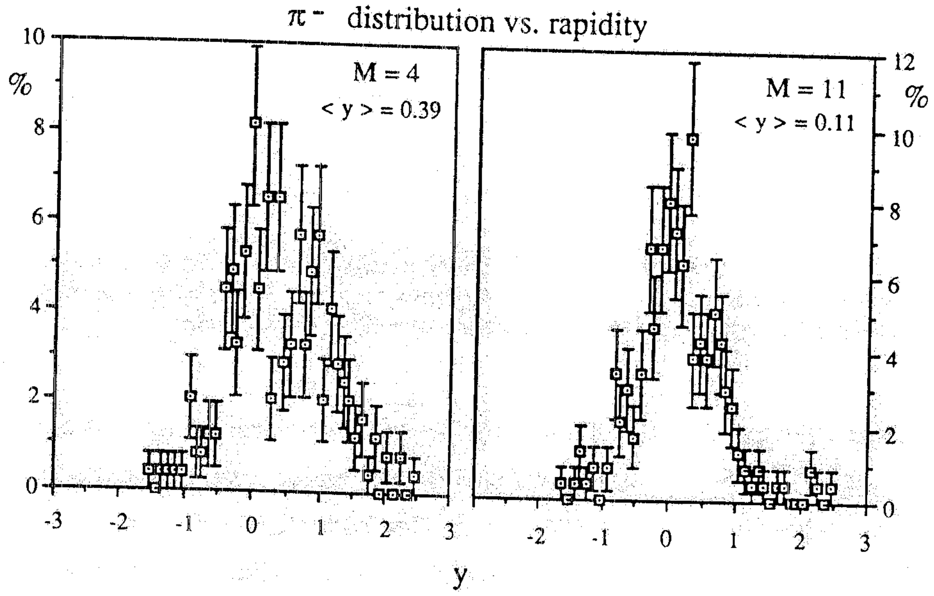

FIG. 3 - Negative pion distributions vs rapidity for 607 MeV/c antiproton annihilation on ^{20}Ne (PS 179 experiment).

Selection of deep annihilations (PS 187 experiment)

The experiment has developed an interesting new technique (Mc Gaughey et al., 1986b), based on the use of a silicon detector/target (SDT), to experimentally select the annihilation radius of low-energy antiprotons in silicon. The intrinsic silicon transmission detector was placed at the center of the CALLIOPE circular magnetic spectrometer. The silicon pulse height was recorded with each good event in a detector module, allowing off-line sorting of energy deposition in SDT for a given class of measured ejectiles. Through a careful use of the results from MonteCarlo intranuclear cascade and evaporation calculations, the energy deposited in the detector was correlated to the annihilation radius.

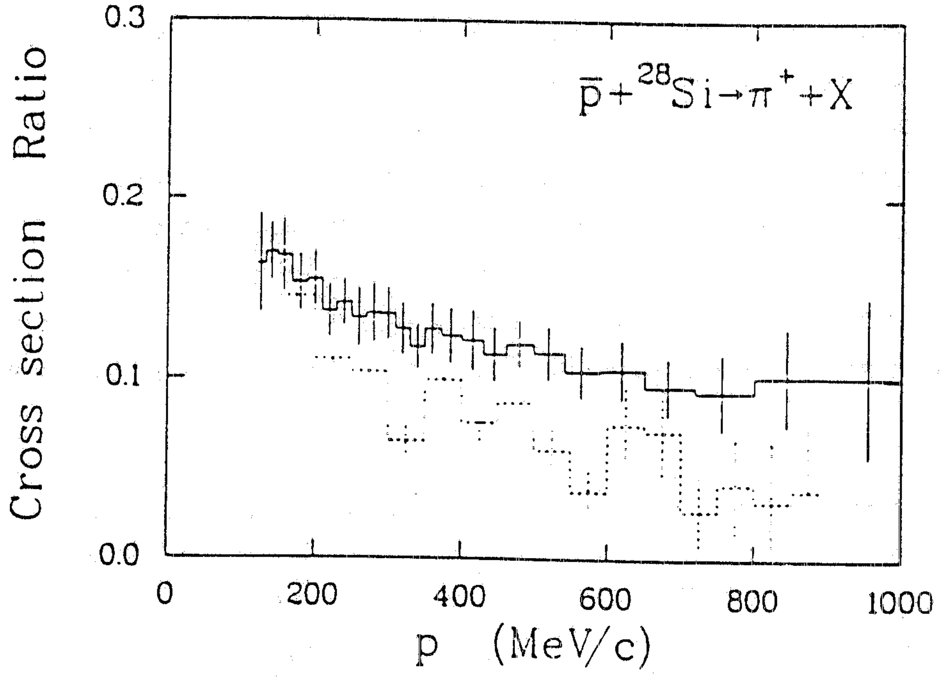

FIG. 4 - The ratio of the ungated and gated (by an energy deposit of 80 MeV or more) inclusive momentum distributions for π^{+} from 608 MeV/c antiproton annihilation on ^{28}Si. The dashed histogram represents the model calculation (PS 187 experiment).

A threshold energy deposit in the detector /target was computed, above which events consisted primarily of annihilations occurring deeper than the half-density radius. Experimental tests of the technique were in good qualitative agreement with the model result. For instance, by requiring an energy deposit of at least 80 MeV, one enhanced the number of annihilations occurring within the half-density radius (3.4 fermi for Silicon) by about a factor of 2, while annihilations beyond 4.5 fermi were completely eliminated.

The effect of a software cut (corresponding to 80 MeV energy deposit or more) is shown in Figure 4, which gives the ratio of ungated and gated inclusive pion momentum distribution. It is evident an enhancement of the secondary low-energy pion bump when a large energy deposit is required. This true central annihilation result stresses, in the most direct way, the role of pions in the energy transferring mechanism.

UNUSUAL ANNIHILATIONS AND STRANGENESS PRODUCTION

It has been suggested that the antiproton annihilation can occur on a number of nucleons, creating a deconfined region of rather high local energy density within the nucleus. Such possibility has been firstly put forward some years ago by Rafelski (Rafelski, 1980), who suggested the picture of the creation of a fireball with baryon number zero, which can collide with other neighbouring nucleons and absorb them into a domain of space similar in nature to the interior of a hadron. If such an extended quark-gluonic blob is formed, the production of strangeness would be enhanced (Rafelski and Müller, 1982).

A different approach, based on kinematical constraints operating in a pure hadronic phase, yields observables very similar to those obtained by Rafelski (Cugnon and Vandermeulen, 1984). The most important consequence of the Cugnon and Vandermeulen model is the prediction that strangeness production is favoured in B>0 compared to B=0 annihilations. The predicted branching ratios for the various channels of B=1 annihilations at rest display a 13.5% of events involving strangeness, compared to 5% in B=0 annihilations. Of the strange events, 76.3% are hyperon events, which are not produced at all in $\bar{N}N$ annihilations at rest.

Two experiments (PS 179 and PS 183) have studied unusual behaviors in $\bar{p}$ annihilation and associated strangeness production going to look specifically for reactions characterized by their intrinsic multinucleon nature in the annihilation process, i.e.:

a) one-pion annihilation on deuterium at rest (PS 183 experiment)

b) Λ and K^0_S production under threshold from complex nuclei (PS 179 experiment).

In PS 183 experiment the simplest system in which one might expect to find B=1 annihilation, the deuteron, has been studied (Smith, 1987) looking for the channel $\bar{p}d\rightarrow\pi^-p$ at rest, for which the theoretical prediction of a $\bar{N}NN$ annihilation gives a branching ratio of $\sim 3.10^{-4}$. Clear clusters of events ($\sim 40\ \pi^-$, ~ 40 p) were seen in plots of momentum versus angle between the particle detected in the spectrometer and a second away-side particle for π^- tracks and p tracks. The events were recognized at 1250 MeV/c and 180°, exactly where the $\bar{p}d\rightarrow\pi^-p$ events at rest are expected. These ~ 80 events give a branching ratio of $(28\pm3)\cdot10^{-6}$ per annihilation, which suggests a B=1 rate of ~10% . This interesting new result is a factor of 3 greater that the only reported in literature branching ratio for this reaction, based on 6 old events in bubble chamber (Bizzarri et al., 1969).

With the streamer chamber of the PS 179 experiment, the inclusive production of V_0 from 600 MeV/c antiproton annihilations in Neon was investigated (Balestra et al., 1987a). Λ and K^0_S were observed through their charged decay modes. The Λ and K^0_S production cross sections can be compared with recent results obtained on Ta at 4 GeV/c (Miyano et al., 1984) and ^2H at 450-921 MeV/c (Parkin et al., 1986).

Both this and Miyano et al. experiment, performed on medium and medium-heavy nuclei, obtain the same value (~2.4) for the ratio $R=\sigma(\Lambda)/\sigma(K^0_S)$, independently on energy. On light nuclei, according to the recent data on deuterium of Parkin et al., the R value is less than unity. Since the kinematic origin of the ejectiles appears again to be the same: multinucleon clusters for Λ production in Ne and in Ta, few nucleons in K^0_S production, one might hypothesize a substantially similar production mechanism, with some kind of "peripheral-like" origin for K^0_S and a "deeper" origin for Λ. Then, in a lighter nucleus, such as deuteron, the enhanced surface production would inverte the value of the ratio. If this is true, the surface character of annihilation at rest ought to give a lower value for R in complex nuclei. Preliminary data of PS 179 on annihilation at rest on Neon seem to confirm this trend, with a value for R near unity.

ANTIPROTON-NUCLEUS BOUND STATES

The antiproton-nuclear states, which are other thing respect to the more known antiprotonic atom states bound by the Coulomb interaction, can exist under the conditions that:

a) the $\bar{p}$-nucleus interaction, described by an optical potential, is sufficiently attractive;

b) the absorptive imaginary part of the potential, which describes the annihilation, is not too large near the nuclear surface. Unfortunately, the properties of the $\bar{p}$-nucleus interaction, as determined by the recent experiments at LEAR on elastic and inelastic scattering of antiprotons (Garreta et al., 1985) and on antiprotonic atoms (Poth et al., 1985) are not very encouraging ($V_0<50$ MeV, $W(R)\geq 2\ V(R)$). However, the uncertainties in the presently available theoretical predictions leave still room for an experimental programme of research.

The experiment PS 184 has followed the method of the knock-out reaction $A(\bar{p}, p)\ X$ on ^2H, ^6Li, ^{12}C, ^{63}Cu, ^{208}Pb, ^{209}Bi targets at 600 MeV/c, to look for $\{\bar{p}\text{-}(A\text{-}1, Z\text{-}1)\}$ states. The main advantage of the method is that, by detecting the proton at $\theta_{lab}=0°$, it carries away most antiproton incoming momentum, leaving the antiproton almost "recoilless", thus favouring the formation of $\bar{p}$-nucleus states.

Concerning the specific initial objective, no evidence for narrow bound or resonant $\bar{p}$-nucleus states could be found (Aslanides et al., 1987). Upper limits for their production are one order of magnitude lower than theoretical predictions, although consistent with the properties of $\bar{p}$-nucleus interaction. However, the experiment was for many aspects successfull, since it performed a careful study of the inclusive proton spectra produced on various targets, which is doubly interesting: because a quantitative understanding of the proton continuum is important, being this the main physical background for $\bar{p}$-nucleus states, and since it allows to obtain the dependence of the proton production cross section on the target mass. For heavier targets (C, Cu, Bi), $\sigma_R \propto A^{2/3}$. For light targets (D,Li), $\sigma_R \propto A^{5/3}$.

The quasi-free backward elastic scattering on individual protons of the lighter targets could also be observed, for which an effective number of protons could be defined by comparison with the $\bar{p}p \rightarrow p\bar{p}$ cross section at the same energy.

Looking at future perspectives, recently (Baltz, 1985), the strong spin and/or isospin dependence of the imaginary part of the $\bar{N}N$ interaction was considered for a possible reduction of the annihilation probability of antiprotons in nuclei. As a consequence, systems like $\bar{N}NN$ and $\bar{N}NNN$ might form, in principle, relatively narrow bound states. From an experimental point of view, the knock-out reaction on ^3He $p+^3He \rightarrow p+X$ with $X\equiv\{\bar{p}\text{-}(pn)\}$ could be considered.

RESIDUAL NUCLEI AFTER ANTIPROTON ANNIHILATION

During the intranuclear cascade, the nucleus is heated up and finally evaporates nucleons. At the end, an excited residual nucleus if left in most cases.

The first measurements of yields of residual nuclei were performed at LEAR, by the experiment PS 186 (Moser et al., 1986) . Targets of ^{95}Mo, ^{98}Mo, ^{165}Ho and ^{238}U were irradiated with a total of about $2{\cdot}10^8$

stopped antiprotons. The radioactivity was measured using a hyperpure Ge detector for the gamma spectra and a Si(Li) detector for X rays.

Up to 30 nucleons were observed to be emitted from ^{98}Mo and up to 49 from ^{165}Ho. On the opposite site, in a few percent of the annihilations only one proton and few, if any, neutrons were removed from the nucleus. In these cases, evidently, no pion entered the nucleus. Figure 5 shows a part of the chart of the nuclides with the observed residual isotopes of the ^{98}Mo target. Only neutron deficient isotopes were seen.

The distribution of residual nuclei exhibits a substantial odd-even effect with a reduction of 30% per unpaired protons and neutrons in the Mo isotopes and of 50% for unpaired protons in Ho only. This effect may be explained by the easier evaporation of unpaired nucleons due to the lower binding energies, thus producing even nucleon numbers.

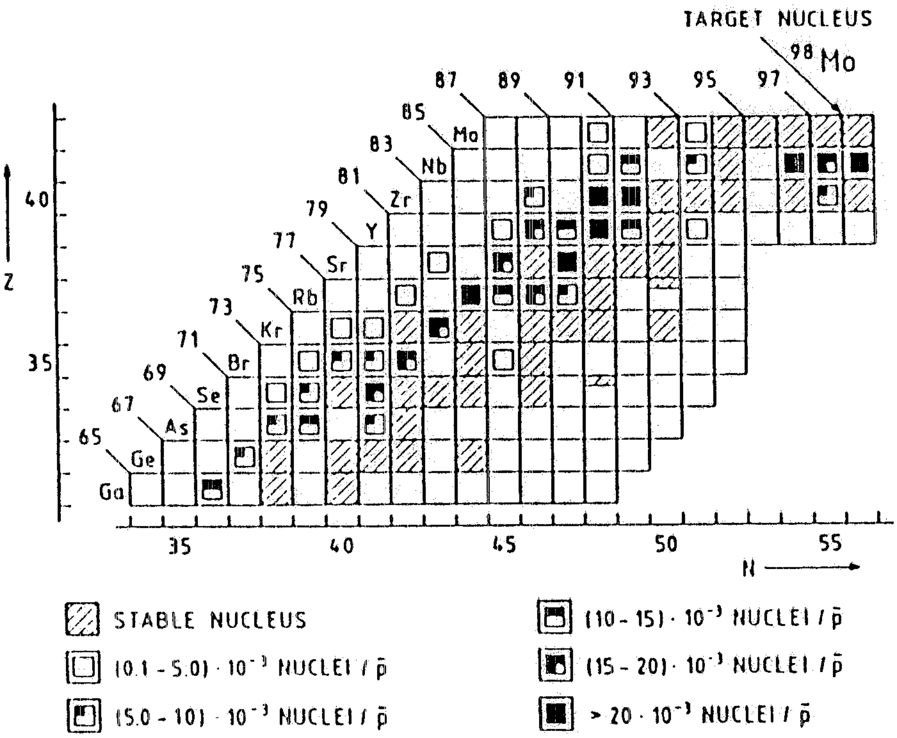

FIG. 5 - Distribution of residual nuclei in ^{98}Mo after stopped $\bar{p}$ annihilation (PS 186 experiment).

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