INS--976

JP9310194

INS-Rep.-976
May 1993

INSTITUTE FOR NUCLEAR STUDY
UNIVERSITY OF TOKYO
Tanashi, Tokyo 188
Japan

16 pages

A NATURALLY OCCURRING TRAP FOR ANTIPROTONS

J. Eades
CERN
Geneva 23, Switzerland

N. Morita
Institute for Molecular Science
Myodaiji, Okazaki 444, Japan

T.M. Ito, Y. Ito, A. Kawachi, S.N. Nakamura, R.S. Hayano, M. Iwasaki, K. Shigaki, H. Tamura
Department of Physics and Meson Science Laboratory, University of Tokyo
Bunkyo-ku, Tokyo 113, Japan

I. Sugai, E. Widmann, T. Yamazaki
Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188, Japan

W. Higemoto, N. Nishida
Tokyo Institute of Technology
Tokyo, Japan

F.J. Hartmann, H. Daniel, T. von Egidy, P. Hofmann, Y.-S. Kim
Physik Department, Technische Universität München
D-8046 Garching, Germany

Invited talk given by J. Eades at the Workshop on Traps for Antimatter and Radioactive Nuclei, TRIUMF, Vancouver, 25-27 Feb. 1993

Version April 21, 1993

A NATURALLY OCCURRING TRAP FOR ANTIPROTONS

J. Eades
CERN
Geneva 23, Switzerland

N. Morita
Institute for Molecular Science
Myodaiji, Okazaki 444, Japan

T.M. Ito, Y. Ito, A. Kawachi, S.N. Nakamura, R.S. Hayano, M. Iwasaki, K. Shigaki, H. Tamura
Department of Physics and Meson Science Laboratory, University of Tokyo
Bunkyo-ku, Tokyo 113, Japan

I. Sugai, E. Widmann, T. Yamazaki
Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188, Japan

W. Higemoto, N. Nishida
Tokyo Institute of Technology
Tokyo, Japan

F.J. Hartmann, H. Daniel, T. von Egidy, P. Hofmann, Y.-S. Kim
Physik Department, Technische Universität München
D-8046 Garching, Germany

Invited talk given by J. Eades at the Workshop on Traps for Antimatter and Radioactive Nuclei, TRIUMF, Vancouver, 25-27 Feb. 1993

ABSTRACT

The phenomenon of delayed annihilation of antiprotons in helium is the first instance of a naturally occurring trap for antimatter in ordinary matter. Recent studies of this effect at CERN are summarised, and plans are described for laser excitation experiments to test its interpretation in terms of metastable exotic helium atom formation.

In the last few days, we have heard a great deal about the many tricks which have been developed for trapping charged particles and 'holding them still for examination' to use Prof. Dehmelt's graphic phrase. These ingenious contraptions have until now all been constructed from materials such as copper wire and pieces of iron. In this talk I will describe a new kind of charged particle trap made out of helium.

HISTORICAL SURVEY

The idea that nature may provide us with natural sites at which antiprotons can be stored in stable or metastable equilibrium with ordinary matter has often seemed to be more a matter of faith and hope than reason. As early as 1947, Fermi and Teller [1] had estimated that negatively charged particles in matter should slow down from 2 keV kinetic energy, get captured by an atom of the stopping substance and cascade down to states from which strong interactions could take place, in a time which could not be longer than 10^{-13} s in solids or liquids, and 10^{-9} s in air. A similarly insightful estimate of deceleration times in hydrogen was made in 1950 by Wightman [2], who also considered the case of a ' ...negative proton...(with) mass assumed to be 1837 m...' and concluded that 2.4×10^{-10}s should suffice for the still hypothetical antiproton to go from 10 MeV to capture in a hydrogen molecule.

In the 1950's and 1960's, a proper understanding of the behaviour of very low energy negative hadrons in bubble chamber liquids became quite important, since it was necessary to know the angular momentum of the atomic state from which they undergo strong interactions. A picture emerged in which atomic capture occurred only when the hadron energy fell below the ionisation potential of the surrounding atoms, and resulted in its changing places with an atomic electron. It then occupied an atomic orbit with binding energy approximately equal to that of the displaced electron. Perturbation theory approaches were then brought to bear on the de-excitation cascade of this exotic atom, and were in general agreement that the time between atomic capture and strong interaction could not exceed a few picoseconds in hydrogen [3],[4] or helium [5]. While these figures were quite adequate in hydrogen, far too many K^-were being seen to decay at rest (i.e. in atomic orbits) in liquid helium bubble chambers [6]. Simply by counting these decays, the average time spent in the atomic cascade could be inferred to be of order 10^{-10} sec. Fetkovich and Pewitt [6] suggested that the cascade could be slowed down to the experimental value if Stark processes with neighbouring atoms were inoperative in liquid helium, although no convincing argument was presented why this should be so.

Finally Condo [7] came up with a new idea, (developed in greater detail later by Russell [8]) that the observed cascade time in helium was a mean value for *a)* a few percent of the negative hadrons which had somehow got trapped in 'special' atomic states of the exotic helium atom, and *b)* the rest, or the fast component in our current jargon, which came within strong interaction range with normal time delays (of order 10^{-12} s). According to Condo and Russell, these trapped states corresponded to circular or almost circular Bohr orbits of the hadron with large n (about 38 in the antiproton case, which as Russell pointed out, would represent an extreme case of

the effect.) The second electron, which in previous calculations was assumed to have been ejected within 10^{-15} s of the formation of the exotic atom, remained and played an essential role in the metastability - it could not easily be ejected as this required a $24.6eV$ energy release while competing radiative $\bar{p}$ transition energies were only about $2eV$, and its presence acted as an inhibitor of penetrating interactions with neighbouring (ordinary) helium atoms via the Pauli principle. The neutrality of this exotic atom also meant that it was not subject to the molecular Stark effect caused by the weak electric field of the helium atom. All fast routes to the nucleus were thus closed off in this model, and a relatively slow electromagnetic cascade alone could take place until the $\bar{p}$ could eject the second electron. From this point the fast $\bar{p}$ He^{++}cascade as in [5] took over and the hadron's picoseconds were numbered. Of course, the trapped state lifetimes had to be much longer than 10^{-10} sec to give the right average when included with the more numerous untrapped ones. (For a more detailed discussion of the historical material covered above, please consult [9].)

RECENT STUDIES

These ideas seem to have been unnoticed by people looking for naturally occuring antiproton traps. Inokuti's speculations [10] on places where $\bar{p}$ might hide from the strong interaction included lattice sites in crystals and $\bar{p}$ analogues of the hydrated electron but did not include helium atoms, while Campbell [11] discussed the possibility of trapping $\bar{p}$ outside atoms of superfluid ^{4}He and degenerate liquid ^{3}He rather than inside them.

The Condo-Russell model first received direct confirmation in 1989 when [12] 2% of the K^-beam stopped in liquid helium was directly observed to have a trapping lifetime of about 60 ns. In a later experiment here in TRIUMF the corresponding effect was observed with π^-[13] with 2.3% trapping fraction and 7.26 ± 0.12 ns lifetime. In both cases, the trapping effect is cut short by the meson decay, and it was clear that the most interesting effect would be with $\bar{p}$ which are stable. A great effort was made at KEK early in 1991 [14], and $\bar{p}$ trapping was finally observed in liquid helium at a level of 3.6% using a beam containing only 28 $\bar{p}$ per second and a thousand times as many π^-. More than one lifetime component was visible in the data, but the overall trapping lifetime was evidently of the order of μs. At this point it became clear that LEAR in CERN was the only machine which would allow detailed study of this fascinating phenomenon as its $\bar{p}$ beams are 100% pure, have excellent emittance and are available at energies down to 5 MeV. These characteristics would allow the effect to be studied with $\bar{p}$ stopped in gas as well as liquid helium targets.

Figure 1 shows schematically the layout of the apparatus used during our first runs at LEAR in Aug 1991 and September 1992. The $\bar{p}$ beam enters a target chamber containing liquid, gaseous or solid helium via a thin beam particle scintillation counter (B). Moderation foils (not shown) are inserted to tune the energy to a value such that the $\bar{p}$ stop in the centre of the chamber. A small fraction of ensuing annihilation products are detected by scintillation counter hodoscopes H1 and H2, which permit us to check that the annihilations do in fact occur in the helium and not in the windows

or walls of the target vessel. The annihilation scintillation counters (A) surrounding the target vessel are large enough to detect (charged) annihilation products with high, though not perfect, efficiency.

A beam $\bar{p}$ passing through B starts a time to digital converter which is stopped by the arrival of a charged annihilation product in A. This procedure alone is quite insufficient to establish delayed annihilation as can be seen from figure 2, which shows the time spectrum obtained with the target empty, so that the $\bar{p}$ strike the end plate and annihilate there. They do so promptly (via a normal fast cascade as discussed above) and produce the sharp peak at annihilation time t equal to zero. The $t > 0$ (delayed) events in fig 2a are entirely spurious, and correspond to typical accidental coincidences in which a B count is followed by an unrelated A count from the annihilation of a different $\bar{p}$, occurring by chance within the time region of interest. These have been removed in fig 2b by a 'confusion elimination' technique described in detail in [15]. The apparent 2.2μs delayed component which remains (fig 2b) is also spurious and corresponds to pions from prompt annihilations which have stopped in the vessel walls and other material. These produce muon decays with that lifetime and the resulting e^-or $e^+$are detected in A. By requiring two simultaneous particles in A we can largely eliminate these events (fig 2c), although it is necessary to demand three of them to get rid of this effect completely (fig 2d).

Having convinced you that we took all the right precautions to see no delayed annihilations when none are in fact there, I can show some spectra from the 1991 run which show the genuine effect. Figure 3a is one of the first spectra we took with a gas helium target. The fraction f of $\bar{p}$ trapped and the average lifetime between 100ns and 25μs are indicated. It was no small surprise to find that these values were very close to those observed at KEK with liquid helium (see fig 4a), although there are some important differences of detail. When we introduced only 20 ppm of hydrogen into the helium, a quite strong quenching effect appeared (fig 3b) and at 400 ppm (fig 3c) the portion of the spectrum later than 4μs disappeared almost entirely. On the contrary, when we added neon, we found we could go up to about 5% concentration with no effect at all on the spectrum. Figures 4b and 4c show quite a strong isotope effect in the gas phase at 3 atm. The mean lifetime (evaluated here between 1μs and 25μs) changes by about 14% in going from ^{4}He to ^{3}He . Figures 3 and 4 have been reproduced from our recent paper in Nature [15], in which more detail and discussion can be found.

The above results have been presented without comment, and it is indeed difficult to find a consistent overall interpretation of our numerous spectra, which are full of intriguing similarities and differences. In the 1992 runs we tried many new things including a search for trapping in lithium. There was no effect at all, whether we looked at polycrystalline LiF, Li metal, or LiH. We also looked at the effect in cold helium gas (which allowed us to reach higher number densities than we could get with a pressurised room temperature target), in solid ^{4}He , and in mixtures of helium with other noble gases, and investigated the effect of hydrogen, nitrogen and oxygen impurities more closely. The difference between an admixed gas and a gas present as an impurity, as far as we are concerned, is that at impurity concentrations foreign atoms (molecules) can only affect the exotic atoms after formation; in mixtures the

foreign atoms are present in sufficient numbers to influence the formation process itself by changing the energy distribution at capture. This changes the maximum angular momentum which can be brought into the exotic atom by the $\bar{p}$ and consequently changes the way the $\bar{p}$ are distributed among the available atomic states. Mixtures studied so far include He-Ne, He-Ar, He-Kr and He-Xe. It seems to be a general feature that molecular gases have strong quenching effects at impurity concentrations, while noble gas admixtures quench much moderately but with successively greater efficiency as we move up the periodic table.

These data were discussed at the LEAP '92 conference and more details can be found in its *Proceedings* [16]. It is true to say that they have added more mystery to an already mysterious situation. The conclusion of an informal workshop held on the slopes of Mt. Fuji a few days before this one was that we now need to look at different aspects of the effect before we can really understand what is going on.

FUTURE INVESTIGATIONS

The isotope effect described above and some other features of the data are consistent with the results of the Condo-Russell model as developed most recently in [17]. The direction in which we have chosen to move is to adopt this as a working hypothesis and to carry out laser spectroscopy from its metastable states using excimer-pumped dye lasers. Figure 5 shows the part of the level scheme of the $\bar{p}$ He e^-atom with n between 37 and 41 and total angular momentum L of this atom between 31 and 39 (the electron being predominantly in a $1S$ state) as calculated in [17]. The calculated radiative and Auger rates are indicated for several $\bar{p}$ levels. There is a clear boundary between metastable and short-lived states near the $L = 35$ and $L = 36$ columns and this has been indicated by drawing the states with lifetime less than 2.5 ns with broken lines. A $1 MW/cm^2$ 10 ns laser pulse at about $2eV(600nm)$ can excite transitions across this boundary from the column of four long-lived states at L=35 at a rate matched to the formation rate of a few kHz which we achieve in our low-intensity parasitic $\bar{p}$ beam. This is a very sensitive way of doing laser spectroscopy of these trace concentration states, as it results in almost instantaneous destruction or 'forced annihilation' of the antiproton via rapid Auger transitions to $\bar{p}$ He^{++}states also shown. A second laser will permit forced annihilation in two steps from several other metastable states at L=36 and L=37. The dye lasers can be tuned over the range 320 to 950 nm permitting many other spectroscopic experiments with these atoms. As we will work with the metastable states on an individual basis, we must fire the laser only when we are sure that one of them has been formed. This implies that very high efficiency must be obtained in all scintillation counters which participate in the veto condition that no charged particle passing through A immediately after a given B hit generates a trigger. Prompt neutral as well as charged annihilation products must therefore be detected with high efficiency, and the A counters of fig 1 are consequently being replaced by lead/scintillator sandwich stacks.

The minimum laser pulse delay after a trigger is about $1\mu s$. The effect on the time spectrum of a trigger at this delay has been simulated by a computer programme

and the result is given in figure 6 for the transition $(n, L) = (37, 35)$ to $(n, L) = (38, 34)$. The forced $\bar{p}$ annihilations occur in a time short compared to typical trapping times, resulting in a peak at $1\mu s$ in the annihilation time spectrum followed by a slight depletion at later times. The resonance will first have to be found by scanning the laser pulse near the calculated values, since these are only accurate to about 0.1%. However, locating the first resonance essentially calibrates the calculations and subsequent transitions should be quite easy to find. Full details of the simulations can be found in [18].

SUMMARY

Further studies have been made of the naturally occurring antiproton trap in helium first discovered at KEK. The dependence of the effect on the helium isotope used is consistent with an interpretation which assigns metastability to high angular momentum states of an atom consisting of a $\bar{p}$ and $e^-$and a helium nucleus. The details of the annihilation time spectrum are still imperfectly understood, as are the effects of adding foreign gases at trace and admixture levels. Laser excitation experiments are planned to test the above atomic model of the metastability.

ACKNOWLEDGEMENTS

The work described herein could not have been accomplished without the continuous and enthusiastic efforts of the CERN LEAR staff. The present work is supported by a Grant-in-Aid for Scientific Research and International Scientific Research of the Japanese Ministry of Education, Science and Culture, by the International Joint Research Project of the Japan Society for the Promotion of Science, and by the German Ministry of Research and Technology. S.N.N. and E.W. acknowledge the receipt of JSPS Fellowships.

References

[1] E. Fermi and E. Teller, *Phys. Rev.* **72** (1947) 399.

[2] A.S. Wightman, *Phys. Rev.* **77** (1950) 521.

[3] M. Leon and H.A. Bethe, *Phys. Rev.* **127** (1962) 636.

[4] G.A. Baker Jr., *Phys. Rev.* **117** (1960) 1130.

[5] T.B. Day, *Il Nuovo Cimento* **XVIII** (1960) 381.

[6] J.G. Fetkovitch and E.G. Pewitt, *Phys. Rev. Lett.* **11** (1963) 290.

[7] G.T. Condo, *Phys. Lett.* **9** (1964) 65.

[8] J.E. Russell, *Phys. Rev. Lett.* **23** (1969) 63; *Phys. Rev.* **188** (1969) 187; *Phys. Rev.* **A1** (1970) 721, 735, 742; *J. Math. Phys.* **12** (1971) 1906; *Phys. Rev.* **A6** (1972) 2488.

[9] R.S. Hayano, M Iwasaki, and T. Yamazaki, *Perspectives of Meson Science* p417, Eds. T. Yamazaki, K.Nakai and K. Nagamine, North-Holland 1992.

[10] M. Inokuti, *Nucl. Tracks Radiat. Meas.* **16** (1989) 115.

[11] L.J. Campbell, *Proceedings of the RAND Workshop on Antiproton Science and Technology* p342, Eds. B.W. Augenstein, B.E. Bonner, F.E. Mills and M.M. Nieto, World Scientific 1988.

[12] T. Yamazaki *et al.*, *Phys. Rev. Lett.* **63** (1989) 1590.

[13] S.N. Nakamura *et al.*, *Phys. Rev. A* **45** (1992) 6202;
S.N. Nakamura, Master thesis, March 16 1991, Department of Physics, Faculty of Science, University of Tokyo

[14] M. Iwasaki *et al.*, *Phys. Rev. Lett.* **67** (1991) 1246.

[15] T. Yamazaki *et al.*, *Nature*, **361**, No. 6409, (1993) 238.

[16] Proceedings of the Second Biennial Conference on Low Energy Antiproton Physics (LEAP '92), Courmayeur, Italy, 14-19 September 1992, to be published as a special issue of *Nucl. Phys A*.

[17] T. Yamazaki and K. Ohtsuki, *Phys. Rev. A*, **45** (1992) 7782.

[18] N. Morita, K. Ohtsuki and T. Yamazaki, Institute for Nuclear Study University of Tokyo, report INS-Rep.-963 (Dec. 1992), also submitted for publication in Nucl. Instr. and Methods.

FIGURE CAPTIONS

Fig. 1: Experimental setup at LEAR in September 1991 and 1992. The beam momentum was $105 MeV/c$ in 1991 and $200 MeV/c$ in 1992.

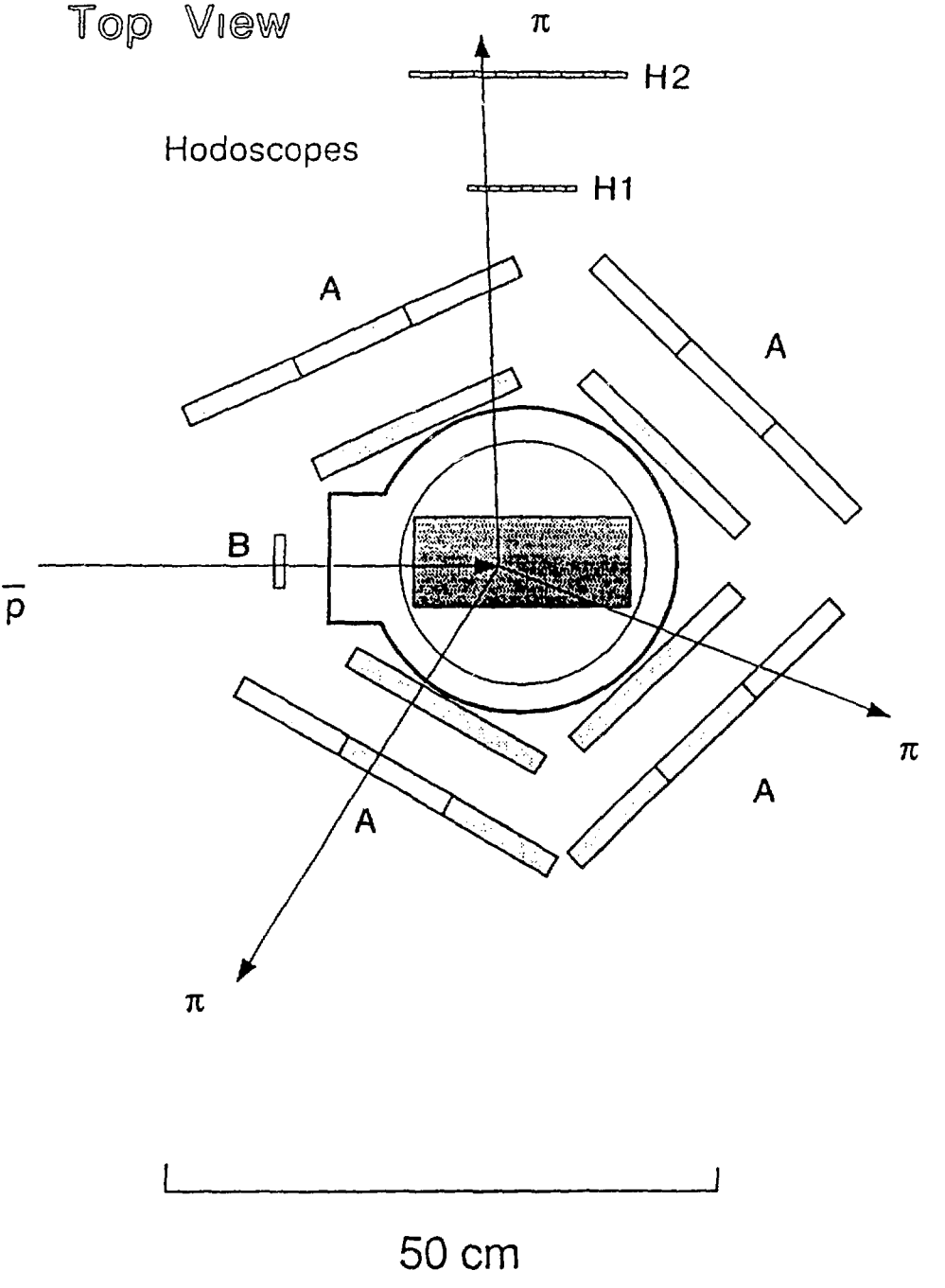
Fig. 2: Time spectra of empty target: *a)* raw data, *b)* data after pile up rejection ('confusion elimination'), *c)* with additional $\geq 2\pi$ tag and *d)* $\geq 3\pi$ tag.

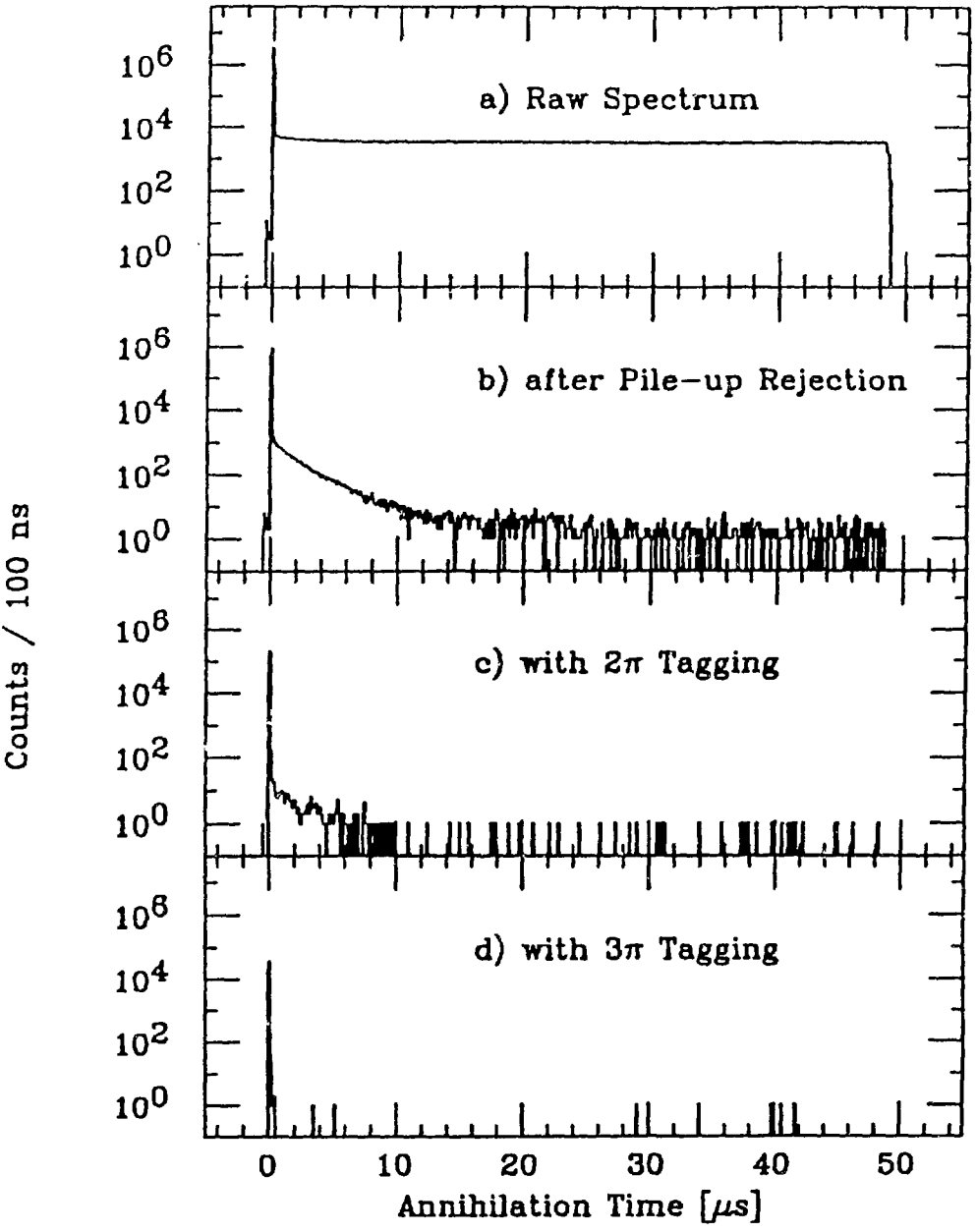
Fig. 3: Time spectra of pure ^{4}He at 6 atm, *a)* pure He *b)* with 20 ppm hydrogen *c)* with 400 ppm hydrogen

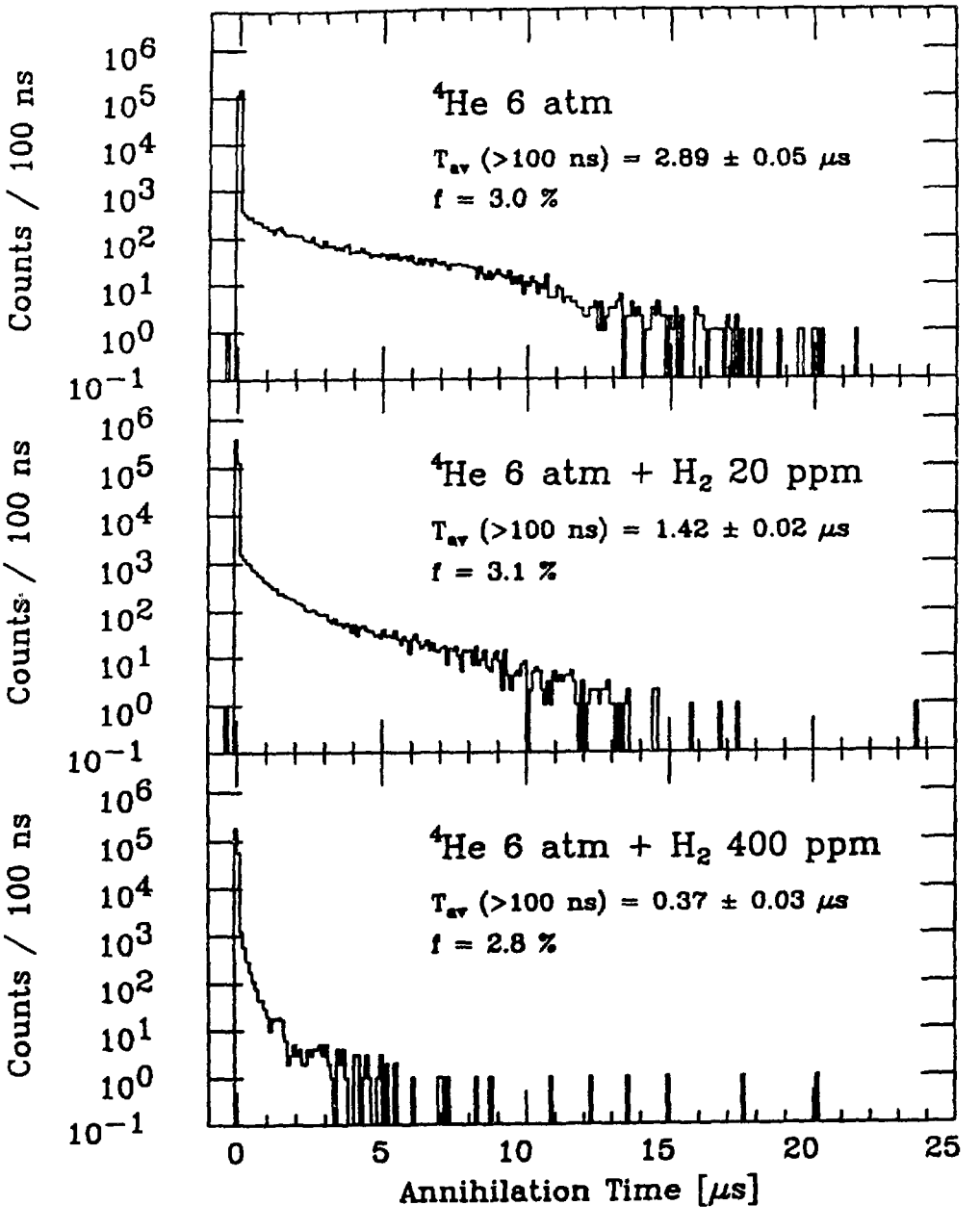
Fi. 4: Time spectra of delayed annihilations: *a)* KEK result with liquid helium, shown for comparison, *b)* ^{4}He at 3 atm *c)* ^{3}He at 3 atm.

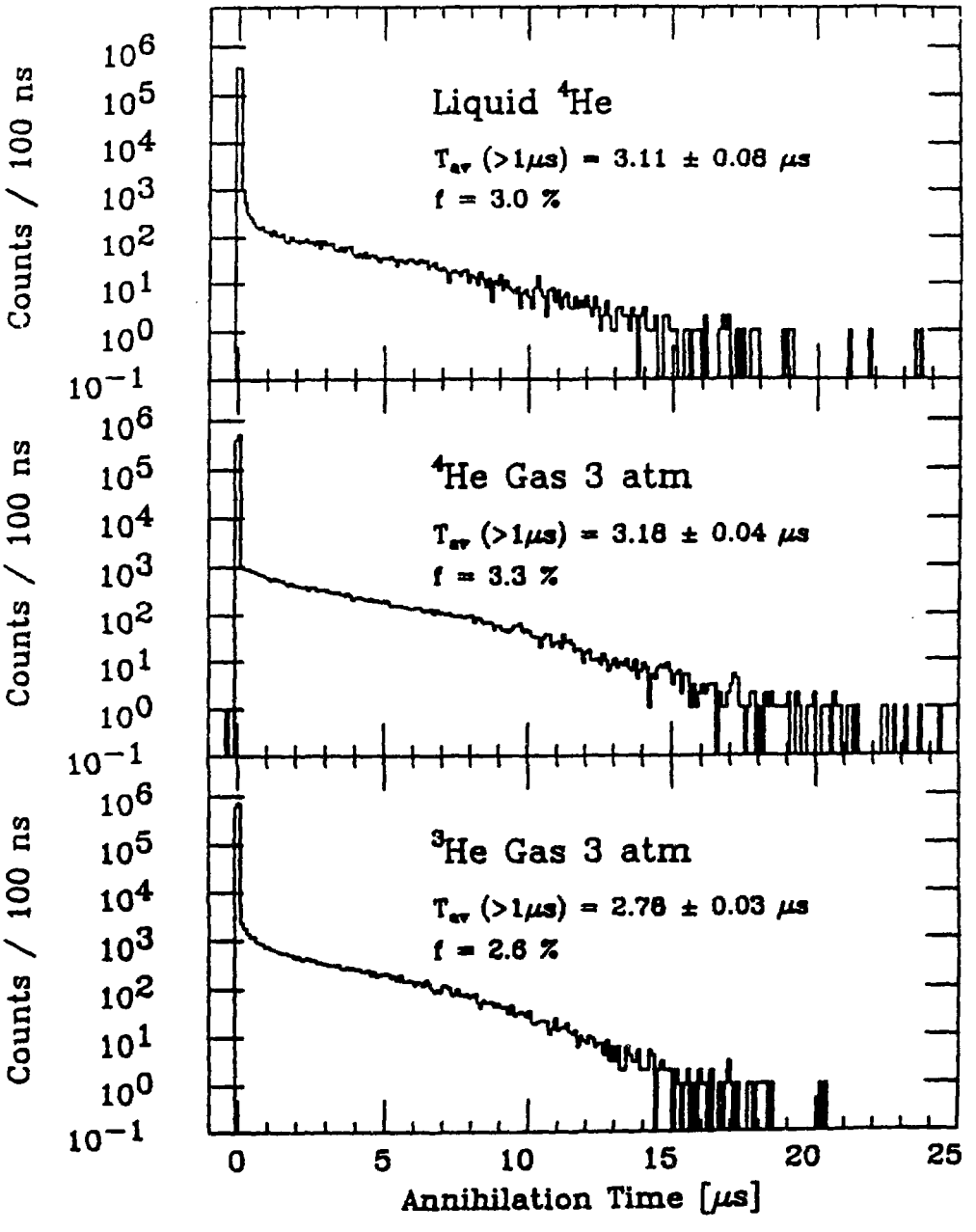
Fig. 5: Level structure and transition rates of metastable antiprotonic helium atoms calculated by K. Ohtsuki. Solid lines represent metastable states with lifetime longer than $2.5 ns$, broken lines represent shorter lived states of this atom. The two states $(n, L) = (39, 34)$ and $(n, L) = (38, 34)$ deexcite to the ionised state $\bar{p}\, He^{++}$ with $n = 32$ and $l = 31$ by Auger emission. The former states can be reached from the column of four metastable states with $L = 35$ by laser excitation/deexcitation near $2eV, 600nm$.

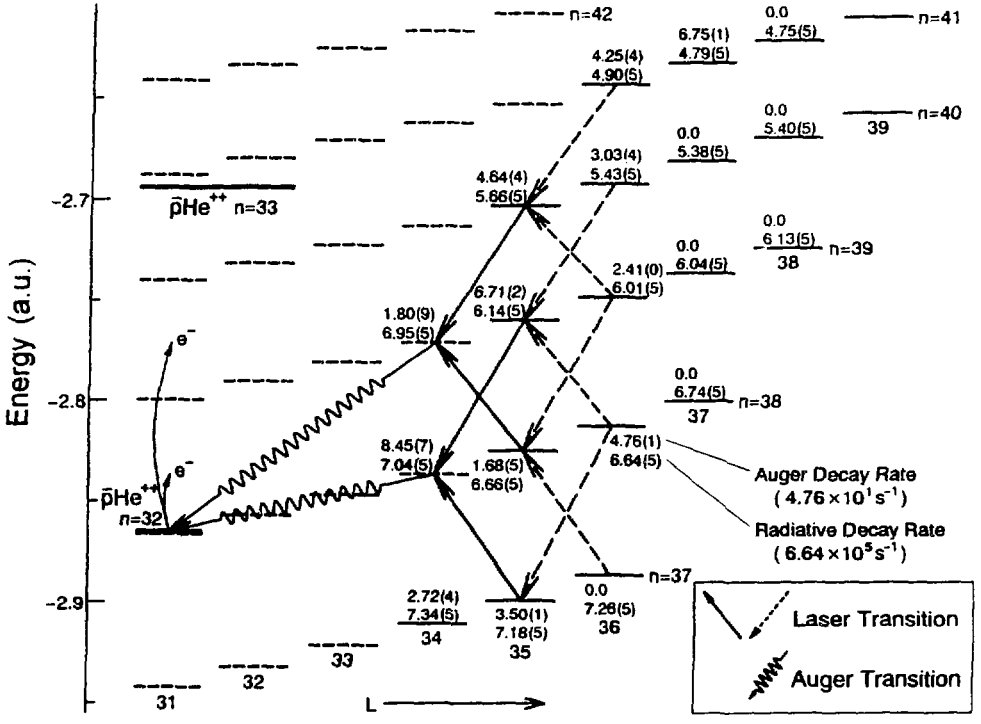
Fig. 6: Computer simulation of the effect on the time spectrum of delayed annihilations of laser-induced transition from $(n, L) = (37, 35)$ to $(n, L) = (38, 34)$. The sharp spike represents forced annihilation from the non-metastable state via the transition. The population of states calculated by Ohtsuki is assumed, and the laser is triggered $1\mu s$ after the electronic logic indicates a ' $\bar{p}$ without prompt annihilation ' signal. After $1\mu s$ the entire spectrum is deficient by the total number of forced annihilations.

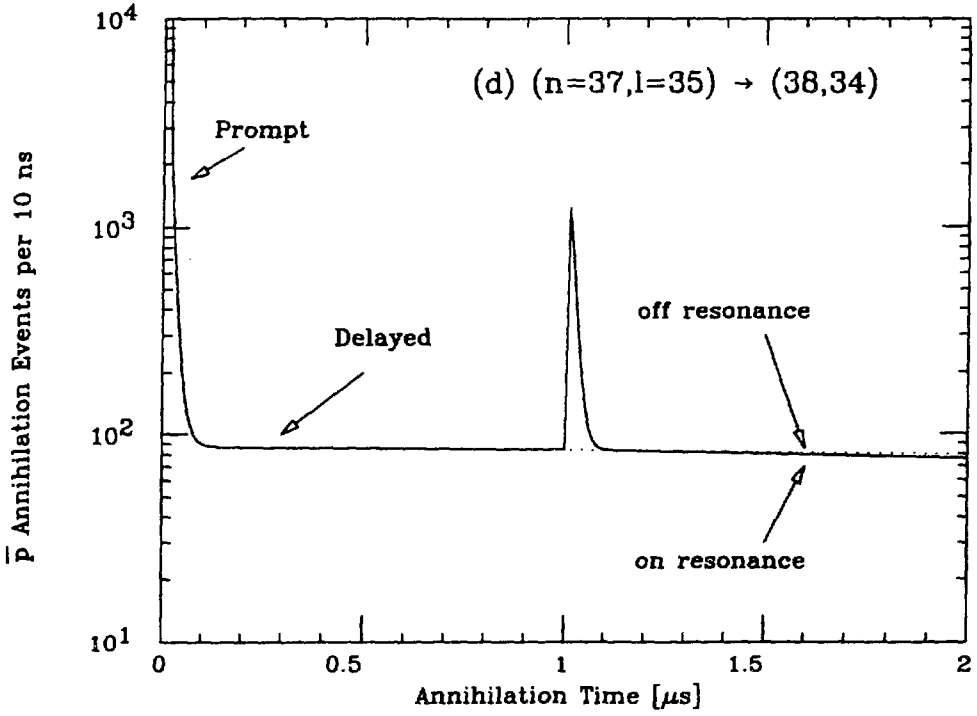

Top View
π
H2
Hodoscopes
H1
A
A
B
p̄
π
A
A
π
50 cm


a) Raw Spectrum
b) after Pile–up Rejection
c) with 2π Tagging
d) with 3π Tagging
Counts / 100 ns
Annihilation Time [μs]
0
10
20
30
40
50


^{4}He 6 atm
T_{av} (>100 ns) = 2.89 ± 0.05 μs
f = 3.0 %
^{4}He 6 atm + H_2 20 ppm
T_{av} (>100 ns) = 1.42 ± 0.02 μs
f = 3.1 %
^{4}He 6 atm + H_2 400 ppm
T_{av} (>100 ns) = 0.37 ± 0.03 μs
f = 2.8 %
Counts / 100 ns
Annihilation Time [μs]


Liquid ^{4}He
T_{av} (>1μs) = 3.11 ± 0.08 μs
f = 3.0 %
^{4}He Gas 3 atm
T_{av} (>1μs) = 3.18 ± 0.04 μs
f = 3.3 %
^{3}He Gas 3 atm
T_{av} (>1μs) = 2.78 ± 0.03 μs
f = 2.6 %
Counts / 100 ns
Annihilation Time [μs]


Energy (a.u.)
-2.7
-2.8
-2.9
p̄He++ n=33
p̄He++ n=32
e-
e-
n=42
n=41
n=40
n=39
n=38
n=37
4.25(4)
4.90(5)
6.75(1)
4.79(5)
0.0
4.75(5)
0.0
5.40(5)
39
3.03(4)
5.43(5)
4.64(4)
5.66(5)
0.0
5.38(5)
0.0
6.13(5)
38
2.41(0)
6.01(5)
0.0
6.04(5)
6.71(2)
6.14(5)
1.80(9)
6.95(5)
0.0
6.74(5)
37
8.45(7)
7.04(5)
1.68(5)
6.66(5)
4.76(1)
6.64(5)
Auger Decay Rate
(4.76×10¹s⁻¹)
Radiative Decay Rate
(6.64×10⁵s⁻¹)
2.72(4)
7.34(5)
34
3.50(1)
7.18(5)
35
0.0
7.28(5)
36
31
32
33
L
Laser Transition
Auger Transition


(d) (n=37,l=35) → (38,34)
Prompt
Delayed
off resonance
on resonance
10^4
10^3
10^2
10^1
0
0.5
1
1.5
2
$\bar{p}$ Annihilation Events per 10 ns
Annihilation Time [μs]