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Abstract. The main objective of the present paper is to discuss the consequences of matter-antimatter interaction at low energy. The production of large number of cooled antimatter in laboratory and the formation of exotic atoms composed of particles and antiparticles are reviewed. Particularly, the quantum mechanical treatment of Four-Body exotic molecules is shortly discussed. The main goal of the paper is to shed light on possible novel discoveries and applications based on the coexistence of matter and antimatter.

1. Introduction
The existence of Antiparticles was predicted by P. Dirac [1] in 1930 and discovered D. V. Anderson [2]. The first discovery of a bound state composed of the electron and its antiparticle (positron) was made by Deutsch in 1951 [3] and was referred to as positronium (Ps). Theoretical prediction of quasimolecular structures composed of two positroniums was established by different authors (for a review see Abdel-Raouf [4]). The experimental proof of possible formation of Ps2 was provided by Mills group [5, 6].

The real interest in antimatter physics has started with the discovery of antiprotons in Berkeley’s Bevatron in 1955 by Owen Chamberlain and Emilio Segre’ [7]. With the construction of the 600 MeV Synchrocyclotron (SC) at CERN in 1957, revolutionary ideas and experiments in particle and nuclear physics became possible. The establishment of the Proton Synchrotron (PS) at CERN in 1959 has increased the beam energy to 28 GeV. Seeking the production of large number of antiparticles through the collision of fast protons with hard blocks was hindered due to the transfer of most of energy to recoil energy absorbed by the block. To overcome this difficulty, a proton-proton collider was developed at CERN and the Intersecting Storage Rings (ISR), came into operation in January 1971.

The development of the Initial Cooling Experiment (ICE) at CERN [8], which allowed in 1978 for the storage on few cooled Antiprotons with lifetime 32 hours, and its further development in 1982 to the Low Energy Antiproton Ring (LEAR) [9] has paved the road towards the discovery of new physics focusing on antimatter production and matter-antimatter interaction at low energy. It is interesting to mention that LEAR had operated until 1996, when it was converted into the Low Energy Ion Ring (LEIR) and to the Extra Low ENergy Antiproton (ELENA) ring [10] which provides the Antiprotons for the LHC Experiments.

The main objective of the present work is to explore the physics behind the interaction of matter with antimatter at low energies and shed light on possible novel discoveries and applications. The paper is displayed in other three sections. In section 2 the discovery of various antiatoms are reviewed. The section is concerned mainly with the production of various quasi particle-antiparticle atomic structures. Section 3 is devoted to the discussion of possible formation of quasimolecules composed of atoms and antiatoms. There are presented quantum mechanical treatment of four-body problems and solutions leading to the formation of four-body bound states. In section 4 we discuss novel consequences of the coexistence of matter and antimatter. The paper is concluded with the list of all references given in the text.
2. Matter-Antimatter Quasi Atomic Structures

The development of the Low Energy Antiproton Ring (LEAR) at CERN in 1982, (figure 1) was the first step towards the production and accumulation of reasonable number of cooled antiprotons. The Proton Synchrotron (PS) accelerates protons to energy of 26 GeV. The collision of protons with iridium target yields enough energy for the production of antiprotons with temperature of 10 trillion K (1013 K). It has been noticed that one antiproton is produced for each 200,000 protons collide with the target. The lowest temperature to which the antiprotons can be cooled is 4.2 K.

The production of large number of cooled antiprotons encouraged the establishment of the ATHEANA Experiments[8] which led to the formation of the first Antiatom, namely the Antihydrogen, at CERN in 1995 [11, 12], (for a review see e.g. [13], (see also figure 2).

![Figure 1. Low Energy Antiprotons Ring (LEAR) and Machine at CERN 1982.](image)

![Figure 2. ATHENA experiment (a) and the indication (b) of the first formation of Antihydrogen Atom [11].](image)

Figure (2b) demonstrates the annihilation of the constituents of the Antihydrogen; the antiproton into four charged pions (yellow tracks) and the positron into two, back-to-back 511 keV gamma rays (red tracks). On the other hand, it was shown for the first time in 2011 that two Antiprotons and two Antineutrons could form a bound state referred to as Antihilium which was detected by the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (figure 3) [14].
Figure 3. (a) The Relativistic Heavy Ion Collider (RHIC) with the red track confirming the formation of Antihilium demonstrated in (b) [14].

Fundamental development of the physics of particle-antiparticle interaction at low energy was achieved by ATHENA GROUP at CERN in 2006 [15], (see Figure 4). It was proved for the first time that the collision of a proton with an Antihydrogen leads to the formation of a bound state composed of a proton and an antiproton, (identified by the Authors as antiprotonic hydrogen), in which both particles are rotating around each other. The binding energy of the antiprotonic hydrogen was calculated as $E_0 = -0.75$ keV and the lifetime is $\tau \sim 1.0 \times 10^{-6}$ s.

Figure 4. Formation of Antiprotonic Hydrogen by ATHENA EXPERIMENT at CERN [15].

With the discovery of the antiprotonic hydrogen, it the possible formation of quasi onium atoms was confirmed. The most familiar ones are:

1. Positronium (Ps, composed of an $e^-$ and a $e^+$) with $E_0 = -6.8$ eV, formed as singlet state (para-positronium) with lifetime $\tau \sim 10^{-10}$ s and as triplet state (ortho-positronium) with lifetime $\tau \sim 10^{-7}$ s,
2. Protonium [15] (Pn, composed of a $p^+$ and a $p^-$) with $E_0 = -0.75$ keV),
3. True Muonium [16] (Mu, composed of a muon $\mu^-$ and an antimuon $\mu^+$) with $E_0 = -1407$ eV, formed as singlet state (para-muonium) with lifetime $\tau \sim 0.602 \times 10^{-12}$ s and triplet state (ortho-muonium) with lifetime $1.81 \times 10^{-12}$, and
4. Pionium [17] ($\Lambda_{2\pi}$, consisting of a pion, $\pi^+$, and an antipion $\pi^-$ with $E_0 = -1860$ eV and a lifetime $\tau \sim 2.89 \times 10^{-15}$ s.
3. Matter-Antimatter Quasimolecular Structures

From the preceding section we note that both experimental and theoretical investigations have shown that Particles and Antiparticles can form quasi atomic structures in nature. The possible formation of quasimolecular structures composed of particles and antiparticles was investigated by Abdel-Raouf [18] on the basis of a Four-Body mathematical scheme [19]. Theoretical proof of coexistence of Antihydrogen with Hydrogen, Deuterium and Tritium was provided by Abdel-Raouf and Ladik [20]. The determination of the binding energies of these exotic molecules could only be established on computational level. In fact, investigations concerned with the possible formation of positronium entities (Ps± and Ps2) go back to the early work of John Wheeler [21]. Unlike Ps±, his attempt to show that Ps2 could be formed in nature had failed due to the elementary form of the trial wavefunction used. Hylleraas and Ore [22] had shown that the binding energy of this molecule is -0.116 eV. (Theoretical calculations of the binding energy of Ps2 have improved over the years, (see e.g. El-Gogary et al [23] which has been reported by Cassidy and Mills [6]). Works on formation and annihilation of positronium molecules were reviewed within the context of the Four-Body Theory by Abdel-Raouf et al [24].)

Let us now consider the quantum mechanical treatment of a Four-Body system composed of two particles and two antiparticles aiming to test its possible formation by calculating its binding energy using Rayleigh – Ritz variational method [25]. The Four-Body system defined in Figure 5 is governed by the full Hamiltonian

$$H = -\frac{\hbar^2}{2m_1} \nabla_1^2 - \frac{\hbar^2}{2m_2} \nabla_2^2 - \frac{\hbar^2}{2m_3} \nabla_3^2 - \frac{\hbar^2}{2m_4} \nabla_4^2 + Z e^+ (\frac{1}{r_{13}} + \frac{1}{r_{24}} + \frac{1}{r_{23}} + \frac{1}{r_{14}})$$

(1)

where $m_i^+$ is the mass of the $i^{th}$ particle, $r_{ij}$ is the internal distance between the $i$ and $j$ particles and $Ze^+$ is the charge of the $\pm$ particle.

The calculation of the binding energy using Rayleigh-Ritz’ variational method is carried out by diagonalising the Hamiltonian (1) in the Hilbert space $\{|\phi_i\rangle\}_{i=1}^\infty$, spanned by the Hylleraas type vectors.

Figure 5. Schematic representation of a Four-Body System.
\[ \chi_i = A(1 \leftrightarrow 3, 2 \leftrightarrow 4) \{ s_1 m_i s_2 n_i \ Exp \{-\alpha_i(s_1 + s_2)\} \ t_1 k_i \ t_2 \ell_i \ \cosh \{\beta_i(t_1 - t_2)\} v_{q_i} e^{-\gamma_i v}\}, \]

With the following set of parameters:

\[ s_i = (r_{i3} + r_{i4})/r_{34} ; i = 1,2 \]
\[ t_i = (r_{i3} - r_{i4})/r_{34} ; i = 1,2 \]
\[ s_3 = (r_{13} + r_{23})/r_{12} , s_4 = (r_{14} + r_{24})/r_{12} , \]
\[ t_3 = (r_{13} - r_{23})/r_{12} , t_4 = (r_{14} - r_{24})/r_{12} , \]
\[ u = r_{12} / r_{34} , v = r_{34} . \] (3)

The calculations have been carried out using the first 50 components of the Hylleraas vectors for the following four-body systems:

1. e^-e^- e^+ e^-
2. e^-e^- \mu^- \mu^+
3. e^-e^- p^- p^+
4. e^-e^- \pi^- \pi^+
5. e^-e^- p^- d^+
6. e^-e^- p^- t^+

The bound-state of any of these systems is said to be confirmed if and only if the variational binding energy supports the coexistence of the lowest threshold of this system, i.e. if the system is stable against all possible corresponding dissociation channels.

Let us proceed by defining the following quantities:

\[ \sigma = m_i/m_j^+ , \] where \( i = 1,2 \) and \( j = 3,4 \), i.e. \( \sigma \) is the mass ratio between negatively charged and positively charged particles,
\[ E_{th} = (E_{12} + E_{34}) , \] is total energy of the lowest threshold channel (or the dissociation energy)

of the four-bodies, composed of the two separate quasiatoms (\( m_1^-m_2^+ \) and \( m_3^-m_4^+ \)).
\[ W(\sigma) = E_b = \text{Binding energy of the Four-Body system, where } W(\sigma) < 0 \text{ guarantees that the system} \]

is bound and can be formed in nature,
\[ E = \text{is the total energy of the Four-Body system,} \]
\[ \varepsilon (\sigma) = E(\sigma) /E_{th} \] the energy ratio between the total energy of the considered Four-Body system

and the sum of the total energies of the two quasiatoms of the lowest possible dissociation channel, and
\[ \omega (\sigma) = \varepsilon (\sigma) - 1, \] where. \( \varepsilon (\sigma) > 1 \) and \( \omega (\sigma) > 0 \) indicate that the system is bound.

The first step in our elaborate calculations was to find the optimum values of the nonlinear parameters appearing in \( |\chi_i\rangle \) and to test the convergence of the resulting binding energies with increasing number of superpositions. It was found that the first 50 superpositions of \( |\chi_i\rangle \) are enough to provide quite stable converging results.

The final calculations of the parameters mentioned above are displayed in Table 1

Table 1: Total, Threshold and Binding Energies of Various Four-Body Systems
The results presented in the fourth and sixth column of the table support the conclusion that all Four-Body systems given in the first column are bound and could form quasi-molecular structures in nature stable against dissociation to their lowest possible channels. Thus, apart from direct annihilation channels, particle-antiparticle interactions at low energies are also accompanied with the formation of quasiatomic structures and exotic molecular compounds.

4. Consequences of the Matter-Antimatter Coexistence

In the following subsections we discuss three possible consequences of the possible coexistence of matter-antimatter at low energies.

4.1. Matter-Antimatter Chemistry

Compounds composed of Atoms and Antiatoms could lead to the discovery of a new field to be referred to as Antimatter Chemistry [26] and better understanding of our universe. In this work we studied possible formation of Antihydrogen -Hydrogen, -Deuterium and -Tritium compounds which had been referred to as Heterohydrogens, [27] where the prefix “Hetro” identifies a molecular structure composed of an atom and its antiatom. Theoretical investigations of positronic compounds are given by different Authors [28, 29]. Much earlier calculations on Ps2O, (the so called positronium water) were performed by Jiang and Schrader [30]. Antimatter chemical compounds are subjected to various chemical operations and could be implemented in laboratory.

4.2. Cold Fusion and Production of Fuel for Space Shuttles

The idea of nuclear cold fusion was theoretically and experimentally studied by Martin Fleischman and collaborators [31-34]. It demands the injection and fusion of Hydrogen, Deuterium, Tritium and Muonium in Palladium molecular crystal, (see also [35] and [36]).

The creation of large number of Antihydrogen at Laboratory, (see e.g. ATRAP Experiment at CERN) suggests a new scenario of cold fusion (see Abdel-Raouf [37]) in which Hydrogen followed by Antihydrogen are injected in a sheet of Palladium Crystals. The advantage of the realization of fusion energy based on matter-antimatter annihilation is threefold:

(1) It is considerably larger than fusion energy obtained from nuclear reactions,
(2) It is cold, and
(3) Controllable

As alternative to the preceding scenario, we consider the possible production of huge amount of Energy through the formation of highly populated medium (Plasma), composed of electrons and positrons, injected via electron and positron guns into palladium sheets. In this case we argue that if a thermalized beam of positrons passes through a palladium sheet in which a large number of free (or localized) electrons are populated different positronium entities could be formed as well as positron-
electron plasma. The resulting annihilation processes could provide us with a source of considerable amount of energy. (In Table 2 are presented the orders of magnitudes of energies gained by different sources).

Table 2: Comparison between the orders of energies produced by different processes

| Process                             | Energy (Joule/Kilogram) |
|-------------------------------------|--------------------------|
| Chemical Reaction                   | $1 \times 10^7$          |
| Nuclear Fission                     | $8 \times 10^{13}$       |
| Nuclear Fusion                       | $3 \times 10^{14}$       |
| Fusion based on Annihilation         | $9 \times 10^{16}$       |

One of the most interesting consequences of low energetic matter-antimatter interaction is the development of a novel source of energy which could be employed as fuel for engines for space Labs, (see Abdel-Raouf 38). The idea is to store a tiny amount (few micrograms) of antimatter (say Antihydrogen) in electromagnetic controlled cavity and allow part of it to mix with a huge amount of stored matter (say Hydrogen, Deuterium, Tritium or Helium Gas). The resulting annihilation energy could be stored and used as a fuel for space shuttle engines, (see [38] and [39]).

The vigorous interest of space scientists and engineers working at NASA in building up such engines for space shuttles is twofold:

1. The engine would be extremely light, i.e. the mass of the whole Space Shuttle would be considerably small,
2. The energy gained from the fuel of this engine is much larger than the energy produced by any other fuel, which means that it would be extremely useful for carrying out long distance space trips in short times.

The annihilation of thermalized antiparticles may find wide medical applications, e.g. Diagnosing and Therapy of Cancer. In particular, positron emission tomography (PET) is considered now as one of the most effective treatments of cancer [40, 41].

4.3. Fate of Antiparticles immediately after the Big Bang

One of the most difficult dilemmas facing our understanding of the Universe on the basis of Modern Physics is the fact that the number of Antiparticles occurring is minimal in comparison with the number of Particles. Modern Particle Physics was established on the following well known fundamental Concepts:

1. Einstein’s Mass-Energy Equivalence principle is true. Which means that mass can be totally converted into energy and energy can be totally converted into mass. This fact has found over the years wide experimental proofs.
2. The Big Bang Theory is the ultimate explanation of the creation of our Universe. The theory is supported by the standard model which is supported by all fundamental discoveries in Particle Physics.
3. The numbers of particles and antiparticles produced by the Big Bang must be identical, which is the basis of the baryon conservation law. The fact that there are rare traces of antiparticles in our Universe violates this law and suggests the occurrence of symmetry breaking accompanied with the Big Bang.

Apart from the rareness dilemma of Antiparticles, two other dilemmas were exposed by Modern Particle Physics, namely dark matter [42] (it is an unseen matter forming about 85% of our Universe) and dark energy [43], (it is an unknown form of energy considered as responsible for the expansion of our Universe and represents about 63% of its total energy).

On the other hand the coexistence of matter and antimatter discussed in the preceding sections suggests a different hypothetical explanation for the fate of antiparticles immediately after the Big Bang [44-47]. According to this proposed explanation, particles and antiparticle were subjected to two different forms of
immediately after their formation, which led to the creation of our Universe and an Antiuniverse. This argument contradicts with Einstein picture of gravity; it encourages searching the existence of an opposite form of gravity referred to as antigravity [48] and perhaps the discovery particles with negative masses. It was also argued that there is an overlapping area between the two universes in which continues creation and annihilation processes take place. The antiparticles appearing in our Universe are the ones escaping from this area: The hypotheses of overlapping Universe and Antiuniverse could provide us with plausible explanation for the sources of dark matter and dark energy in our Universe as well as the source of high energetic Gamma Rays detected at the edge of our Universe [49-51]. (For very recent support for the possible existence of Antiuniverse, see [52]).

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