Vacuum, matter and antimatter [1]

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Abstract

In this talk I first present the vacuum for the e^+-e^- field of QED and show how it is modified for baryons in nuclear environment. Then I discuss the possibility of producing new types of nuclear systems by implanting an antibaryon into ordinary nuclei. The structure of nuclei containing one antiproton or antilambda is investigated within the framework of a relativistic mean-field model. Self-consistent calculations predict an enhanced binding and considerable compression in such systems as compared with normal nuclei. I present arguments that the life time of such nuclei with respect to the antibaryon annihilation might be long enough for their observation.

[1] I dedicate this talk to Professor Renato Ricci, the promoter of Italian and European Nuclear Physics, on occasion of his 75th birthday. Over many years we worked together at Italian, Croatic and other European Conferences. His advice and critical remarks were always highly appreciated. I wish him health, happiness in his family and the Lord's blessing for many years to come.

It is generally accepted that physical vacuum has nontrivial structure. This conclusion was first made by Dirac on the basis of his famous equation for a fermion field which describes simultaneously particles and antiparticles. The Dirac equation in the vacuum has a simple form

$$(i\gamma^\mu \partial_\mu - m)\Psi(x) = 0 \ , \tag{1}$$

where $\gamma^\mu = (\gamma^0, \boldsymbol{\gamma})$ are Dirac matrices, m is the fermion mass and $\Psi(x)$ is a 4-component spinor field. For a plane wave solution $\Psi(x) = e^{-ipx}u_p$ this equation is written as

$$(\widehat{p} - m)u_p = 0 \ , \tag{2}$$

where $\widehat{p} = \gamma^0 E - \boldsymbol{\gamma}\mathbf{p}$. Multiplying by $(\widehat{p} + m)$ and requiring that $u_p \neq 0$ one obtains the equation $E^2 - \mathbf{p}^2 - m^2 = 0$ which has two solutions

$$E^\pm(\mathbf{p}) = \pm\sqrt{\mathbf{p}^2 + m^2} \ . \tag{3}$$

Here the + sign corresponds to particles with positive energy $E_N(\mathbf{p}) = E^+(\mathbf{p})$, while the $-$ sign corresponds to solutions with negative energy. To ensure stability of the physical vacuum Dirac has assumed that these negative-energy states are occupied forming what is called now the Dirac sea. Then the second solution of eq. (3) receives natural interpretation: it describes holes in the Dirac sea. These holes are identified with antiparticles. Their energies are obviously given by $E_{\overline{N}}(\mathbf{p}) = -E^-(-\mathbf{p}) = \sqrt{\mathbf{p}^2 + m^2}$. Unfortunately, the Dirac sea brings divergent contributions to physical quantities such as energy density, and one should introduce a proper regularization scheme to rid off these divergences. This picture has received numerous confirmations in quantum electrodynamics and other fields.

One of the most fascinating aspects is the structure of the vacuum in QED and its change into charged vacuum states under the influence of strong (supercritical) electric fields [1]. I shortly remind of this phenomenon.

Fig. 1 shows the diving of the deeply bound states into the lower energy continuum of the Dirac equation. In the supercritical case the dived state is degenerate with the (occupied) negative electron states. Hence spontaneous e^+e^- *paircreation* becomes possible, where an electron from the Dirac sea occupies the additional state, leaving a hole in the sea which escapes as a positron while the electron's charge remains near the source. This is a fundamentally new process, whereby the neutral vacuum of QED becomes unstable in supercritical electrical fields. It decays within about $10^{-19}s$ into a charged vacuum. The charged vacuum is now stable due to the Pauli principle, that is the number of emitted particles remains finite. The vacuum is first charged twice because two electrons with opposite spins can occupy the $1s$ shell. After the $2p_{1/2}$ shell has dived beyond $Z_{cr} = 185$, the vacuum is charged four times, etc. This change of the vacuum structure is not a perturbative effect, as are the radiative QED effects (vacuum polarization, self-energy, etc.).

The time-dependence of the energy levels in a supercritical heavy-ion collision is depicted in Fig. 2. An electron (or hole) which was in a certain molecular eigenstate

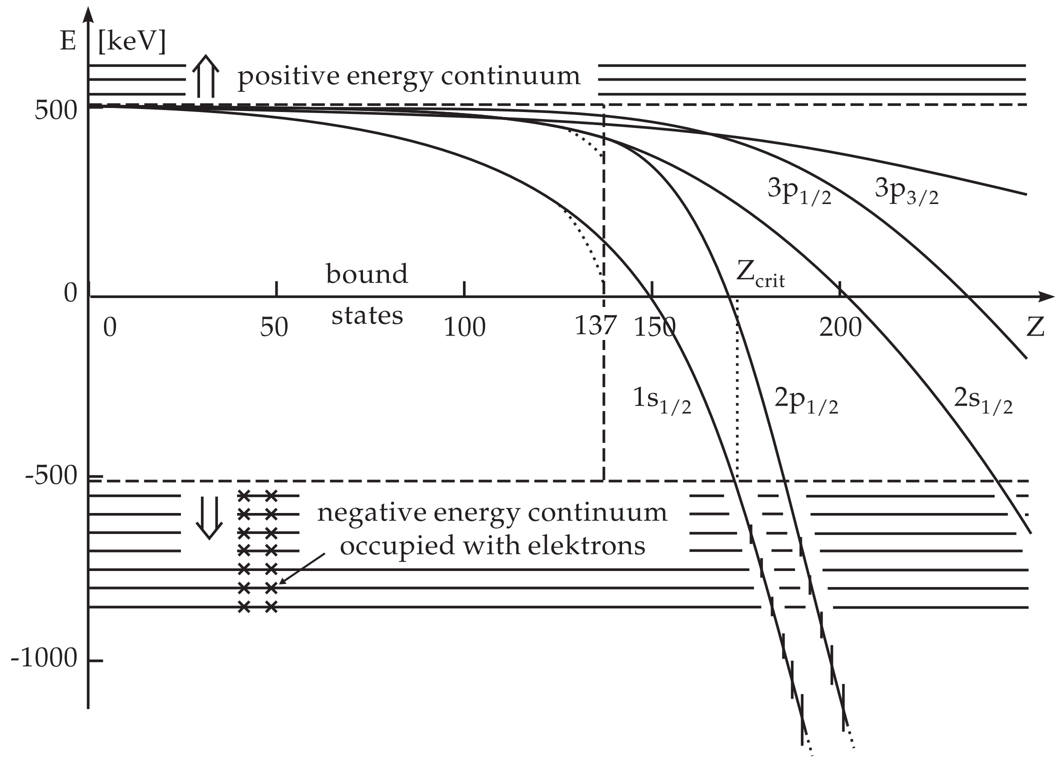

Figure 1: Lowest bound states of the Dirac equation for nuclei with charge Z. While the Sommerfeld fine-structure energies (dashed line) for $\xi = 1$ (s states) end at $Z = 137$, the solutions for extended Coulomb potentials (full line) can be traced down to the negative-energy continuum reached at the critical charge $Z_{\rm cr}$ for the $1s$ state. The bound states entering the continuum obtain a spreading witdth as indicated.

at the beginning of the collision can be transfered with a certain probability into different states by the dynamics of the collision. This can lead to the hole production in an inner shell by excitation of an electron to a higher state and/or hole production by ionization of an electron to the continuum. Further possibilities are induced positron production by excitation of an electron from the lower continuum to an empty bound level and direct pair production [2].

A comparison of the theoretical predictions and expectations and experimental data is shown in figure 3. Sharp positron peeks can be expected if there were a mechanism in the heavy ion collision leading to a time delay. This may be caused by a pocket in the potential between the two ions. Spontaneous pair production should then be enhanced in supercritical systems. Until now, however, the situation remains inconclusive [2].

It has been noticed already many years ago (see e. g. ref. [3]) that nuclear physics may provide a unique laboratory for investigating the Dirac picture of vacuum. The

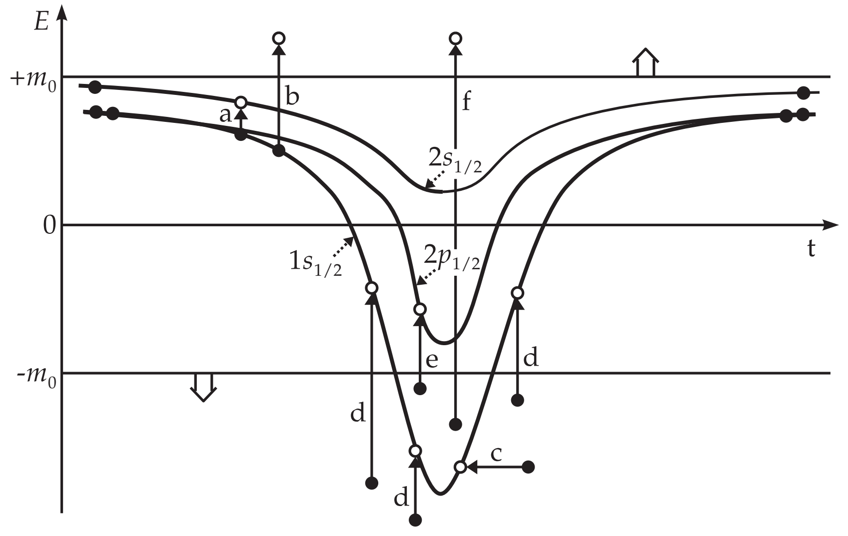

Figure 2: Time dependence.of the quasi-molecular energy levels in a supercritical heavy ion collision. The arrows denote various excitation processes which lead to the production of holes and positrons.

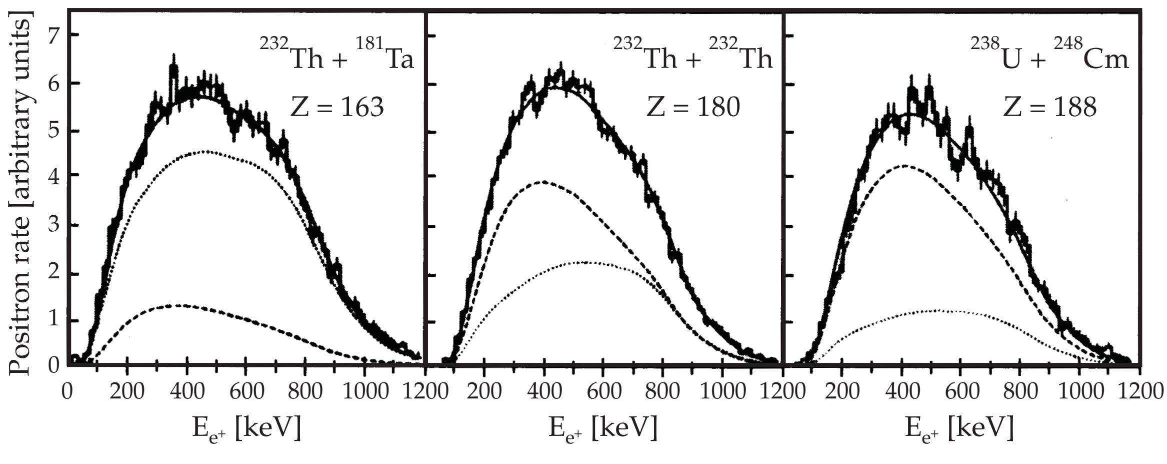

Figure 3: Positron energy spectra measured in collisions of Th+Ta, Th+Th, and U+Cm at energies of about 6 MeV per nucleon. The QED predictions (dashed lines) and the experimentally determined background from nuclear pair conversion (dotted lines) add up to the full lines which are in close agreement with experiment.

basis for this is given by relativistic mean-field models which are widely used now for describing nuclear matter and finite nuclei. Within this approach nucleons are described by the Dirac equation coupled to scalar and vector meson fields. Scalar S and vector V potentials generated by these fields modify plane-wave solutions of the Dirac equation as follows

$$E^{\pm}(\mathbf{p}) = V \pm \sqrt{\mathbf{p}^2 + (m - S)^2} \, . \tag{4}$$

Again, the + sign corresponds to nucleons with positive energy $E_N(\mathbf{p}) = V + \sqrt{\mathbf{p}^2 + (m - S)^2}$, and the $-$ sign corresponds to antinucleons with energy $E_{\bar{N}}(\mathbf{p}) = -E^-(-\mathbf{p}) = -V + \sqrt{\mathbf{p}^2 + (m - S)^2}$. It is remarkable that changing sign of the vector potential for antinucleons is exactly what is expected from the G-parity transformation of the nucleon potential. As follows from eq. (4), in nuclear environment the spectrum of single-particle states of the Dirac equation is modified in two ways. First, the mass gap between positive- and negative-energy states, $2(m - S)$, is reduced due to the scalar potential and second, all states are shifted upwards due to the vector potential. These changes are illustrated in Fig. 1.

It is well known from nuclear phenomenology that good description of nuclear ground state is achieved with $S \simeq 350$ MeV and $V \simeq 300$ MeV so that the net potential for nucleons is $V - S \simeq -50$ MeV. Using the same values one obtains for antinucleons very a deep potential, $-V - S \simeq -650$ MeV. Such a potential would produce many strongly bound states in the Dirac sea. However, if these states are occupied they are hidden from the direct observation. Only creating a hole in this sea, i.e. inserting a real antibaryon into the nucleus, would produce an observable effect. If this picture is correct one should expect the existence of strongly bound states of antinucleons with nuclei. Below I report on our recent study of antibaryon-doped nuclear systems [4].

Unlike some previous works, we take into account the rearrangement of nuclear structure due to the presence of a real antibaryon. The structure of such systems is calculated using several versions of the relativistic mean–field model (RMF): TM1 [5], NL3 and NL-Z2 [6]. Their parameters were found by fitting binding energies and charge form-factors of spherical nuclei from ^{16}O to ^{208}Pb. The general Lagrangian of the RMF model is written as

$$\begin{aligned}
\mathcal{L} = & \sum_{j=B,\overline{B}} \overline{\psi}_j \left(i\gamma^\mu \partial_\mu - m_j \right) \psi_j \\
& + \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{b}{3}\sigma^3 - \frac{c}{4}\sigma^4 \\
& - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{d}{4}(\omega^\mu \omega_\mu)^2 \\
& - \frac{1}{4}\vec{\rho}^{\,\mu\nu}\vec{\rho}_{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}^{\,\mu}\vec{\rho}_\mu \\
& + \sum_{j=B,\overline{B}} \overline{\psi}_j \left(g_{\sigma j}\sigma + g_{\omega j}\omega^\mu \gamma_\mu + g_{\rho j}\vec{\rho}^{\,\mu}\gamma_\mu \vec{\tau}_j \right) \psi_j
\end{aligned}$$

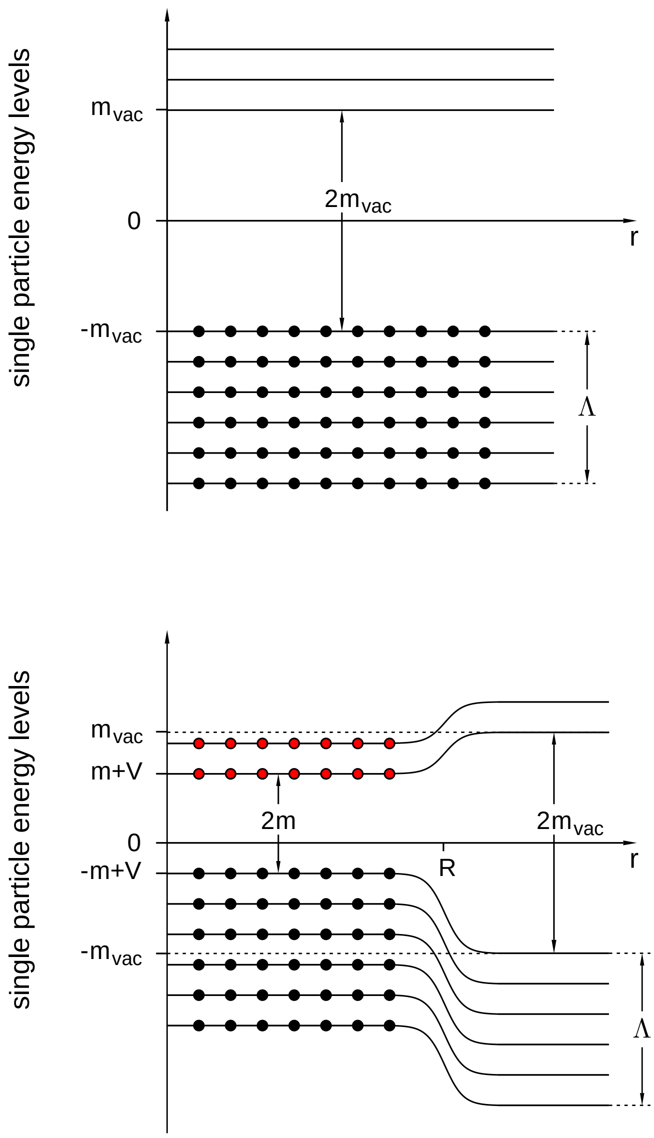

Figure 4: Schematic spectrum of Dirac equation in vacuum (upper panel) and in a nucleus of radius R (lower panel). A divergent contribution of negative-energy states is often regularized by introducing a cut-off momentum Λ

$$+\,\text{Coulomb part} \tag{5}$$

Here summation includes valence baryons B, in fact the nucleons forming a nucleus, and valence antibaryons $\overline{B}$ inserted in the nucleus. They are treated as Dirac particles coupled to the scalar-isoscalar (σ), vector-isoscalar (ω) and vector-isovector ($\vec{\rho}$) meson fields. The calculations are carried out within the mean-field approximation where the meson fields are replaced by their expectation values. Also a "no-sea" approximation is used. This implies that all occupied states of the Dirac sea are "integrated out" so that they do not appear explicitly. It is assumed that their effect is taken into account by nonlinear terms in the meson Lagrangian. Most calculations are done with antibaryon coupling constants which are given by the G-parity transformation ($g_{\sigma\overline{N}} = g_{\sigma N}$, $g_{\omega\overline{N}} = -g_{\omega N}$) and $SU(3)$ flavor symmetry ($g_{\sigma\overline{\Lambda}} = \frac{2}{3}g_{\sigma\overline{N}}$, $g_{\omega\overline{\Lambda}} = \frac{2}{3}g_{\omega\overline{N}}$). In isosymmetric static systems the scalar and vector potentials for nucleons are expressed as $S = g_{\sigma N}\sigma$ and $V = g_{\omega N}\omega^0$.

Following the procedure suggested in Ref. [7] and assuming the axial symmetry of the nuclear system, we solve effective Schrödinger equations for nucleons and an antibaryon together with differential equations for mean meson and Coulomb fields. We explicitly take into account the antibaryon contributions to the scalar and vector densities. It is important that antibaryons give a negative contribution to the vector density, while a positive contribution to the scalar density. This leads to increased attraction and decreased repulsion for surrounding nucleons. To maximize attraction, nucleons move to the center of the nucleus, where the antiproton has its largest occupation probability. This gives rise to a strong local compression of the nucleus and leads to a dramatic rearrangement of its structure.

Results for the ^{16}O nucleus are presented in Fig. 2 which shows 3d plots of nucleon density distributions. The calculations show that inserting an antiproton into the ^{16}O nucleus leads to the increase of central nucleon density by a factor 2–4 depending on the parametrization. Due to a very deep antiproton potential the binding energy of the whole system is increased significantly as compared with 130 MeV for normal ^{16}O. The calculated binding energies of the $\overline{p}-^{16}$O system are 830, 1050 and 1160 MeV for the NL–Z2, NL3 and TM1, respectively. Due to this anomalous binding we call such systems super bound nuclei (SBN). In the case of antilambdas we rescale the coupling constants with a factor 2/3 that leads to the binding energy of 560÷700 MeV for the $\overline{\Lambda}-^{16}$O system.

As a second example, we investigate the effect of a single antiproton inserted into the ^{8}Be nucleus. The normal ^{8}Be nucleus is not spherical, exhibiting a clearly visible 2α structure with the ground state deformation $\beta_2 \simeq 1.20$. As seen in Fig. 6, inserting an antiproton in ^{8}Be results in a much less elongated shape ($\beta_2 \simeq 0.23$) and disappearance of its cluster structure. The binding energy increases from 53 MeV to about 700 MeV. Similar, but weaker effects have been predicted [8] for the K^- bound state in the ^{8}Be nucleus.

The calculations have been performed also with reduced antinucleon coupling constants as compared to the G-parity prescription. We have found that the main

Sum of proton and neutron densities for ^{16}O (top),
^{16}O with $\bar{\Lambda}$ (bottom left) and ^{16}O with $\bar{p}$ (bottom right)

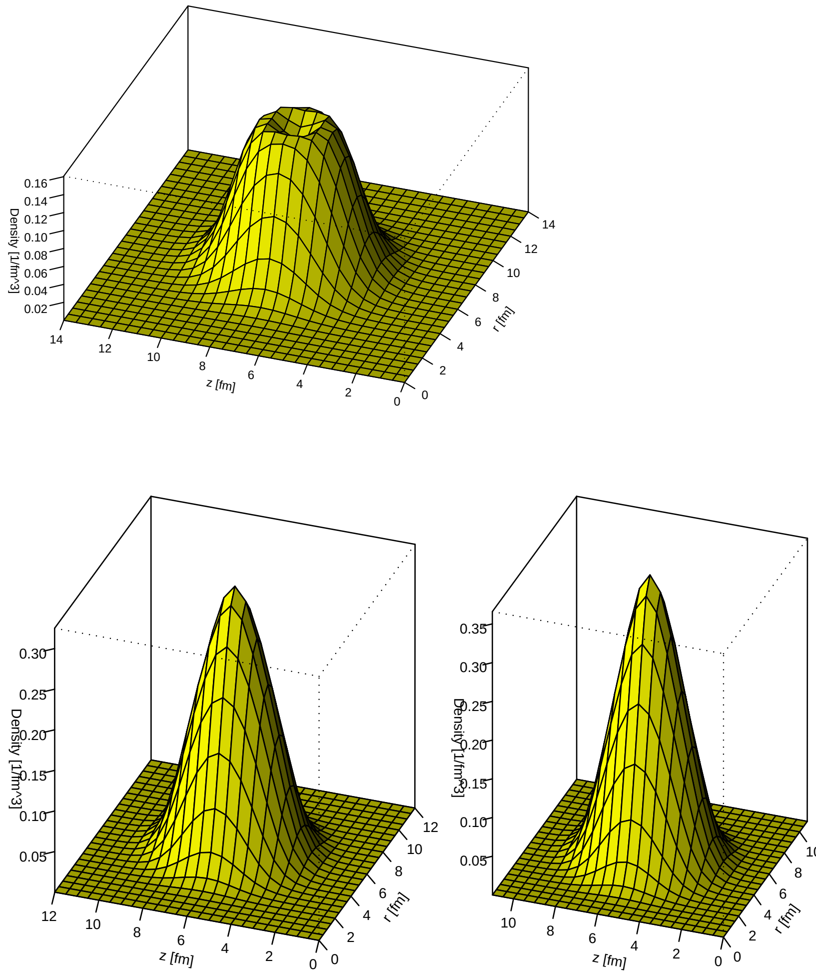

Figure 5: Sum of neutron and proton densities for ^{16}O (top), ^{16}O with $\overline{p}$ (bottom right) and ^{16}O with $\overline{\Lambda}$ (bottom left) calculated with the parametrization NL-Z2.

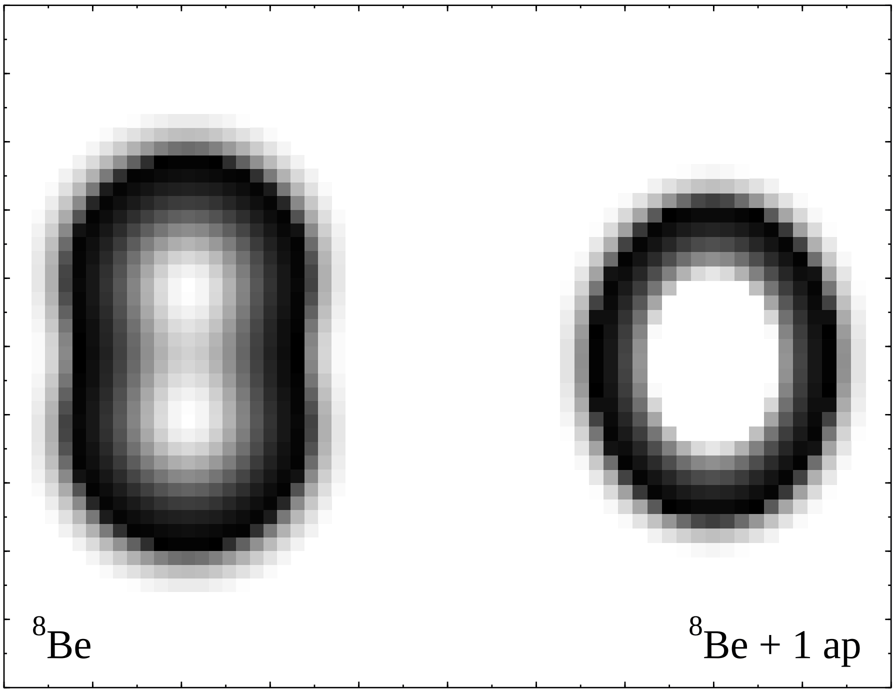

Figure 6: Contour plot of nucleon densities for ^{8}Be without (left) and with (right) antiproton calculated with the parametrization NL3.

conclusions about enhanced binding and considerable compression of $\overline{p}$-doped nuclei remain valid even when coupling constants are reduced by factor 3 or so.

The crucial question concerning possible observation of the SBNs is their life time. The main decay channel for such states is the annihilation of antibaryons on surrounding nucleons. The energy available for annihilation of a bound antinucleon equals $Q = 2m_N - B_N - B_{\overline{N}}$, where B_N and $B_{\overline{N}}$ are the corresponding binding energies. In our case this energy is at least by a factor 2 smaller as compared with the vacuum value of $2m_N$. This should lead to a significant suppression of the available phase space and thus to a reduced annihilation rate in medium. We have performed detailed calculations assuming that the annihilation rates into different channels are proportional to the available phase space. All intermediate states with heavy mesons like ρ, ω, η as well as multi-pion channels have been considered. Our conclusion is that decreasing the Q value from 2 GeV to 1 GeV may lead to the reduction of total annihilation rate by factor 20÷30. Then we estimate the SBN life times on the level of 5-25 fm/c which makes their observation feasible. This large margin in the life times is mainly caused by uncertainties in the overlap integral between antinucleon and nucleon scalar densities. Longer life times may be expected for SBNs containing antihyperons. The reason is that instead of pions more heavy kaons must be produced in this case. We have also analyzed multi-nucleon annihilation channels (Pontecorvo-like reactions) and have found their contribution to be less than 40% of the single-nucleon annihilation.

We believe that such exotic nuclear states can be produced by using antiproton beams of multi-GeV energy, e.g. at the future GSI facility. It is well known that low-energy antiprotons annihilate on the nuclear periphery (at about 5% of the normal density). Since the annihilation cross section drops significantly with energy, a high-energy antiproton can penetrate deeper into the nuclear interior. Then it can be stopped there in an inelastic collision with a nucleon, e. g. via the reaction $A(\bar{p}, N\pi)_{\bar{p}}A'$, leading to the formation of a $\bar{p}$-doped nucleus. Reactions like $A(\bar{p}, \Lambda)_{\overline{\Lambda}}A'$ can be used to produce a $\overline{\Lambda}$-doped nuclei. Fast nucleons or lambdas can be used for triggering such events. In order to be captured by a target nucleus final antibaryons must be slow in the lab frame. Rough estimates of the SBN formation probability in a central $\bar{p}A$ collision give the values $10^{-5} - 10^{-6}$. With the $\bar{p}$ beam luminocity of $2{\cdot}10^{32}$ cm^{-2}s^{-1} planned at GSI this will correspond to the reaction rate of a few tens of desired events per second.

Several signatures of SBNs can be used for their experimental observation. First, annihilation of a bound antibaryon can proceed via emission of a single photon, pion or kaon with an energy of about 1 GeV (such annihilation channels are forbidden in vacuum). So one may search for relatively sharp lines, with width of 10÷40 MeV, around this energy, emitted isotropically in the SBN rest frame. Another signal may come from explosive disintegration of the compressed nucleus after the antibaryon annihilation. This can be observed by measuring radial collective velocities of nuclear fragments.

It is interesting to look at the antibaryon-nucleus system from somewhat different point of view. An antibaryon implanted into a nucleus acts as an attractor for surrounding nucleons. Due to the uncompensated attractive force these nucleons acquire acceleration towards the center. As the result of this inward collective motion the nucleons pile up producing local compression. If this process would be completely elastic it would generate monopole-like oscillations around the compressed SBN state. The maximum compression is reached when the attractive potential energy becomes equal to the compression energy. Simple estimates show that local baryon densities up to 5 times the normal nuclear density may be obtained in this way. It is most likely that the deconfinment transition will occur at this stage and a high-density cloud containing an antibaryon and a few nucleons will appear in the form of a multi-quark-antiquark cluster. One may speculate that the whole ^{4}He or even ^{16}O nucleus can be transformed into the quark phase by this mechanism. As shown in ref. [9], an admixture of antiquarks to cold quark matter is energetically favorable. The problem of annihilation is now transferred to the quark level. But the argument concerning the reduction of available phase space due to the entrance-channel nuclear effects should work in this case too. Thus one may hope to produce relatively cold droplets of the quark phase by the inertial compression of nuclear matter initiated by an antibaryon.

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