POSITRON STATES IN DUSTY SPACE PLASMA

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It has been demonstrated that monitoring the 0.511-MeV annihilation line of extraterrestrial origin allows information to be obtained concerning not only the availability of positron–electron pairs, but also their energy (and, hence, the velocity) at the annihilation moment, the direction of their motion with respect to the Earth, the distance to the pair source, and some properties of the medium where the annihilation of positrons took place. It has been shown that positroniums in dusty space plasma with a high concentration of charged dust particles can be formed by means of the processes of positron interaction with H atoms, free electrons, and the charged particles of dusty space plasma. A positronium yield of almost 100% is possible for such space plasma, which is evidenced by experimental data of the "Integral" space laboratory. Basing on the values for the diffusion coefficient, the dimensions of dust particles in space plasma proved to be larger than 100 nm. The dimensions of a dust particle is comparable with the diffusion length of positrons (0.01–1 μm). The initial energy of positrons can be equal to a few kiloelectronvolts. Thus, the obtained dimensions of dust particles agree well with the results of estimations derived from optical observation data.

Creation of space γ-telescopes installed on the board of orbital stations and laboratories, orbiting outside the Earth's atmosphere, i.e. in space plasma [1], invokes the problem of interpreting the γ-spectra that are registered from various regions of the Universe including the Sun. Of special interest is the study of the Doppler broadening of the annihilation line (DBAL) at an energy of about 0.511 MeV, which corresponds to the annihilation of slow electron–positron pairs. Recently, large progress has been achieved in the field of gamma-ray astronomy of solar flares and gamma-rays from the region near to the galactic center; in particular, in the framework of the SPI "Integral" (the Institute for Space Researches of the Russian Academy of Science) [2], and AMS-01 and AMS-02 (the International Space Station) international programs [3]. Observations were performed from both balloons and artificial satellites of the Earth. The modern installation, which was used, was intended for the long-term study of antimatter (including positrons) in the flux of the primary space radiation up to energies of several teraelectronvolts.

The annihilation line corresponding to an energy of about 0.511 MeV arises owing to the annihilation of positron–electron pairs in a singlet state. The annihilation of such a pair is accompanied by the emission of two γ-quanta. If the center of mass of this pair is at rest in the laboratory coordinate system, the γ-quanta fly away in opposite directions with an identical energy of 0.511 MeV. The motion of the center of mass of the annihilating pair in the laboratory coordinate system results in both the deviation of the angle of divergence of γ-quanta from 180° and the Doppler symmetric broadening of the 0.511-MeV annihilation line. But if the motion of a pair in the laboratory coordinate system is combined with the motion of the coordinate system itself with respect to a coordinate system coupled to a recording equipment, the shift of the 0.511-MeV annihilation line caused by the Doppler effect [1] will be observed. The motion of the source of γ-quanta and the recording equipment towards each other will give rise to the shift of the annihilation line in the direction of energies higher than 0.511 MeV (a blue shift). If the source and the receiver move in the opposite directions, the shift of annihilation line towards the energy range lower than 0.511 MeV (a red shift) will be observed. For instance, knowing the red shift z, one can determine the recession velocity v of a positron source. If the value of the latter is low in comparison with the speed of light, it is expressed by a simple formula $v = cz$. If the value of z measured by spectral annihilation lines exceeds unity, the velocity v is connected with z by a more complicated relation, but always remains less that the speed of light.

The 0.511-MeV annihilation line is apparently a line in the γ-range that is "standard" enough for other galaxies as well. Therefore, with the enhancement of γ-telescope sensitivity, it can be used to estimate Hubble's constant H_0, provided that the distances r to the source is known – or to estimate a distance to the source, provided that the value of H_0 is known – by the known cosmological formula $v = H_0 r$. For example, for $H_0 = 75$ (km/s)/Mpc [1] and a characteristic Doppler broadening of the order of $\delta = 0.01$, the red shift corresponding to this δ-value amounts to $z = \delta = (\lambda - \lambda_0)/\lambda_0 = 0.01$, which, in its turn, corresponds to distances $r = cz/H_0 = 40$ Mpc. Hence, it is clear that the distances to galaxies should be larger than 40 Mpc in this case (i.e. the source should be located at a distance that is more than 5×10^4 times longer than the distance to the Galactic Center, and, therefore, the corresponding flux of γ-quanta should be 2×10^7 times weaker than that from the Galactic Center). This means that the sensitivity of even advanced γ-telescopes must be substantially improved. Undoubtedly, the angular resolution must be improved as well, because the resolution of the order of a few angular seconds, which is required for similar problems to be solved, is unattainable nowadays. It is also possible to put forward a hypothesis that the intensities of the 0.511-MeV line for various normal galaxies are approximately identical. In this case, this line can be used in cosmology as a "standard candle", similarly to what is now done for supernovas of the Ia type, although there is no doubt that it is a matter of a distant future.

To observe the Doppler broadening of the 0.511-MeV annihilation line, Ge(Li) detectors are used, and their pulses are registered by an amplitude analyzer. Modern devices allow the Doppler broadening of the 0.511-MeV annihilation line to be registered reliably enough.

Additional information concerning the presence of positron–electron pairs can be obtained by analyzing the optical spectra in the ultra-violet range (180–240 nm). This range includes the Lyman series in the spectra of excited positronium states (6.8–5.1 eV) [1].

The researches of the parameters of gamma-spectra and the S-shape parameter of the DBAL spectra for various regions of the Universe and the Sun raise the question of the origin of positron states in them; first of all, in extremely rarefied gases and space plasma. As was indicated in work [4], positrons with an initial energy E of about 10^8 eV, being subjected to the action of interstellar magnetic fields with the strength $H \approx (10^{-5} \div 10^{-6})$ Oe, move along helical paths with the curvature radius $R = EH/300 \approx (10^{10} \div 10^{11})$ cm, i.e. of the order of the Sun's radius, around the force lines of the magnetic field. By cosmic standards, this is a very short distance; therefore, positrons are practically locked in that region (volume) where they have been formed. At their passage through the interstellar gas with the ordinary density $n \approx 1$ cm^{-3}, positrons participate in the following main processes of interaction with hydrogen atoms: 1) ionization of hydrogen atoms; in this case, there arise braking (owing to the interaction with nuclear and atomic fields) and synchrotron radiation (due to the interaction between fast positrons and the magnetic field of space plasma); 2) annihilation in flight; 3) formation of positronium (Ps) atoms; 4) quasielastic processes of collisions with hydrogen (H) atoms; 5) formation and decay of quasiatomic e$^+$H systems; and 6) annihilation of slow and "quasithermalized" positrons in the interstellar gas.

Consider, in brief, the characteristic features of those processes, following works [4–7]. In the range of high energies, positrons, interacting with hydrogen atoms, spend their energy mainly on ionization of hydrogen atoms and synchrotron irradiation. Note that, in this case, a small fraction of positrons' energy ($< 20\%$) is spent on bremsstrahlung and a very small fraction ($< 0.2\%$) on cyclotron radiation and collisions with light quanta (the inverse Compton effect). The slowing-down time for the processes of energy loss for ionization and synchrotron irradiation amounts to about 10^{14} s $\approx 3 \times 10^6$ years, provided that the density is $n \approx 1$ cm^{-3} and the initial energy of positron is of 10^8 eV, whereas the positron annihilation lifetime is equal to 1.3×10^6 years [5]. Note that the times concerned become approximately six orders of magnitude longer in the intergalactic medium, because the density of hydrogens in this medium is $n \approx 1$ m^{-3}. Really, the mean path length of positrons in the galactic medium until they become slowed down to thermal equilibrium with hydrogen atoms amounts to approximately 3×10^{24} cm, i.e. 100 times as long as the distance to the galactic center. In the intergalactic medium, this distance becomes approximately one million times longer, i.e. 3×10^{30} cm, which is approximately 10^8 times longer than the distance to the galactic center. However, it is known [7] that the galactic magnetic field prohibits cosmic beams (including positrons) from escaping into the intergalactic space, which gives rise to the phenomenon of galactic beam diffusion. Only cosmic beams with very high energies are capable of escaping into the intergalactic space. In the galactic environment, there may probably be the fluxes of positrons in every energy range, from ultrarelativistic energies to the energies corresponding to the thermal balance between positrons and the atoms of galactic medium, provided that the positron sources are galactic objects (black holes, supernova outbursts, and so on). Note that, while estimating the times of various processes, a possibility of positron acceleration in the galactic and intergalactic space through various mechanisms [7] was neglected.

Hence, some portion of fast positrons loses the energy and becomes slowed down to energies comparable with the energy of atomic electrons in galactic and intergalactic media for the time interval shorter than the lifetime before their annihilation. The calculations show [5] that the process of pair annihilation in flight is less probable in the range of high energies than the process of ionization energy losses. The fraction of positrons annihilating in flight amounts to 1–3% of the common positron number. In this energy range, positrons are scattered quasielastically, with the cross-section of the process being equal, by the order of magnitude, to geometrical dimensions of an H atom. The slowing-down time of positrons in this energy range is determined by the expression [5]

$$t = \left(2m^{1/2}/\sqrt{2}\right)(\zeta n\sigma)^{-1}\left[(1/E_I)^{1/2} - (1/E_0)^{1/2}\right],$$

where m is the positron mass; $\zeta = 2m/M$ is the average energy losses of a positron in a collision, expressed in relative units; σ is the transverse cross-section of collisions; E_0 and E_I are the initial and final energies of the positron, respectively; M is the mass of hydrogen atom; and n is the concentration of hydrogen atoms in the space. Estimations carried out in accordance with this formula enable one to conclude that the value of t is much less than the positron lifetime before its annihilation at collisions [5]. Thus, positrons can be enough decelerated in the space plasma atmosphere.

Of special importance are the processes of formation of Ps atoms and quasiatomic systems positron+atom and positron+anion [8–19] in space plasma which drastically shorten the positron lifetime. Really, experimental data confirm the abundant yield of positronia in the space plasma of the galactic center. The formation of positronia at hydrogen atoms, which are the component of the space medium, was considered in work [2] in detail. Among all possible processes of interaction between slow positrons and the atoms of space plasma, the most probable are those with the participation of hydrogen atoms and negative hydrogen ions, which may probably exist in a charged dusty space plasma. In this case, the processes of formation of positron ions e^+H and positronium hydride e^+H^- (PsH) cannot be excluded in principle. For the simplest positron ions e^+H, the issue concerning the existence of stable bound states has not been ultimately resolved yet. The e^+H systems were studied by variational methods [15]. Taking advantage of a function that is symmetrized in the coordinates of particles with the same charge sign and making allowance for positronium coupling in the trial function in an explicit form, the best value $E = -10.59$ eV for the total energy, which characterizes the quasistationary state, was obtained, whereas the value of the total energy of hydrogen atom amounts to $E = -13.65$ eV. This proves that the e^+H system is dynamically unstable with respect to positron emission. Therefore, its existence in space plasma was not taken into consideration in this work.

Note that now only the PsH e^+H^- can be assigned to rigorously stable systems, i.e. stable with respect to emission of a positron and a positronium, with the annihilation channel remaining the unique channel of decay. This system, as well as other positron–anion systems, was studied making use of both the Hartree–Fock [9–11] and variational [12–14] methods. The following values of the parameters were found: the total energy of the e^+H^- system $E = -21.48$ eV, the binding energy between a positron and an H^- ion $E_p \approx 7.0296$ eV, and the binding energy between a positronium and an H atom $E_d = 1.001$ eV. The positron lifetime before two-quantum annihilation amounts to $\tau = 4.3\times10^{-10}$ s in the ground state of the e^+H^- system.

The results obtained by variational methods demonstrate that the e^+H^- system is stable with respect to its decay into a positron and an H^- ion in both the ground and excited states. However, the following important circumstance should be taken into consideration: the probabilities of radiation capture of positrons into excited states of the e^+H^- system calculated in the framework of the Hartree–Fock method are higher, by an order of magnitude and more, than the probability of radiation capture of positrons into the ground state of e^+H^-. The probabilities of capture into highly excited states of the e^+H^- system are especially high. This testifies that it is these e^+H^- states that prevail in space plasma. The binding energy of a positron for these states drastically diminishes, and the e^+H^- system becomes dynamically unstable with respect to its decay into a positronium and a hydrogen atom. However, as was pointed out in works [8, 12], negative H^- ions easily interact with atomic hydrogens, H, prevailing in space plasma, to form a molecular hydrogen H_2 following the reaction $H + H^- \rightarrow H_2 + e^-$. Therefore, owing to a small concentration of H^- ions, the processes of their interaction with positrons can be neglected.

However, it is of interest to consider other mechanisms of positronium formation in the space environment, in particular, through the processes of interaction between positrons and the particles of dusty space plasma, the latter having characteristic dimensions $a = (0.01 \div 1)$ μm [20–29]. It is known that, in the Galactic Plane, in particular, in the vicinity of the Galactic Center, there is a plenty of interstellar dust with the characteristic dimensions of particles smaller than 1 μm [20–22], which makes the observation of those regions in the optical range complicated. The dust is responsible for two observable phenomena in the optical range. First, it is an attenuation of the observable photon flux (the so-called interstellar absorption). Second, it is an interstellar reddening of spectra, because dust particles, owing to their dimensions, scatter mainly the quanta with the wavelengths corresponding to the blue range of the spectrum, so that the observable spectrum becomes more red than the emitted one, whereas the spectrum of the scattered light is more blue than the initial one. A similar phenomenon takes place in the terrestrial atmosphere as well.

The sticking of electrons from the interstellar gas to dust space particles and the photoionization of dust particles by ultra-violet radiation make them electrically charged; their electric charges can achieve the values of the order of ten elementary charges. The electric charge of a dust space particle, through the action of the Lorentz force, couples it with the interstellar magnetic field, which is always present in galaxies. Those scattering particles usually consist of charged particles of carbon, carbides, silicates, and, probably, other charged ions surrounded by hydrogen atoms and molecules of hydrogen, water, helium, and so on. In the densest areas of the interstellar environment, the concentration of those dust particles can reach the values $n \geq 10^6$ cm^{-3} [29]. The scenario of the interaction between positrons and the particles of such kinds can be imagined as follows. A positron penetrates into the particle's volume and becomes thermalized in it. Further, the thermalized positron diffuses to the particle's surface. Since the diffusion coefficient of a positron in quartz and silicon carbide amounts to $D_+ = (1 \div 2)$ cm^2/s and its lifetime before annihilation is about 10^{-10} s, it travels a distance longer than 100 nm [30, 31] and, therefore, reaches the surface of the negatively charged dust space particle. If the thermalized positron interacts with one of the electrons on the particle's surface, the formation of a positronium atom with the binding energy of 6.8 eV is energetically beneficial. It should be noted that, under condition that the concentration of hydrogen atoms n_H and that of dust particles n_d with the dimensions of about 100 nm in a dusty plasma are equal (e.g., $n_H = n_d = 1$ cm^{-3}), the effective cross-section of the process of interaction between a positron and a charged dust particle σ_p – if to judge from the geometrical dimensions of the particles, $\sigma_p \approx 10^{-12}$ cm^2 – is approximately four orders of magnitude larger than the cross-section of their interaction with H atoms, $\sigma_H \approx 10^{-16}$ cm^2.

Similar considerations are eligible in the case of the Ps formation in the dust particle's volume through the recombination of a thermalized positron with one of the electrons along the positron's path followed by the diffusion exit of the Ps onto the surface.

Thus, the formation of positronia in dusty space plasma with a high concentration of charged dust particles can occur by means of the processes of interaction of positrons with H atoms and free electrons [2], as well as through the processes of interaction between a positron and negatively charged plasma particles. In such space plasma, a positronium yield of almost 100% can be reached, which is evidenced for by experimental data of the "Integral" space laboratory [2]. Proceeding from the values of the diffusion coefficient given above, we obtain that the dimensions of dust particles in dusty space plasma are larger than 100 nm. Hence, the dimensions of dust particles agree well with the estimations derived from optical observations.

It would be of interest to consider the mechanisms of interaction between positrons and dusty space plasma in the framework of the theoretical models in more details (see, e.g., works [1, 20–24]).

In the analysis given above, a suggestion was made that the implantation depth of positrons does not exceed the diffusion length of thermalized positrons in the medium, otherwise some portion of positrons would annihilate either in the free state or participate in pick-off annihilation, which would give rise to an increase of the fraction of the 2γ-annihilation channel contribution. The implantation depth l depends on the positron energy E_β and the properties of the medium.

The distribution of positrons over the depth, $F(z)$, is usually described by the expression [32, 33]

$$F(z) = \frac{1}{l}\exp\left(-z/l\right), \tag{1}$$

where

$$l = (\mu\rho)^{-1} \tag{2}$$

is the positron absorption length, μ the mass attenuation coefficient for a positron beam, and ρ the density of substance in units of g/cm^3. The relation between the parameter μ and the energy of positrons E_β is determined by the expression

$$\mu = 17,0E_\beta^{-1,43}, \tag{3}$$

where E_β is measured in MeV.

Knowing the diffusion coefficient (from terrestrial experiments) and the lifetime of positrons in the medium, one can estimate the dimensions of dust particles and the initial energy of positrons. For instance, the diffusion length of positrons in Si and Al is equal to 0.5 and 0.15 μm, respectively [31, 32], being of the same order of magnitude for the majority of condensed media. Among the total number of positrons in the medium, the fraction of positrons, which reach the surface, significantly depends on the positron energy, i.e. on the ratio between the diffusion and absorption lengths. For example, the absorption length for positrons with an energy of about 1.5 MeV is approximately 600 and 500 μm in Si and Al, respectively; while, for positrons with an energy of 2 keV, the relevant values are three orders of magnitude shorter. For relatively slow positrons with an energy of about a few kiloelectronvolts, the diffusion and absorption lengths are comparable with each other and are equal to several hundred nanometers for the majority of media.

Therefore, one may assume that the dimensions of dust particles are comparable with the diffusion length of positrons, i.e. $0.01 - 1$ μm, and the initial energy of positrons amounts to a few kiloelectronvolts.

The broadening of the 511-keV annihilation line in "Integral" experiments was (2.37 ± 0.25) keV [2]. Such a broadening can be connected with the energy of an annihilating positron-electron pair of a few (1–2) electronvolts, i.e. the energy of a quasithermalized positronium.

It should be noted that, if the annihilation of free positrons with electrons of the space environment (the dust particles) gives a contribution to the intensity of the 511-keV annihilation line (this information can be obtained from the comparison of the intensities of 2γ- and 3γ-annihilation, registered by the "Integral" observatory), the dimensions of dust particles would be larger; they can be estimated by engaging the data concerning the annihilation of positrons in condensed media.

Works with the application of positron spectroscopy have been carried on at the Institute for Theoretical and Experimental Physics for a long time, and, by now, a large body of experimental material concerning the annihilation of positrons in various media has been accumulated [4]. Those materials can be used for the interpretation of experimental data obtained from space γ-telescopes.

1. H. Alfvén, *Cosmic Plasma* (D. Riedel Publ. Co., Dordrecht, 1981).
2. E.M. Churazov, R.A. Syunyaev, S.Yu. Sazonov, M.G. Revnivtsev, and D.A. Varshalovich, Usp. Fiz. Nauk **176**, 334 (2006); E. Churazov, R. Sunjaev, S. Sazonov, M. Revnivtsev, and D. Varshalovich, Month. Notes Roy. Astr. Soc. **357**, 1377 (2005).
3. AMS Collaboration (M. Aguilar, J. Alcaraz, J. Allaby *et al.*), Phys. Rep. **366**, 331 (2002); J. Alcaraz, D. Alvisi, B. Alpat *et al.*, Phys. Lett. B **472**, 2156 (2000).
4. V.I. Grafutin and E.P. Prokopiev, Usp. Fiz. Nauk **172**, 67 (2002).
5. N.A. Vlasov, *Antimatter* (Atomizdat, Moscow, 1966) (in Russian).
6. E.P. Prokopiev, Astronom. Zh. **70**, 906 (1994).
7. V.S. Berezinskii, S.V. Bulanov, V.L. Ginzburg, V.L. Dogel, and V.S.Ptuskin, *Astrophysics of Cosmic Rays* (North-Holland, Amsterdam, 1990).
8. A. Ore, Univ. Bergen Arbook **9**, 12 (1949).
9. V.I. Goldanskii, A.V. Ivanova, and E.P. Prokopiev, Zh. Èksp. Teor. Fiz. **47**, 659 (1964).
10. C.J. Cranell *et al.*, Astrophys. J. **210**, 582 (1976).
11. V.I. Goldanskii, A.V. Ivanova, and E.P. Prokopiev, in *Nuclear Chemistry* (Nauka, Moscow, 1965), p. 249 (in Russian).
12. R.J. Drachman, in *Positron Annihilation*, edited by P.G. Coleman, S.C. Sharma, and L.M. Diana (North-Holland, Amsterdam, 1982), p. 37.
13. P.U. Arifov, E.P. Prokopiev, *et al.*, in *Systems with Positrons and Positron Diagnostics* (FAN, Tashkent, 1978), p. 192 (in Russian).
14. V.I. Grafutin, O.V. Ilyukhina, E.P. Prokopiev, G.G. Myasishcheva, and Yu.V. Funtikov, Khim. Fiz. **19**, 36 (2000); Khim. Vysok. Energ. **34**, 460 (2000).
15. Din Van Hoang, Dokl. Akad. Nauk Belorus. SSR **8**, 717 (1964); **9** 152 (1965).
16. T.C. Griffith and G.R. Heyland, Phys. Rep. **39**, 169 (1978).
17. C.M. Surko, G.F. Gribakin, and S.J.Buckman, J. Phys. B **38**, R57 (2005).

18. M.C. Surko, M. Leventhal, and A. Passner, Phys. Rev. Lett. **62**, 901 (1989).
19. S.A. Gavrilov, V.I. Grafutin, O.V. Ilyukhina, G.G. Myasishcheva, E.P. Prokopiev, S.P. Timoshenkov, and Yu.V. Funtikov, Pis'ma Zh. Eksp. Teor. Fiz. **81**, 680 (2005).
20. S.A. Kaplan and S.B. Pikelner, *The Interstellar Medium* (Harvard University Press, Cambridge, 1970).
21. L. Spitzer, *Physical Processes in the Interstellar Medium* (Wiley, New York, 1978).
22. J. Dyson, *Physics of Interstellar Medium* (Taylor and Francis, London, 1997).
23. A.P. Nefedov, O.F. Petrov, and V.E. Fortov, Usp. Fiz. Nauk **167**, 1215 (1997).
24. B.M. Smirnov, Usp. Fiz. Nauk **167**, 1169 (1997).
25. W.H. Zurek, Astrophys. J. **289**, 603 (1985).
26. N. Guessoum, R. Ramaty, and R.E. Lingenfelter, Astrophys. J. **378**, 170 (1991).
27. N. Guessoum, P. Jean, and W. Gillard, Astron. and Astrophys. **436**, 171 (2005).
28. W.D. Watson, J. Opt. Soc. Amer. **63**, 64 (1973).
29. S.V. Bozhokin, Soros. Obrazov. Zh. N 6, 72 (2006).
30. A.I. Gusev, *Nanomaterials, Nanostructures, and Nanotechnologies* (Fizmatlit, Moscow, 2005) (in Russian).
31. Yu.A. Novikov, A.V. Rakov, A.B. Khorev, and V.P. Shantarovich, Poverkhnost **8**, 62 (1992).
32. W. Brandt and R. Paulin, Phys. Rev. B **15**, 2511 (1977).
33. *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegban (North-Holland, Amsterdam, 1965).

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ПОЗИТРОННІ СТАНИ У ПИЛОВІЙ КОСМІЧНІЙ ПЛАЗМІ

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Резюме

Вказано, що спостереження за анігіляційною лінією 0,511 МеВ позаземного походження дозволяє отримувати інформацію не тільки про наявність позитрон-електронних пар, а й про їхні енергії (а відповідно й швидкості) у момент анігіляції, про напрям руху відносно Землі і відстань до джерела цих пар та про деякі властивості середовища, в якому відбулася анігіляція позитронів. Показано, що утворення позитронію у пиловій космічній плазмі з великою концентрацією заряджених частинок пилу може відбуватися і шляхом взаємодії позитронів з атомами Н та вільними електронами, і шляхом взаємодії позитронів із зарядженими частинками пилової космічної плазми. В такій плазмі можливий практично 100%-вий вихід позитронію, про що свідчать експериментальні дані з космічної лабораторії "Інтеграл". Визначений за значенням коефіцієнта дифузії розмір частинок пилу в космічній плазмі перевищує величину порядку 100 нм. Розмір порошинок є порівнянним з довжиною дифузії позитронів, 0,01 – 1 мкм, і початкова енергія позитронів може становити кілька електронвольт. Таким чином, отримані розміри порошинок добре узгоджуються з оцінками, що їх дають оптичні спостереження.